TRANSACTIONS

OF THE

AMERICAN INSTITUTE

OF

ELECTRICAL ENGINEERS

JANUARY TO DECEMBER 1934

Including certain 1933
material, as explained in
the preface

VOLUME 53

PUBLISHED BY THE
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
33 WEST THIRTY-NINTH STREET
NEW YORK, N.Y., U.S.A.
1934

Copyright 1934
By The
American Institute of Electrical Enneers

Printed in the United States of America by
The Mack Printing Company, Easton, Pennsylvia

Errata

1. Page 170 near bottom of second column—equation should read

$$E_{R2} = IR_2 = \frac{EA_0 p}{p^2 + A_1 p + A_2}$$

2. Page 175, fifth line from bottom of first column—the second remainder should be $k_2 - \alpha(k - 3\alpha)$

3. Page 175, Appendix III—equations should be corrected as follows

$$\frac{P^n\,1}{P^3 + K_2P^2 + K_3P + K_4} = \frac{(-\alpha)^{n-1}e^{-\alpha t}}{(\alpha - \beta)^2 - \omega^2} + \frac{(-\beta + \omega)^{n-1}e^{(-\beta+\omega)t}}{2\omega(\alpha - \beta - \omega)} + \frac{(-\beta - \omega)^{n-1}e^{(-\beta-\omega)t}}{-2\omega(\alpha - \beta - \omega)} + R \quad (1)$$

should be ⊕

$R = \frac{1}{K_4}$ for $n = 0$; $R = 0$ for $n = 1, 2,$ or 3

Where $P_1 = \alpha$, $P_2 = -\beta + j\omega$, and $P_3 = -\beta - j\omega$

should be ⊖

should be P_1 (P1)

$$\frac{P^1}{P^3 + K_2P^2 + K_3P + K_4} = \frac{1}{(\alpha - \beta)^2 + \omega^2}\left[e^{-\alpha t} - e^{-\beta t}\left\{\cos \omega t + \frac{\beta - \alpha}{\omega}\sin \omega t\right\}\right] \quad (3)$$

should be

$$\frac{P^2\,1}{P^3 + K_2P^2 + K_3P + K_4} = \frac{1}{(\alpha - \beta)^2 + \omega^2}\left[-\alpha e^{-\alpha t} - e^{-\beta t}\left\{-\alpha \cos \omega t - \frac{\beta^2 + \omega^2 - \alpha\beta}{\omega}\sin \omega t\right\}\right] \quad (4)$$

$-\epsilon^{-\beta t}$

$$\frac{P^n\,1}{P^4 + K_2P^3 + K_3P^2 + K_4P + K_5} = \frac{(-\alpha)^{n-1}e^{-\alpha t}}{A_1} + \frac{(-\beta)^{n-1}e^{-\beta t}}{A_2} + \frac{(-\gamma)^{n-1}e^{-\gamma t}}{A_3} + \frac{(-\delta)^{n-1}e^{-\delta t}}{A_4} + R \quad (6)$$

should be $-\alpha^3$

$R = \frac{1}{K_5}$ for $n = 0$; $R = 0$ for $n = 1, 2, 3,$ or 4

should be $-\beta^3$

$A_1 = -\alpha^3 + \alpha^2(\beta + \gamma + \delta) - \alpha(\beta\gamma + \beta\delta + \gamma\delta) + \beta\gamma\delta$
$A_2 = -\beta^3 + \beta^2(\alpha + \gamma + \delta) - \beta(\alpha\gamma + \alpha\delta + \gamma\delta) + \alpha\gamma\delta$
$A_3 = -\gamma^3 + \gamma^2(\alpha + \beta + \delta) - \gamma(\alpha\beta + \alpha\delta + \beta\delta) + \alpha\beta\delta$
$A_4 = -\delta^3 + \delta^2(\alpha + \beta + \gamma) - \delta(\alpha\beta + \alpha\gamma + \beta\gamma) + \alpha\beta\gamma$

should be P_1 (P1)

$$\frac{P^1}{P^4 + K_2P^3 + K_3P^2 + K_4P + K_5} = \frac{e^{-\alpha t}}{A_1} + \frac{e^{-\beta t}}{A_2} + \frac{2e^{-\gamma t}}{A_3^2 + A_4^2}\left[A_3 \cos \omega t + A_4 \sin \omega t\right] \quad (8)$$

4. Page 258, Table I—second item in last column should be 1.02

5. Page 770—title of paper by D. C. Jackson should be "The Evolution of Engineering Education."

6. Page 1316, 21st line from top of second column should read "general constants of . . . ."

Preface

This, the fifty-third volume of the TRANSACTIONS of the American Institute of Electrical Engineers, is the first of a new series of annual volumes initiated under the Institute's unified publication plan which became effective January 1, 1934. Under this plan this volume embraces the entire editorial content of the 12 1934 issues of ELECTRICAL ENGINEERING.

As explained in some detail on p. 1689, this volume embraces also 19 technical papers that were on the 1934 winter convention program and were published in ELECTRICAL ENGINEERING during the closing months of 1933, but not included in the final (September–December 1933) number of the quarterly TRANSACTIONS, v. 52.

Discussions of technical papers, printed from month-to-month in ELECTRICAL ENGINEERING are thoroughly correlated in the comprehensive multi-entry annual reference index that begins on p. 1815 of this volume. A reference to any one of the several subject entries for any technical paper will lead directly to any discussion that may have been published on that paper.

1934 Index—A.I.E.E. Transactions

Division I—Technical Subject Index

A 7,000-Ampere Station Bus. Unland, Morton, Bacon 994
Disc., 1646; clos 1650
A-C Potentiometer, An. Burgwin 108
Disc 624
Actions on Electric and Magnetic Units. Kennelly 402
Aerial Communication Cable, Iron Armored. Gilkeson, Hanks 890
Disc., 1324; clos 1325
(Air Conditioning) Steam Ejector for Car Conditioning. Ashley 406
Air, Impulse and 60-Cycle Strength of. Bellaschi, Teague 1638
Alternating Current Versus Direct Current. Stillwell 708
Alternators for Signaling Purposes, Inductor. Merrill 78
Amplification, Limits to. Johnson, Llewellyn 1449
Amplifiers, Auditory Perspective. Scriven 25
Disc 461
Amplifiers, Stabilized Feed-Back. Black 114
Disc., 461, 590; clos 1311
Analytical Representation of a Magnetizing Curve. Van Niekerk 1186
Anemometer, A Glow Discharge. Lindvall 1068
Arc at Low Pressures, Reignition of an. Mackeown, Bowden, Cobine 1081
Arc Electric Furnaces, Rocking Indirect. Crosby 132
Disc 452, 454, 591
Arc Furnace, The 3-Phase Electric. Arnold 1712
Disc., 492, 593; clos 594
Arc, High Velocity Streams in the Vacuum. Easton, Lucas, Creedy 1454
Arcover in Air, Insulator. Maxstadt 1062
Armature Windings, Insulation Resistance of. Wiseman 1010
Disc., 1407; clos 1524
Armored Aerial Communication Cable, Iron. Gilkeson, Hanks 890
Disc., 1324; clos 1325
Atmospheric Conditions, Corona Loss Vs. Hegy, Dunlap 272
Atoms and Molecules, Electronic Theory of Valence, Structure of. Huggins 851
Attenuation and Distortion of Waves. Bewley 1749
Disc., 471, 595; clos 597
Auditory Perspective—(See Communication)
Automatic Reclosing of Oil Circuit Breakers. Anderson 48
Disc., 466, 614; clos 615
(Automatic Stations) A Compensated Automatic Synchronizer. Seeley 960
Clos 1528
(Automatic Stations) Electronic Regulator for A-C Generators. Gulliksen 877
Disc., 1530; clos 1531
(Automatic Stations) Load Totalizing in the New York Area. Zogbaum 886
Disc., 1529; clos 1529
(Automatic Stations) Some New Developments in Supervisory Control. Reagan 949

B

Better Instrument Springs. Carson 283
Board of Directors, Report of the 1095
(Boulder Dam) Corona Losses From Conductors of 1.4-Inch Diameter. Carroll, Cozzens, Blakeslee 1727
Disc., 470, 600; clos 1310
(Boulder Dam) Power Limits of 220-Kv Transmission Lines. Kroneberg, Macferran 1795
Disc., 473; 601; clos 601
Bridge for Field Tests, Portable Schering. Hill, Watts, Burr 176
Disc., 478, 618; clos 1311
(Bklyn. (N. Y.) Ed. Co.) Switching at the Hudson Avenue Station. Gilt 1741
Disc., 456; clos 585
Budget, The Story of the Institute. Meyer 375
(Buffalo, Niagara & Eastern Pwr. Co.) Fundamentals of Design of Electric Energy Delivery Systems. Johnson, Henry 1704
Disc., 489, 493, 610; clos 612
Bus, A 7,000-Ampere Station. Unland, Morton, Bacon 994
Disc., 1646; clos 1650

C

Cable, Iron Armored Aerial Communication. Gilkeson, Hanks 890
Disc., 1324; clos 1325
Cable, The New Italy-Sardinia 528
Cables, Iron Shielding for Telephone. Moore 274
Disc., 1323; clos 1324
Cables, Resistance and Reactance of 3-Conductor. Salter, Shanklin, Wiseman 1581
Calculus, Operational. Gardner 1339
Calibration of the Sphere Gap. Meador. Disc., 1652; clos 1659
Carbon and Graphite, Electrodes—Vosburgh 1717
Disc 452
Carbon Arc, Characteristics and Uses of the. Kalb 1173
Carrier, Recent Developments in Power Line. Johnson 542
Disc 1325
Cast Iron and Its Production. Healey 120
Disc 452, 455, 590
Cathode Ray Tubes and Their Application. Stinchfield 1608
Cellulose Paper, Dielectric Properties of. Parts I and II. Whitehead, Greenfield 1389, 1949
Century of Progress in 50 Years, A. Rice 689
"Century of Progress," Lighting. Ryan 731
Characteristics and Uses of the Carbon Arc. Kalb 1173
Characteristics of a Group of Engineers. Spooner 1571
Circuit Breaker, A New High Speed Air. Keep 322
Circuit Breaker, The Expulsion Oil. Schwager 1108
Circuit Breakers, Automatic Reclosing of Oil. Anderson 48
Disc., 466, 614; clos 615
Circuit Formulas, Impulse Generator. Thomason 169
Disc 622
Circuits in Stability Studies, Equivalent. Dahl, Fitzgerald 1272
Circuits, Resonant Lines in Radio. Terman 1046
Circuits, Two Applications of Nonlinear. Austin, Cooper 293
Coaxial Communication Transmission Lines. Schelkunoff 1592
Coaxial Lines, Wide Band Transmission Over. Espenschied, Strieby 1371
(Com. rept.) A Survey of Hydroelectric Developments 988, 1086
Disc., 1651; clos 1652
(Com. rept.) Flashover Voltages of Insulators and Gaps 882
Disc 1531, 1537
(Com. rept.) Lightning Performance of 220-Kv Lines 1143
(Communication) A New Type of Warble Tone Generator. Bliss 547
(Communication) A 100-Kw Vacuum Tube 1266
(Communication) A Thermionic-Tube Measuring Instrument. Wagner 1621
(Communication) Auditory Perspective—Amplifiers. Scriven 25
Disc 461
(Communication) Auditory Perspective—Basic Requirements. Fletcher 9
Disc 461
(Communication) Auditory Perspective—Loud Speakers and Microphones. Wente, Thuras 17
Disc 461
(Communication) Auditory Perspective—Physical Factors. Steinberg, Snow 12
Disc 461
(Communication) Auditory Perspective—System Adaptation. Bedell, Kerney 216
Disc 461
(Communication) Auditory Perspective—Transmission Lines. Affel, Chestnut, Mills 28
Disc 461
Communication Cable, Iron Armored Aerial. Gilkeson, Hanks 890
Disc., 1324; clos 1325
(Communication) Cathode Ray Tubes and Their Application. Stinchfield 1608
(Communication) Effects of Rectifiers on System Wave Shape. Blye, Kent 54
Disc., 483, 608; clos 609
(Communication) Inductor Alternators for Signaling Purposes. Merrill 78
(Communication) Iron Shielding for Telephone Cables. Moore 274

This multientry annual reference index covers comprehensively the following divisions of material contained in this annual volume of the A.I.E.E. TRANSACTIONS:

1. The entire text portion of ELECTRICAL ENGINEERING for 1934, January to December inclusive;

2. A 126-page bound-in supplement containing 19 technical papers on the 1934 winter convention program that were published in ELECTRICAL ENGINEERING during the closing months of 1933, but not included in the final (September–December 1933) number of the quarterly TRANSACTIONS.

For convenience in reference use this index is subdivided into the following five general divisions:

1. **Technical subjects**
2. **Authors, including the writers of discussion**
3. **News items pertaining to Institute activities**
4. **Non-Institute news items**
5. **Biographical items**

Page Allocation

1. **Twelve Issues ELECTRICAL ENGINEERING 1–1688**
2. **1933 Supplement 1689–1814**

Disc., 1323; clos. 1324
(Communication) Joint Use of Poles With 6,900-Volt Lines. Bullard, Keyes 1763
Disc., 489, 491; clos. 610
(Communication) Limits to Amplification. Johnson, Llewellyn 1449
(Communication) Line Filter for Program System. Clement 562
Communication—Past and Present. Gherardi 745
(Communication) Ratings of Industrial Electronic Tubes. Pike, Ulrey 1577
(Communication) Recent Developments in Power Line Carrier. Johnson 542
Disc. 1325
(Communication) Resonant Lines in Radio Circuits. Terman 1046
(Communication) Stabilized Feed-Back Amplifiers. Black 114
Disc. 461, 590, 1311
(Communication) Telegraph Men Founders of the A.I.E.E. McNicol 675
(Communication) Television by Electronic Methods. Brolly 1153
(Communication) The "Compandor"—An Aid Against Radio Static. Mathes, Wright 860
(Communication) The "Ignitron" Inverter. Wagner, Ludwig 1384
(Communication) The New Italy-Sardinia Cable 528
(Communication) The "Thyratron" Motor. Alexanderson, Mittag 1517
(Communication) Theory of Multielectrode Tubes. Pidgeon 1485
Communication Transmission Lines, Coaxial. Schelkunoff 1592
(Communication) Vacuum Tubes as High Frequency Oscillators. Kelly, Samuel 1504
(Communication) Wide-Band Open-Wire Program System. Hamilton 550
(Communication) Wide Band Transmission Over Coaxial Lines. Espenschied, Strieby 1371
"Compandor"—An Aid Against Radio Static, The. Mathes, Wright 860
Compensated Automatic Synchronizer, A. Seeley 960
Clos. 1528
Composite Systems, Steady State Stability of. Crary 1809
Disc., 475, 477; clos. 594
Conduction, The Present Theory of Electric. Herzfeld 523
Conductor Vibration, Field Tests on. Wright, Mini 1123
Conductors of 1.4-Inch Diameter, Corona Losses From. Carroll, Cozzens, Blakeslee 1727
Disc., 470, 600; clos. 1310
Conductors, Vibration Analysis—Transmission Line. Buchanan 1478
Connors Creek Plant, Switching at the. Fugill 162
Disc., 456; clos. 586
(Control) Induction Motors as Selsyn Drives. Nowacki 1721
Control of Distance Relay Potential Connections. Warrington 206
Disc., 465; clos. 617
Control of Transients in Welding Generators. Hornby 1598
Control of Voltage and Power Factor, Simultaneous. Blume, Woods 1757
Disc. 483, 607
Control, Some New Developments in Supervisory. Reagan 949
Control, Voltage Regulation and Load. Forbes, Searing 903
Disc., 1525; clos. 1528
Corona Loss Vs. Atmospheric Conditions. Hegy, Dunlap 272
Corona Losses From Conductors of 1.4-Inch Diameter. Carroll, Cozzens, Blakeslee 1727
Disc., 460, 600; clos. 1310
Counterpoise Tests at Trafford. Fortescue, Fielder 1116
Counterpoise, Theory and Tests of the. Bewley 1163
Counterpoises for Transmission Lines. Fortescue 1781
Disc., 467, 473, 598; clos. 599
Cross Current of a 5-Arm Network. Seletsky, Anderson 1004
Disc., 1660; clos. 1660
Cross Potential of a 4-Arm Network. Seletsky 1734
Disc. 478

D

Decrement Curves for Power Systems. Dalziel 331
Delivery Systems, Fundamentals of Design of Electric Energy. Johnson, Henry 1704
Disc., 489, 493, 610; clos. 612
Demand Meter, A New. Smith 94
Disc., 625; clos. 626
Design Features of the Port Washington Power Plant. Post 264
Design of Electric Energy Delivery Systems, Fundamentals of. Johnson, Henry 1704
Disc., 489, 493, 610; clos. 612
Developments in Electric Power Transmission. Ryan 712
Developments in Power Line Carrier, Recent. Johnson 542
Disc. 1325
Developments, Significant Electrical 840
Dielectric Properties of Cellulose Paper. Parts I and II. Whitehead, Greenfield 1389, 1498
(Dielectrics) Impulse and 60-Cycle Strength of Air. Bellaschi, Teague 1638
Dielectrics, Measurement of Wetting of. McLean, Kohman 255
Diesel Electric Rail Cars and Locomotives. Storer 1461
Direct Current, Alternating Current Versus. Stillwell 708
Discharge Anemometer, A Glow. Lindvall 1068
Discharges, Electric Discharges in Gases — III, Self-Maintained. Slepian, Mason 511
Distance Relay Action During Oscillations. Bancker, Hunter 1073
Disc., 1320; clos. 1322
Distortion of Waves, Attenuation and. Bewley 1749
Disc., 471, 595; clos. 597
(Distribution) A New Laboratory for High Voltage Testing. Lusignan, Rorden 1255
(Distribution) A New Porcelain Post Insulator. Lapp 922
Disc., 1531, 1540; clos. 1541
Distribution, An Economic Study of Suburban. Sweetnam, Corney 97
(Distribution) Attenuation and Distortion of Waves. Bewley 1749
Disc., 471, 595; clos. 597
(Distribution) Corona Losses From Conductors of 1.4-Inch Diameter. Carroll, Cozzens, Blakeslee 1727
Disc., 470, 600; clos. 1310
(Distribution) Counterpoise Tests at Trafford. Fortescue, Fielder 1116
(Distribution) Decrement Curves for Power Systems. Dalziel 331
(Distribution) Dielectric Properties of Cellulose Paper. Parts I and II. Whitehead, Greenfield 1389, 1498
(Distribution) Distance Relay Action During Oscillations. Bancker, Hunter 1073
Disc., 1320; clos. 1322
(Distribution) Effects of Rectifiers on System Wave Shape. Blye, Kent 54
Disc., 483, 608; clos. 609
(Distribution) Field Tests on Conductor Vibration. Wright, Mini 1123
(Distribution) Flashover Voltages of Insulators and Gaps. (Com. rept.) 882
Disc. 1531, 1537
(Distribution) Fundamentals of Design of Electric Energy Delivery Systems. Johnson, Henry 1704
Disc., 489, 493, 610; clos. 612
(Distribution) High Voltage Insulators. Smith, Lusignan 969
Disc., 1531, 1536; clos. 1536
(Distribution) Insulator Arcover in Air. Maxstadt 1062
(Distribution) Insulator Surface and Radio Effects. Hillebrand, Miller 1213
(Distribution) Joint Use of Poles With 6,900-Volt Lines. Bullard, Keyes 1763
Disc., 489, 491; clos. 610
(Distribution) Lightning Investigation on a 220-Kv System. Bell 1188
(Distribution) Lightning Investigation on Transmission Lines—IV. Lewis, Foust 1180
(Distribution) Lightning Measured on 4-Kv Overhead Circuits. Halperin, McEachron 33
Disc., 465, 616; clos. 617
(Distribution) Lightning Performance of 132-Kv Lines. Sporn, Gross 1195
(Distribution) Lightning Performance of 220-Kv Lines. (Com. rept.) 1443
(Distribution) Loading a Bank of Dissimilar Transformers. Book 1597
(Distribution) Measurement of Noise From Power Transformers. Fugill 1603
(Distribution) Multiple Lightning Strokes. McEachron 1633
(Distribution) Overvoltages on Transmission Lines. Gilkeson, Jeanne 1301
Distribution, Radial Versus Primary Network. Wulfing 38
Disc. 489, 492, 610
(Distribution) Radio Influence Insulator Characteristics. Gilchrest 899
Disc., 1531, 1539; clos. 1539
Distribution Ratio Method, Locating Grounds by. Dunkle, DeShazo 258
(Distribution) Recent Developments in Suspension Insulators. Barrow 867
Disc., 1531, 1539; clos. 1540
(Distribution) Resistance and Reactance of 3-Conductor Cables. Salter, Shanklin, Wiseman 1581
(Distribution) Selection and Performance of Suspension Insulators. Sporn, Peterson, Mulford 936
Disc., 1531, 1538; clos. 1538
(Distribution) Some Recent Relay Developments. Hunt, Kroneberg 530
(Distribution) The Insulator String. Sorensen 1221
(Distribution) The Suspension Insulator. Hawley 895
Disc., 1531, 1536; clos. 1536
(Distribution) Theory and Tests of the Counterpoise. Bewley 1163
(Distribution) Theory of Primary Networks. Parts I and II. Starr 310, 426
Disc. 1315
(Distribution) Voltage Regulation and Load Control. Forbes, Searing 903
Disc., 1525; clos. 1528

E

Economic Study of Suburban Distribution, An. Sweetnam, Corney 97
Disc. 489, 610
(E.C.P.D.) Engineers of the Next Generation. Hirshfeld 857
Disc., 1413; clos. 1416
(Education) Characteristics of a Group of Engineers. Spooner 1571
(Education) Electric Discharges in Gases, Ionization and Excitation. Tonks 239
(Education) Electric Discharges in Gases—II, Ions in Dense Gases. Darrow 388
(Education) Electric Discharges in Gases—III, Self-Maintained Discharges. Slepian, Mason 511
(Education) Electron Emission. Dushman 1054

(Education) Encouraging Initiative in the Engineering Student. Dawes... 910
Disc., 1413, 1416; clos. 1417
(Education) Engineers of the Next Generation. Hirshfeld 857
Disc., 1413; clos. 1416
(Education) Fundamental Electrical Properties of Mercury Vapor and Monatomic Gases. Hull 1435
(Education) Fundamental Laws of Photo-Electricity. Hughes 1149
(Education) Fundamental Properties of the Electron. Waterman 3
Education, Industry Demands and Engineering. Morrow 518
Disc., 1413, 1418; clos. 1422
Education Is Meeting the Challenge, Engineering. Bibber 1356
(Education) Mapping of Fields. Weber 1563
(Education) On the Schooling of Engineers. Dow 1589
(Education) Operational Calculus. Gardner 1339
(Education) Recent Theories of Ferromagnetism. Bitter 1246
(Education) Structure of Atoms and Molecules, Electronic Theory of Valence. Huggins 851
Education, The Evolution of Electrical Engineering. Jackson 770
(Education) The Pitt-Westinghouse Graduate Program. Dyche, Hellmund 103
Disc., 446, 587; clos. 588
Effect of Oil Pressure on Insulation Strength. Scott 308
Effect of Overloads on Transformer Life. Nichols 1616
Effects of Rectifiers on System Wave Shape. Blye, Kent 54
Disc., 483, 608; clos. 609
Efficiency Tests of Induction Machines. Leader, Phillips 1628
Ejector System for Car Conditioning, Steam. Ashley 406
Electric and Magnetic Units, Actions on. Kennelly 402
Electric Conduction, The Present Theory of. Herzfeld 523
Electric Discharges in Gases, Ionization and Excitation. Tonks 239
Electric Discharges in Gases—II, Ions in Dense Gases. Darrow 388
Electric Discharges in Gases—III, Self-Maintained Discharges. Slepian, Mason 511
Electric Energy Delivery Systems, Fundamentals of Design of. Johnson, Henry 1704
Disc., 489, 493, 610; clos. 612
Electric Furnaces, Rocking Indirect Arc. Crosby 132
Disc. 452, 454, 591
Electric Furnaces, Transformers for. Stephens, Schell 1695
Disc. 452, 454
Electric Power Switching. Lovell 147
Disc. 456
(Electric Welding) A High Power Welding Rectifier. Silverman, Cox 1380
(Electric Welding) A New Timer for Resistance Welding. Stoddard 1366
(Electric Welding) High Velocity Streams in the Vacuum Arc. Easton, Lucas, Creedy 1454
(Electric Welding) Machine Characteristics for Steady Welding. Creedy, Kogge, Danello 1268
(Electric Welding) Transient Voltages in Welding Generators. Miller 1296
Electrical Equipment for Induction Furnaces. Levy 43
Disc. 452
Electrical Figures on Plates in Air. Pleasants 300
Electrical Industry, Some Contributions to. Chesney 726
(Electrical Machinery) A Graphical Solution of Steady State Stability. Dwight 566
Clos. 1316
(Electrical Machinery) An Experimental Ignitron Rectifier. Ludwig, Maxfield, Toepfer 75
Disc., 488, 602; clos. 602
(Electrical Machinery) Effect of Overloads on Transformer Life. Nichols 1616
(Electrical Machinery) Effects of Rectifiers on System Wave Shape. Blye, Kent 54
Disc., 483, 608; clos. 609
(Electrical Machinery) Efficiency Tests of Induction Machines. Leader, Phillips 1628
(Electrical Machinery) Equivalent Reactance of Synchronous Machines. Crary, March, Shildneck 124
Disc., 484, 603; clos. 605
(Electrical Machinery) External Impedance Vs. Short-Circuit Currents. Robertson, Rogers 252
(Electrical Machinery) Factors Influencing the Insulation Coördination of Transformers—II. Bellaschi, Vogel 870
Disc., 1401; clos. 1406
(Electrical Machinery) Grid Controlled Rectifiers and Inverters 926
Disc., 1400; clos. 1401
(Electrical Machinery) Heat Flow in Turbine Generator Rotors. Peck 1359
(Electrical Machinery) Impulse and 60-Cycle Strength of Air. Bellaschi, Teague 1638
(Electrical Machinery) Induction Motor Locked Saturation Curves. Norman 536
Disc. 1312
(Electrical Machinery) Induction Motors as Selsyn Drives. Nowacki 1721
(Electrical Machinery) Inductor Alternators for Signaling Purposes. Merrill 78
(Electrical Machinery) Insulation Resistance of Armature Windings. Wiseman 1010
Disc., 1407; clos. 1524
(Electrical Machinery) Irregular Windings in Wound Rotor Induction Motors. Hellmund, Veinott 342
Disc., 1316; clos. 1317
(Electrical Machinery) Measurement of Noise From Power Transformers. Fugill 1603
(Electrical Machinery) Measurement of Noise From Small Motors. Veinott 1624
(Electrical Machinery) Output Wave Shape of Controlled Rectifiers. Stebbins, Frick 1259
(Electrical Machinery) Overloading of Power Transformers. Montsinger, Dann 1353
(Electrical Machinery) Power Losses in Induction Machines. Narbutovskih 1466
(Electrical Machinery) Protecting Machines From Line Surges. Calvert 139
Disc., 488; clos. 608
(Electrical Machinery) Reactance and Stray Losses of Power Transformers. Cole 338
(Electrical Machinery) Recommended Transformer Standards. Putnam, Clem 1594
(Electrical Machinery) Simultaneous Control of Voltage and Power Factor. Blume, Woods 1757
Disc. 483, 607
(Electrical Machinery) Split Winding Transformers. Chase, Garin 914
Disc., 1411; clos. 1412
(Electrical Machinery) Stray Load Loss Test on Induction Machines. Morgan, Narbutovskih 286
Disc., 1317; clos. 1318
(Electrical Machinery) Transformer Reactance and Losses With Nonuniform Windings. Stephens 346
Disc., 1318; clos. 1319
(Electrical Machinery) Transients in Magnetic Systems. Wagner 418
(Electrical Machinery) Voltage Control of Vapor Rectifiers. Journeaux 976
Disc., 1396; clos. 1399
Electrical Practices in USSR Steel. Fox 1251
Electrical Properties of Mercury Vapor and Monatomic Gases, Fundamental. Hull 1435
(Electrochemistry) (See Electrometallurgy)
Electrodes—Carbon and Graphite. Vosburgh 1717
Disc. 452
(Electromagnetics) Silicon Steel With A-C and D-C Excitation. Edgar 318
(Electrometallurgy) Cast Iron and Its Production. Healey 120
Disc. 452, 455, 590
(Electrometallurgy) Electrical Equipment for Induction Furnaces. Levy 43
Disc. 452
(Electrometallurgy) High Frequency Induction Furnaces. Adams, Hodge, MacKusick 194
Disc. 452, 455, 592
(Electrometallurgy) Rocking Indirect Arc Electric Furnaces. Crosby 132
Disc. 452, 454, 591
(Electrometallurgy) The 3-Phase Electric Arc Furnace. Arnold 1712
Disc., 492, 593; clos. 594
(Electrometallurgy) Transformers for Electric Furnaces. Stephens, Schell 1695
Disc. 452, 454
Electron Emission. Dushman 1054
Electron, Fundamental Properties of the. Waterman 3
Electronic Methods, Television by. Brolly 1153
Electronic Regulator for A-C Generators, Gulliksen 877
Disc., 1530; clos. 1531
Electronic Theory of Valence, Structure of Atoms and Molecules. Huggins 851
Electronic Tubes, Ratings of Industrial. Pike, Ulrey 1577
(Electronics) A Compensated Automatic Synchronizer. Seeley 960
Clos. 1528
(Electronics) A High Power Welding Rectifier. Silverman, Cox 1380
(Electronics) A New Timer for Resistance Welding. Stoddard 1366
(Electronics) A Telemeter With Pilot Coil Transmitter. Lunas, Bernarde 974
Disc., 1660; clos. 1661
(Electronics) A Thermionic-Tube Measuring Instrument. Wagner 1621
(Electronics) A Vacuum Tube Controlled Rectifier. Foos 568
(Electronics) An Experimental Ignitron Rectifier. Ludwig, Maxfield.
Disc., 488, 602; clos. 602
(Electronics) Cathode Ray Tubes and Their Application. Stinchfield 1608
(Electronics) Effects of Rectifiers on System Wave Shape. Blye, Kent 54
Disc., 483, 608; clos. 609
(Electronics) Grid Controlled Rectifiers and Inverters. Herskind 926
Disc., 1400; clos. 1401
(Electronics) High Velocity Streams in the Vacuum Arc. Easton, Lucas, Creedy 1454
(Electronics) Output Wave Shape of Controlled Rectifiers. Stebbins, Frick 1259
(Electronics) The "Thyratron" Motor. Alexanderson, Mittag 1517
(Electronics) Theory of Multielectrode Tubes. Pidgeon 1485
(Electronics) "Thyratron" Tubes in Relay Practice. Wideröe 1347
(Electronics) Two Applications of Nonlinear Circuits. Austin, Cooper 293
(Electronics) Vacuum Tubes as High

Frequency Oscillators. Kelly, Samuel ... 1504
(Electronics) Voltage Control of Vapor Rectifiers. Journeaux ... 976
Disc., 1396; clos. ... 1399
(Electrophysics) Electrical Figures on Plates in Air. Pleasants ... 300
Emission, Electron. Dushman ... 1054
Encouraging Initiative in the Engineering Student. Dawes ... 910
Disc., 1413, 1416; clos. ... 1417
(Letter) McMains ... 1678
Energy Consumption of Multiple Unit Cars. Compton ... 280
Energy Consumption on Street Railways. Thomas ... 326
Engineer a Creator of Leisure, The. McClellan ... 777
Engineering Approach, Social Aspects of the. Wallace ... 395
Engineering Education Is Meeting the Challenge. Bibber ... 1356
Engineering, Research and. Jewett ... 781
Engineers of the Next Generation. Hirshfeld ... 857
Disc., 1413; clos. ... 1416
(Letter) McMains ... 1678
Equation of Electrical Propogation, The. Pupin ... 691
Equivalent Circuits in Stability Studies. Dahl, Fitzgerald ... 1272
Equivalent Reactance of Synchronous Machines. Crary, March, Shildneck ... 124
Disc., 484, 603; clos. ... 605
Evolution of Electrical Engineering Education, The. Jackson ... 770
Excitation, Electric Discharges in Gases, Ionisation and. Tonks ... 239
Excitation, Silicon Steel With A-C and D-C. Edgar ... 318
Experimental Ignitron Rectifier, An. Ludwig, Maxfield, Toepfer ... 75
Disc., 488, 602; clos. ... 602
Experiments in Fatal Electric Shock. Conrad, Haggard ... 399
Expulsion Oil Circuit Breaker, The. Schwager ... 1108
External Impedance Vs. Short-Circuit Currents. Robertson, Rogers ... 252

F

Factors Influencing the Insulation Coordination of Transformers—II. Bellaschi, Vogel ... 870
Disc., 1401; clos. ... 1406
Ferromagnetism, Recent Theories of. Bitter ... 1246
Field Tests on Conductor Vibration. Wright, Mini ... 1123
Fiftieth Anniversary
(See Also Under "News of A.I.E.E. Activities")
Alternating Current Versus Direct Current. Stillwell ... 708
Century of Progress in 50 Years, A. Rice ... 689
Communication—Past and Present. Gherardi ... 745
Developments in Electric Power Transmission. Ryan ... 712
Digging in "The Mines of the Motors." Sprague ... 695
Early Headquarters of the Institute. Dunn ... 685
Engineer a Creator of Leisure, The. McClellan ... 777
Equation of Electrical Propagation, The. Pupin ... 691
Evolution of Electrical Engineering, The. Jackson ... 770
Fiftieth Anniversary of the A.I.E.E., The. Whitehead ... 643
Institute and Industrial Standardization, The. Skinner ... 681
Institute's First Half Century, The. Scott ... 645
Institute's Organization, The. Charlesworth ... 671
Lighting "A Century of Progress." Ryan ... 731
Research and Engineering. Jewett ... 781
Some Contributions to the Electrical Industry. Chesney ... 726
Some High Lights of Electrical History. Thomson ... 758
Some Major Events in the Life of the Institute. Adams ... 686
Some Reminiscences of Niagara. Lincoln ... 720
Telegraph Men Founders of the A.I.E.E. McNicol ... 675
Water Power Development. Lee ... 715
Work of the Institute in Standardization, The. Kennelly ... 676
Filter for Program System, Line. Clement ... 562
Flashover Voltages of Insulators and Gaps. (Com. rept.) ... 882
Disc. ... 1531, 1537
Fundamental Electrical Properties of Mercury Vapor and Monatomic Gases. Hull ... 1435
Fundamental Laws of Photoelectricity. Hughes ... 1149
Fundamental Properties of the Electron. Waterman ... 3
Fundamentals of Design of Electric Energy Delivery Systems. Johnson, Henry ... 1704
Disc., 489, 493, 610; clos. ... 612
Furnace, The 3-Phase Electric Arc. Arnold ... 1712
Disc., 492, 593; clos. ... 594
Furnaces, Electrical Equipment for Induction Furnaces. Levy ... 43
Disc. ... 452
Furnaces, High Frequency Induction. Adams, Hodge, MacKusick ... 194
Disc. ... 452, 455, 592
Furnaces, Rocking Indirect Arc Electric. Crosby ... 132
Disc. ... 452, 454, 591
Furnaces, Transformers for Electric. Stephens, Schell ... 1695
Disc. ... 452, 454

G

Gap, Calibration of the Sphere. Meador ... 942
Disc., 1652; clos. ... 1659
Gaps, Flashover Voltages of Insulators and. (Com. rept.) ... 882
Disc. ... 1531, 1537
Gaseous Discharge Lamps, Low Pressure. Parts I and II. Dushman ... 1204, 1283
Gases, Electric Discharges in, Ionization and Excitation. Tonks ... 239
Gases—Electric Discharges in—II Ions in Dense Gases. Darrow ... 388
Gases—III, Self-Maintained Discharges, Electric Discharges in. Slepian, Mason ... 511
Generation and Measurement—Heavy Surge Currents. Bellaschi ... 86
Disc., 481, 622; clos. ... 623
Generator, A New Type of Warble Tone. Bliss ... 547
Generator Circuit Formulas, Impulse. Thomason ... 169
Disc. ... 622
Generators, Control of Transients in Welding. Hornby ... 1598
Generators, Electronic Regulator for A-C. Gulliksen ... 873
Disc., 1530; clos. ... 1567
Generators, Transient Voltages in Welding. Miller ... 1219
Glow Discharge Anemometer, A. Lindvall ... 1086
Graphical Solution of Steady State Stability, A. Dwight ... 566
Clos. ... 1316
Graphite, Electrodes—Carbon and. Vosburgh ... 1717
Disc. ... 452
Grid Controlled Rectifiers and Inverters. Herskind ... 926
Disc., 1400; clos. ... 1401
Ground Fault Protection, A New Method of. Starr ... 1472
Grounds by Distribution Ratio Method, Locating. Dunkle, DeShazo ... 258

H

Heat Flow in Turbine Generator Rotors. Peck ... 1359
Heavy Surge Currents—Generation and Measurement. Bellaschi ... 86
Disc., 622; clos. ... 623
High Frequency Induction Furnaces. Adams, Hodge, MacKusick ... 194
Disc. ... 452, 455, 592
High Lights of Electrical History, Some. Thomson ... 758
High Power Welding Rectifier, A. Silverman, Cox ... 1380
High Velocity Streams in the Vacuum Arc. Easton, Lucas, Creedy ... 1454
High Voltage Insulators. Smith, Lusignan ... 969
Disc., 1531, 1536; clos. ... 1536
History, Some High Lights of Electrical. Thomson ... 758
Hudson Avenue Station, Switching at the. Gilt ... 1741
Disc., 456; clos. ... 585
(Human Relations) An Insight Into the Workings of the Institute. Johnson ... 1039
(Human Relations) Characteristics of a Group of Engineers. Spooner ... 1571
(Human Relations) Engineers of the Next Generation. Hirshfeld ... 857
Disc., 1413; clos. ... 1416
(Human Relations) Industry Demands and Engineering Education. Morrow ... 518
Disc., 1413, 1418; clos. ... 1422
(Human Relations) On the Schooling of Engineers. Dow ... 1589
(Human Relations) Scientific Thought and Social Reconstruction. Mees ... 381
(Human Relations) Social Aspects of the Engineering Approach. Wallace ... 395
(Human Relations) The Engineer a Creator of Leisure. McClellan ... 777
(Human Relations) Toward the Making of a Profession. Wickenden ... 1147
Hydroelectric Developments, A Survey of. (Com. rept.) ... 988, 1086
Disc., 1651; clos. ... 1652
(Hydroelectric) Some Reminiscences of Niagara. Lincoln ... 720
(Hydroelectric) Water Power Development. Lee ... 715

I

("Ignitron") A High Power Welding Rectifier. Silverman, Cox ... 1380
"Ignitron" Rectifier, An Experimental. Ludwig, Maxfield, Toepfer ... 75
Disc., 488, 602; clos. ... 602
"Ignitron" Type of Inverter, The. Wagner, Ludwig ... 1384
(Illumination) Characteristics and Uses of the Carbon Arc. Kalb ... 1173
(Illumination) Incandescence—Some Theoretical Aspects. Hibben ... 1201
(Illumination) Lighting "A Century of Progress." Ryan ... 731
(Illumination) Low Pressure Gaseous Discharge Lamps. Parts I and II. Dushman ... 1204, 1283
(Illumination) Vapor Conducting Light Sources. Mailey ... 1447
Impedance Vs. Short-Circuit Currents, External. Robertson, Rogers ... 252
Impedances, Investigation of Rail. Trueblood, Wascheck ... 1771
Disc., 450; clos. ... 589
Impulse and 60-Cycle Strength of Air. Bellaschi, Teague ... 1638
Impulse Generator Circuit Formulas. Thomason ... 169
Disc. ... 622

Incandescence—Some Theoretical Aspects. Hibben 1201
Incremental Rates and Their Practical Application to Load Division, The Theory of. Parts I and II. Steinberg, Smith 432, 571
Induction Furnaces, Electrical Equipment for. Levy 43
Disc. 452
Induction Furnaces, High Frequency. Adams, Hodge, MacKusick 194
Disc. 452, 455, 592
Induction Machines, Efficiency Tests of. Leader, Phillips 1628
Induction Machines, Power Losses in. Narbutovskih 1466
Induction Machines, Stray Load Loss Test on. Morgan, Narbutovskih 286
Disc., 1317; clos. 1318
Induction Motor Locked Saturation Curves. Norman 536
Disc. 1312
Induction Motors as Selsyn Drives. Nowacki 1721
Induction Motors, Irregular Windings in Wound Rotor. Hellmund, Veinott 342
Disc., 1316; clos. 1317
Inductor Alternators for Signaling Purposes. Merrill 78
(Industrial) Electrodes—Carbon and Graphite. Vosburgh 1717
Disc. 452
Industrial Electronic Tubes, Ratings of. Pike, Ulrey 1577
(Industrial) The 3-Phase Electric Arc Furnace 1712
Disc., 492, 593; clos. 594
Industry Demands and Engineering Education. Morrow 518
Disc., 1413, 1418; clos. 1422
(Letter) McMains 1678
Insight Into the Workings of the Institute, An. Johnson 1039
Institute, an Insight Into the Workings of the. Johnson 1039
Institute and Industrial Standardization, The. Skinner 681
Institute Budget, The Story of the. Meyer 375
Institute on Its 50th Anniversary, The. Whitehead 1143
Institute's First Half Century, The. Scott 645
Institute's Organization, The. Charlesworth 671
Instrument, A Thermionic-Tube Measuring. Wagner 1621
Instrument Springs, Better. Carson 282
(Instruments) A Glow Discharge Anemometer. Lindvall 1068
(Instruments) A New Demand Meter. Smith 94
Disc., 625; clos. 626
(Instruments) A New Type of Warble Tone Generator. Bliss 547
(Instruments) A Telemeter With Pilot Coil Transmitter. Lunas, Bernarde. 974
Disc., 1660; clos. 1661
(Instruments) A Unique Oscillograph. Oplinger 290
(Instruments) An A-C Potentiometer. Burgwin 108
Disc. 624
(Instruments) Calibration of the Sphere Gap. Meador 942
Disc., 1652; clos. 1659
(Instruments) Cross Current of a 5-Arm Network. Seletzky, Anderson 1004
Disc., 1660; clos. 1660
(Instruments) Cross Potential of a 4-Arm Network. Seletzky 1734
Disc. 478
Instruments for Position Systems, Selsyn. Linville, Woodward 953
Disc. 1660
(Instruments) Heavy Surge Currents—Generation and Measurement 86
Disc., 481, 622; clos. 623
(Instruments) Impulse Generator Circuit Formulas. Thomason 169
Disc. 622
(Instruments) Portable Schering Bridge for Field Tests. Hill, Watts, Burr 176
Disc., 478, 618; clos. 1311
(Instruments) Simplified Measurements of Sound Absorption. Albert, Wagner. 1160
(Insulation) A New Laboratory for High Voltage Testing. Lusignan, Rorden 1255
Insulation Coördination of Transformers—II, Factors Influencing the. Bellaschi, Vogel 870
Disc., 1401; clos. 1406
(Insulation) Dielectric Properties of Cellulose Paper. Parts I and II. Whitehead, Greenfield 1389, 1498
(Insulation) Impulse and 60-Cycle Strength of Air. Bellaschi, Teague 1638
(Insulation) Measurement of Wetting of Dielectrics. McLean, Kohman 255
(Insulation) Protecting Machines From Line Surges. Calvert 139
Disc., 488; clos. 608
Insulation Resistance of Armature Windings. Wieseman 1010
Disc., 1407; clos. 1524
Insulation Strength, Effect of Oil Pressure on. Scott 308
(Insulation) The Life of Impregnated Paper. Whitehead 244
(Insulation) The Present Theory of Electric Conduction. Herzfeld 523
Insulator, A New Porcelain Post. Lapp 922
Disc., 1531, 1540; clos. 1541
Insulator Arcover in Air. Maxstadt 1062
(Letter) Walker 1680
Insulator Characteristics, Radio Influence. Gilchrest 899
Disc., 1531, 1539; clos. 1539
Insulator String, The. Sorensen 1221
Insulator Surface and Radio Effects. Hillebrand, Miller 1213
Insulator, The Suspension. Hawley 895
Disc., 1531, 1536; clos. 1536
Insulators and Gaps, Flashover Voltages of. (Com. rept.) 882
Disc. 1531, 1537
Insulators, High Voltage. Smith, Lusignan 969
Disc., 1531, 1536; clos. 1536
Insulators, Recent Developments in Suspension. Barrow 867
Disc., 1531, 1539; clos. 1540
Insulators, Selection and Performance of Suspension. Sporn, Peterson, Mulford 936
Disc., 1531, 1538; clos. 1538
Inverter, The "Ignitron" Type of. Wagner, Ludwig 1384
Inverters, Grid Controlled Rectifiers and. Herskind 926
Disc., 1400; clos. 1401
Investigation of Rail Impedances. Trueblood, Wascheck 1771
Disc., 450; clos. 589
Ionization and Excitation, Electric Discharges in Gases. Tonks 239
Ions in Dense Gases, Electric Discharges in Gases—II Darrow 388
Iron and Its Production, Cast. Healey.
Disc. 452, 455, 590
Iron Armored Aerial Communication Cable. Gilkeson, Hanks 890
Disc., 1324; clos. 1325
Iron Shielding for Telephone Cables. Moore 274
Disc., 1323; clos. 1324
Irregular Windings in Wound Rotor Induction Motors. Hellmund, Veinott 342
Disc., 1316; clos. 1317
Italy-Sardinia Cable, The New 528

J

Joint Use of Poles With 6,900-Volt Lines. Bullard, Keyes 1763
Disc., 489, 491; clos. 610

L

Laboratory for High Voltage Testing, A New. Lusignan, Rorden 1255
Lamps, Low Pressure Gaseous Discharge. Parts I and II. Dushman 1204, 1283
Letters to the Editor
A Chart for Complex Quantities. Journeaux 502
A Theory Regarding Ionization in Cable Fibers. Del Mar 500
Applications of Nonlinear Circuits. Lubkin 502
Appreciation of the "Science Series." Roach, Palmer, Rhodes 1031
Arcover Caused by Absorption Current. Walker 1680
Cable Failure and Dielectric Deterioration. Dawes, Humphries 1133
Designations of Photo-Electric Devices. Sharp 1682
Early Development of the Transformer. Fleming 634
Electrical Characteristics of Impregnated Cable Paper. Dawes 1235
Engineering Education for Non-Engineers. Seeley 1328
Engineering Education Should Train 2 Types of Engineers. McMains 1678
Engineering Schools and the Changed Conditions. Dawes 364
Engineering Service. James 1427
Excitation and Ionization in Gases. Sohon 1235
Graduate Engineering Study Remote From Industrial Centers. Naeter 501
Graphical Solution of Star-Delta Transformations. Edson 1427
Ball 1680
History of Thomson-Houston Company Name. Price-Hughes 1133
Improving A.I.E.E. Convention Sessions. Holton 500
Information on Oliver Heaviside. Tucker 1554
Jogging the Rotor of an Alternator Electrically. Sills 363
Limiting Reactances of 2-Terminal Reactance Arms. Lutz 634
New Method of Calculating Circuits, A. Barkey 228
Di Toro 229
Kouwenhoven 229
Operational Calculus. Barkey 1681
Overcompounded D-C Generators in Parallel Without Equalizer. Walter. 1553
Potential Available for Gaseous Discharge in Insulation Voids. Baker. 363
Public Versus Private Enterprise. Jakobsen 500
Reignition of an Arc at Low Pressures. Mason 1679
Rocking Indirect Arc Electric Furnaces. Buck 1134
Rhoads 1134
Shunt Wound Neutralized Phase Advancer. R. D. Ball 501
Slide Rule Calculation of $\sqrt{a^2 + b^2}$. Smith 228
Slide Rule Calculation of Unbalanced 3-Phase Currents. Seaman 365, 1031
Stroboscope to Study Hunting of a Synchronous Motor, A New. Winkler 1678
Theory of Probability. Smith 229
Ferman 1235
Wine Makers and Bottle Makers—A Parable. Karapetoff 1681
Life of Impregnated Paper. Whitehead. 244
(Light) Characteristics and Uses of the Carbon Arc. Kalb 1173
(Light) Incandescence—Some Theoretical Aspects. Hibben 1201
(Light) Low Pressure Gaseous Discharge Lamps. Parts I and II. Dushman 1204, 1283
Light Sources, Vapor Conducting. Mailey 1447
Lighting "A Century of Progress Exposition." Ryan 731

(Lightning) Attenuation and Distortion of Waves. Bewley ... 1749
Disc., 471, 595; clos. ... 597
(Lightning) Counterpoises for Transmission Lines. Fortescue ... 1781
Disc., 467, 473, 598; clos. ... 599
(Lightning) Flashover Voltages of Insulators and Gaps. (Com. rept.) ... 882
Disc. ... 1531, 1537
Lightning Investigation on a 220-Kv System. Bell ... 1188
Lightning Investigation on Transmission Lines—IV. Lewis, Foust ... 1180
Lightning Measured on 4-Kv Overhead Circuits. Halperin, McEachron ... 33
Disc., 465, 616; clos. ... 617
Lightning Performance of 132-Kv Lines. Sporn, Gross ... 1195
Lightning Performance of 220-Kv Lines. (Com. rept.) ... 1443
Lightning Strokes, Multiple. McEachron ... 1633
Limits to Amplification. Johnson, Llewellyn ... 1449
Line Filter for Program System. Clement ... 562
Load Division, The Theory of Incremental Rates and Their Practical Application to. Parts I and II. Steinberg, Smith ... 432, 571
Load Loss Test on Induction Machines, Stray. Morgan, Narbutovskih ... 286
Disc., 1317; clos. ... 1318
Load Totalising in the New York Area. Zogbaum ... 886
Disc., 1529; clos. ... 1529
Loading a Bank of Dissimilar Transformers. Bock ... 1597
Locating Grounds by Distribution Ratio Method. Dunkle, DeShazo ... 258
Locked Saturation Curves, Induction Motor. Norman ... 536
Disc. ... 1312
Locomotives, Diesel Electric Rail Cars and. Storer ... 1461
Locomotives, Protective Relays on Pa. Luther ... 261
Long Beach Plant No. 3., Switching at. Kroneberg, Bulkley, Andree ... 1699
Disc. ... 456
Loss Characteristics of Silicon Steel at 60 Cycles With D-C Excitation. Edgar. 318
Loss Vs. Atmospheric Conditions, Corona. Hegy, Dunlap ... 272
Losses in Induction Machines, Power. Narbutovskih ... 1466
Losses of Power Transformers, Reactance and Stray. Cole ... 339
Losses With Nonuniform Windings, Transformer Reactance and. Stephens ... 347
Disc., 1318; clos. ... 1319
Loud Speakers and Microphones, Auditory Perspective. Wente, Thuras ... 17
Disc. ... 461
Low Pressure Gaseous Discharge Lamps. Parts I and II. Dushman ... 1204, 1283
Lubrication Improved, Trolley Wire. Lamson ... 1690
Disc. ... 449, 1314

M

Machine Characteristics for Steady Welding. Creedy, Kogge, Danello ... 1268
Machines, Power Limits of Synchronous. Clarke, Lorraine ... 1802
Disc., 475; clos. ... 601
Magnetic Systems, Transients in. Wagner ... 418
Magnetic Units, Actions on Electric and. Kennelly ... 402
Magnetising Curve, Analytical Representation of a. Van Niekerk ... 1186
Major Events in the Life of the Institute, Some. Adams ... 686
Mapping of Fields. Weber ... 1563
(Mathematics) Operational Calculus. Gardner ... 1339
Measurement, Heavy Surge Currents—Generation and. Bellaschi ... 86
Disc., 481, 622; clos. ... 623
Measurement of Noise From Power Transformers. Fugill ... 1603
Measurement of Noise From Small Motors. Veinott ... 1624
Measurement of Wetting of Dielectrics. McLean, Kohman ... 255
(Measurements) A New Type of Warble Tone Generator. Bliss ... 547
(Measurements) A Telemeter With Pilot Coil Transmitter. Lunas, Bernarde ... 974
Disc., 1660; clos. ... 1661
(Measurements) A Unique Oscillograph. Oplinger ... 290
(Measurements) An A-C Potentiometer. Burgwin ... 108
Disc. ... 624
(Measurements) Calibration of the Sphere Gap. Meador ... 942
Disc., 1652; clos. ... 1659
(Measurements) Corona Loss Vs. Atmospheric Conditions. Hegy, Dunlap ... 272
(Measurements) Cross Current of a 5-Arm Network. Seletzky, Anderson ... 1004
Disc., 1660; clos. ... 1660
(Measurements) Cross Potential of a 4-Arm Network. Seletzky ... 1734
Disc. ... 478
(Measurements) Impulse Generator Circuit Formulas. Thomason ... 169
Disc. ... 622
(Measurements) Investigation of Rail Impedances. Trueblood, Wascheck. 1771
Disc., 450; clos. ... 589
Measurements of Sound Absorption, Simplified. Albert, Wagner ... 1160
(Measurements) Portable Schering Bridge for Field Tests. Hill, Watts, Burr ... 176
Disc., 478, 618; clos. ... 1311
(Measurements) Selsyn Instruments for Position Systems. Linville, Woodward ... 953
Disc. ... 1660
(Measurements) Vibration Analysis—Transmission Line Conductors. Buchanan ... 1478
Measuring Instrument, A Thermionic-Tube. Wagner ... 1621
Mercury Vapor and Monatomic Gases, Fundamental Electrical Properties of. Hull ... 1435
Message From the President. Johnson ... 1142, 1338
(Letter) James ... 1427
Meter, A New Demand. Smith ... 94
Disc., 625; clos. ... 626
(Metering) Load Totalizing in the New York Area. Zogbaum ... 886
Disc., 1529; clos. ... 1529
Microphones, Auditory Perspective—Loud Speakers and. Wente, Thuras 17
Disc. ... 461
Modern Transportation's Most Recent Contribution to Speed and Safety ... 349
Molecules, Electronic Theory of Valence, Structure of Atoms and. Huggins ... 851
Monatomic Gases, Fundamental Electrical Properties of Mercury Vapor and. Hull ... 1435
Motor Locked Saturation Curves, Induction. Norman ... 536
Disc. ... 1312
Motor, The "Thyratron." Alexanderson, Mittag ... 1517
Motors as Selsyn Drives, Induction. Nowacki ... 1721
Motors, Irregular Windings in Wound Rotor Induction. Hellmund, Veinott ... 342
Disc., 1316; clos. ... 1317
Motors, Measurement of Noise From Small. Veinott ... 1624
Multielectrode Tubes, Theory of. Pidgeon ... 1485
Multiple Lightning Strokes, McEachron ... 1633
Multiple Unit Cars, Energy Consumption of. Compton ... 280

N

(National Research Council) The Present Theory of Electric Conduction. Herzfeld ... 523
Network, Cross Current of a 5-Arm. Seletzky, Anderson ... 1004
Disc., 1660; clos. ... 1660
Network, Cross Potential of a 4-Arm. Seletzky ... 1734
Disc. ... 478
Network Distribution, Radial Versus Primary. Wulfing ... 38
Disc. ... 489, 610
(Networks) External Impedance Vs. Short-Circuit Currents. Robertson, Rogers ... 252
Networks, Theory of Primary. Parts I and II. Starr ... 310, 426
Disc. ... 1315
New Demand Meter, A. Smith ... 94
Disc., 625; clos. ... 626
New High Speed Air Circuit Breaker, A. Keep ... 323
New Laboratory for High Voltage Testing, A. Lusignan, Rorden ... 1255
New Method of Ground Fault Protection, A. Starr ... 1472
New Porcelain Post Insulator, A. Lapp ... 922
Disc., 1531, 1540; clos. ... 1541
New Timer for Resistance Welding, A. Stoddard ... 1366
New Type of Warble Tone Generator, A. Bliss ... 547
Nitrogen in Metallic Arc Weld Metal, A Study of ... 1250
Noise From Power Transformers, Measurement of. Fugill ... 1603
Noise From Small Motors, Measurement of. Veinott ... 1624

O

Oil Circuit Breaker, The Expulsion. Schwager ... 1108
Oil Circuit Breakers, Automatic Reclosing of. Anderson ... 48
Disc., 466, 614; clos. ... 615
Oil Pressure on Insulation Strength, Effect of. Scott ... 308
Operational Calculus. Gardner ... 1339
(Letter) Barkey ... 1681
Oscillators, Vacuum Tubes as High Frequency. Kelly, Samuel ... 1504
Oscillograph, A Unique. Oplinger ... 290
Output Wave Shape of Controlled Rectifiers. Stebbins, Frick ... 1259
Overloading of Power Transformers. Montsinger, Dann ... 1353
Overloads on Transformer Life, Effect of. Nichols ... 1616
Overvoltages on Transmission Lines. Gilkeson, Jeanne ... 1301

P

Paper, The Life of Impregnated. Whitehead ... 244
Pantograph Trolleys I—Design Features. Schaake ... 182
Disc., 451, 1313; clos. ... 589
Pantograph Trolleys II—Operating Features. Pickens ... 190
Disc. ... 451, 1313
Petersen Coil Tests on 140-Kv System. North, Eaton ... 63
Disc., 462, 612; clos. ... 614
Photoelectricity, Fundamental Laws of. Hughes ... 1149
Pilot Coil Transmitter, A Telemeter With. Lunas, Bernarde ... 974
Disc., 1660; clos. ... 1661
Pitt-Westinghouse Graduate Program, The. Dyche, Hellmund ... 103
Disc., 446, 587; clos. ... 588
Poles With 6,900-Volt Lines, Joint Use of. Bullard, Keyes ... 1763

Disc., 489, 491; clos. 610
Porcelain Post Insulator, A New. Lapp. 922
Port Washington Power Plant Design. Post 264
Portable Schering Bridge for Field Tests. Hill, Watts, Burr 176
Disc., 478, 618; clos. 1311
Position Systems, Selsyn Instruments for. Linville, Woodward 953
Disc. 1660
Potential of a 4-Arm Network, Cross. Seletsky 1734
Disc. 478
Potentiometer, An A-C. Burgwin 108
Disc. 624
Power Factor, Simultaneous Control of Voltage and. Blume, Woods 1757
Disc. 483, 607
(Power Generation) A 7,000-Ampere Station Bus. Unland, Morton, Bacon 994
Disc., 1646; clos. 1650
(Power Generation) A Survey of Hydroelectric Developments. (Com. rept.). 988, 1086 Disc., 1651; clos. 1652
(Power Generation) Electric Power Switching. Lovell 147
Disc. 456
(Power Generation) Port Washington Power Plant Design. Post 264
(Power Generation) Switching at Long Beach Plant No. 3. Kroneberg, Bulkley, Andree 1699
Disc. 456
(Power Generation) Switching at Richmond Station. Bailey, Ford 156
Disc., 456; clos. 586
(Power Generation) Switching at State Line Station. White 148
Disc., 456; clos. 1312
(Power Generation) Switching at the Connors Creek Plant. Fugill 162
Disc., 456; clos. 586
(Power Generation) Switching at the Hudson Avenue Station. Gilt 1741
Disc., 456; clos. 585
(Power Generation) The Theory of Incremental Rates and Their Practical Application to Load Division. Parts I and II. Steinberg, Smith 432, 571
(Power Generation) Voltage Regulation and Load Control. Forbes, Searing 903
Disc., 1525; clos. 1528
Power Limit of a Transmission System. Peterson 1790
Disc., 477; clos. 602
Power Limits of Synchronous Machines. Clarke, Lorraine 1802
Disc., 475; clos. 601
Power Limits of 220-Kv Transmission Lines. Kroneberg, Macferran 1795
Disc., 473, 601; clos. 601
Power Losses in Induction Machines. Narbutovskih 1466
Power Systems, Decrement Curves for. Dalziel 331
(Power Systems) Shunt Resistors for Reactors—II. Kierstead, Bewley 411
Disc., 1315; clos. 1315
Present Theory of Electric Conduction, The. Hersfeld 523
Primary Network Distribution, Radial Versus. Wulfing 38
Disc. 489, 492, 610
Primary Networks, Theory of. Parts I and II. Starr 310, 426
Disc. 1315
Profession, Toward the Making of a. Wickenden 1146
Program System, Line Filter for. Clement 562
Program System, Wide-Band Open-Wire. Hamilton 550
Protecting Machines From Line Surges. Calvert 139
Disc., 488; clos. 608
(Protection) A New High Speed Air Circuit Breaker. Keep 322
(Protection) Counterpoises for Transmission Lines. Fortescue 1781
Disc., 467, 473, 598; clos. 599
(Protection) Locating Grounds by Distribution Ratio Method. Dunkle, DeShazo 258
(Protection) Some Recent Relay Developments. Hunt, Kroneberg 530
(Protection) The Expulsion Oil Circuit Breaker. Schwager 1108
(Protection) "Thyratron" Tubes in Relay Practice. Widerõe 1347
(Protection) Two Applications of Nonlinear Circuits. Austin, Cooper 293
(Protective Devices) A New Method of Ground Fault Protection. Starr 1472
(Protective Devices) Automatic Reclosing of Oil Circuit Breakers. Anderson 48
Disc., 466, 614; clos. 615
(Protective Devices) Control of Distance Relay Potential Connections. Warrington 206
Disc., 465; clos. 617
(Protective Devices) Lightning Measured on 4-Kv Overhead Circuits. Halperin, McEachron 33
Disc., 564, 616; clos. 617
(Protective Devices) Petersen Coil Tests on 140-Kv System. North, Eaton 63
Disc., 462, 612; clos. 614
(Protective Devices) Shunt Resistors for Reactors—II. Kierstead, Bewley 411
Disc., 1315; clos. 1315
Protective Relays on Pa. Locomotives. Luther 261

R

Radial Versus Primary Network Distribution. Wulfing 38
Disc. 489, 492, 610
Radio Circuits, Resonant Lines in. Terman 1046
Radio Effects, Insulator Surface and. Hillebrand, Miller 1213
Radio Influence Insulator Characteristics. Gilchrest 899
Disc., 1531, 1539; clos. 1539
Rail Impedances, Investigation of. Trueblood, Wascheck 1771
Disc., 450; clos. 589
(Railroads) Steam Ejector System for Car Conditioning. Ashley 406
Railways, Energy Consumption on Street. Thomas 326
Rates and Their Practical Application to Load Division, The Theory of Incremental. Parts I and II. Steinberg, Smith 432, 571
Ratings of Industrial Electronic Tubes. Pike, Ulrey 1577
Reactance and Stray Losses of Power Transformers. Cole 338
Reactance of 3-Conductor Cables, Resistance and. Salter, Shanklin, Wiseman 1581
Reactors—II, Shunt Resistors for. Kierstead, Bewley 411
Disc., 1315; clos. 1315
Recent Developments in Power Line Carrier. Johnson 542
Disc. 1325
Recent Developments in Suspension Insulators. Barrow 867
Disc., 1531, 1539; clos. 1540
Recent Theories of Ferromagnetism. Bitter 1246
Recommended Transformer Standards. Putman, Clem 1594
Rectifier, A High Power Welding. Silverman, Cox 1380
Rectifier, A Vacuum Tube Controlled. Foos 568
Rectifiers and Inverters, Grid Controlled. Herskind 926
Disc., 1400; clos. 1401
Rectifier, An Experimental "Ignitron." Ludwig, Maxfield, Toepfer 75
Disc., 488, 602; clos. 602
Rectifiers on System Wave Shape, Effects of. Blye, Kent 54
Disc., 483, 608; clos. 609
Rectifiers, Output Wave Shape of Controlled. Stebbins, Frick 1266
Rectifiers, Voltage Control of Vapor. Journeaux 976
Disc., 1396; clos. 1399
(Refrigeration) Steam Ejector System for Car Conditioning. Ashley 406
Regulator for A-C Generators, Electronic. Gulliksen 877
Disc., 1530; clos. 1531
Reignition of an Arc at Low Pressures. Mackeown, Bowden, Cobine 1081
(Letter) Mason 1679
Relay Action During Oscillations, Distance. Bancker, Hunter 1073
Disc., 1320; clos. 1322
Relay Developments, Some Recent. Hunt, Kroneberg 530
Relay Potential Connections, Control of Distance. Warrington 206
Disc., 465; clos. 617
Relay Practice, "Thyratron" Tubes in. Widerõe 1347
Relays on Pa. Locomotives, Protective. Luther 261
Report of the Board of Directors 1095
(Research) A Glow Discharge Anemometer. Lindvall 1068
Research and Engineering. Jewett 781
(Research) Characteristics of a Group of Engineers. Spooner 1571
(Research) Dielectric Properties of Cellulose Paper. Parts I and II. Whitehead, Greenfield 1389, 1498
(Research) Experiments in Fatal Electric Shock. Conrad, Haggard 399
(Research) Measurement of Wetting of Dielectrics. McLean, Kohman 255
(Research) Reignition of an Arc at Low Pressure. Mackeown, Bowden, Cobine 1081
(Research) Scientific Thought and Social Reconstruction. Mees 381
(Research) The Life of Impregnated Paper. Whitehead 244
Resistance and Reactance of 3-Conductor Cables. Salter, Shanklin, Wiseman 1581
Resistors for Reactors—II, Shunt. Kierstead, Bewley 411
Disc., 1315; clos. 1315
Resonant Lines in Radio Circuits. Terman 1046
Richmond Station, Switching at. Bailey, Ford 156
Disc., 456; clos. 586
Rocking Indirect Arc Electric Furnaces. Crosby 132
Disc. 452, 454, 591
(Letters)
Buck 1134
Rhoads 1134
Rotors, Heat Flow in Turbine Generator. Peck 1359

S

Sardinia Cable, The New Italy 528
Saturation Curves, Induction Motor Locked. Norman 536
Disc. 1312
Schooling of Engineers, On the. Dow 1589
"Science Series"
Electric Discharges in Gases, Ionization and Excitation. Tonks 239
Electric Discharges in Gases—II, Ions in Dense Gases. Darrow 388
Electric Discharges in Gases—III, Self-Maintained Discharges. Slepian and Mason 511
Electron Emission. Dushman 1054
Fundamental Electrical Properties of Mercury Vapor and Monatomic Gases. Hull 1435
Fundamental Laws of Photoelectricity. Hughes 1149
Fundamental Properties of the Electron. Waterman 3

Mapping of Fields. Weber 1563
Operational Calculus. Gardner 1339
Recent Theories of Ferromagnetism. Bitter 1246
Structure of Atoms and Molecules. Huggins 851
Theory of Probability. Bennett (Nov. 1933)
Scientific Thought and Social Reconstruction. Mees 381
Selection and Performance of Suspension Insulators. Sporn, Peterson, Mulford 936
Disc., 1531, 1538; clos 1538
Selsyn Drives, Induction Motors as. Nowacki 1721
Selsyn Instruments for Position Systems. Linville, Woodward 953
Disc 1660
Shielding for Telephone Cables, Iron. Moore 274
Disc., 1323; clos 1324
Shock, Experiments in Fatal Electric. Conrad, Haggard 399
Short-Circuit Currents, External Impedance Vs. Robertson, Rogers 252
Shunt Resistors for Reactors—II. Kierstead, Bewley 411
Disc., 1315; clos 1315
Signaling Purposes, Inductor Alternators for. Merrill 78
Significant Electrical Developments 840
Silicon Steel With A-C and D-C Excitation. Edgar 318
Simplified Measurements of Sound Absorption. Albert, Wagner 1160
Simultaneous Control of Voltage and Power Factor. Blume, Woods 1757
Disc 483, 607
Social Aspects of the Engineering Approach. Wallace 395
Solution of Steady State Stability, A Graphical. Dwight 566
Clos 1316
Some New Developments in Supervisory Control. Reagan 949
Some Recent Relay Developments. Hunt, Kroneberg 530
Sound Absorption, Simplified Measurements of. Albert, Wagner 1160
(So. Calif. Ed. Co.) Switching at Long Beach Plant No. 3. Kroneberg, Bulkley, Andree 1699
Disc 456
Sphere Gap, Calibration of the. Meador 942
Disc., 1652; clos 1659
Split Winding Transformers. Chase, Garin 914
Disc., 1411; clos 1412
Springs, Better Instrument. Carson 282
Stability, A Graphical Solution of Steady State. Dwight 566
Clos 1316
Stability of Composite Systems, Steady State. Crary 1809
Disc., 475, 477; clos 594
(Stability) Power Limit of a Transmission System. Peterson 1790
Disc., 477; clos 602
(Stability) Power Limits of Synchronous Machines. Clarke, Lorraine 1802
Disc., 475; clos 601
Stability Studies, Equivalent Circuits in. Dahl, Fitzgerald 1272
(Stability) Switching at Long Beach Plant No. 3. Kroneberg, Bulkley, Andree 1699
Disc 456
Stabilized Feed-Back Amplifiers. Black. Disc 461, 590, 1311
Standardization, The Institute and Industrial. Skinner 681
Standardization, The Work of the Institute in. Kennelly 676
Standards, Recommended Transformer. Putman, Clem 1594
State Line Station, Switching at. White 148
Disc., 456; clos 1312
Static, The "Compandor"—An Aid Against Radio. Mathes, Wright 860
Station Bus, A 7,000-Ampere. Unland, Morton, Bacon 994
Disc., 1646; clos 1650
Steady State Stability of Composite Systems. Crary 1809
Disc., 475, 477; clos 594
(Steam-electric) Port Washington Power Plant Design. Post 264
Steam Ejector System for Car Conditioning. Ashley 406
Steel, Electrical Practices in USSR. Fox 1251
Story of the Institute Budget, The. Meyer 375
Stray Load Loss Test on Induction Machines. Morgan, Narbutovskih 386
Disc., 1317; clos 1318
Street Railways, Energy Consumption on. Thomas 326
Structure of Atoms and Molecules, Electronic Theory of Valence. Huggins 851
Student, Encouraging Initiative in the Engineering. Dawes 910
Disc., 1413, 1416; clos 1417
Study of Nitrogen in Metallic Arc Weld Metal, A 1250
Supervisory Control, Some New Developments in. Reagan 949
Survey of Hydroelectric Developments, A. (Com. rept.) 988, 1086
Disc., 1651; clos 1652
Suspension Insulator, The. Hawley 895
Disc., 1531, 1536; clos 1536
Switching at Long Beach Plant No. 3. Kroneberg, Bulkley, Andree 1699
Disc 456
Switching at Richmond Station. Bailey, Ford 156
Disc., 456; clos 586
Switching at State Line Station. White 148
Disc., 456; clos 1312
Switching at the Connors Creek Plant. Fugill 162
Disc., 456; clos 586
Switching at the Hudson Avenue Station. Gilt 1741
Disc., 456; clos 585
Switching, Electric Power. Lovell 147
Disc 456
Synchronizer, A Compensated Automatic. Seeley 960
Clos 1528
Synchronous Machines, Equivalent Reactance of. Crary, March, Shildneck 124
Disc., 484, 603; clos 605
Synchronous Machines, Power Limits of. Clarke, Lorraine 1802
Disc., 475; clos 601

T

Telemeter With Pilot Coil Transmitter, A. Lunas, Bernarde 974
Disc., 1660; clos 1661
Telegraph Men Founders of the A.I.E.E. McNicol 675
Telephone Cables, Iron Shielding for. Moore 274
Disc., 1323; clos 1324
Television by Electronic Methods. Brolly 1153
Testing, A New Laboratory for High Voltage. Lusignan, Rorden 1255
Tests at Trafford, Counterpoise. Fortescue, Fielder 1116
Tests of Induction Machines, Efficiency. Leader, Phillips 1628
Tests of the Counterpoise, Theory and. Bewley 1163
Tests on Conductor Vibration, Field. Wright, Mini 1123
Tests on 140-Kv System, Peterson Coil. North, Eaton 63
Disc., 462, 612; clos 614
Tests, Portable Schering Bridge for Field. Hill, Watts, Burr 176
Disc., 478, 681; clos 1311
The Expulsion Oil Circuit Breaker. Schwager 1108
Theory and Tests of the Counterpoise. Bewley 1163
Theory of Electric Conduction, The Present. Herzfeld 523
Theory of Incremental Rates and Their Practical Application to Load Division, The. Parts I and II. Steinberg, Smith 432, 571
Theory of Multielectrode Tubes. Pidgeon 1485
Theory of Primary Networks. Parts I and II. Starr 310, 426
Disc 1315
Thermionic-Tube Measuring Instrument, A. Wagner 1621
Three-Phase Electric Arc Furnace, The. Arnold 1712
Disc., 452, 593; clos 594
"Thyratron" Motor, The. Alexanderson, Mittag 1517
"Thyratron" Tubes in Relay Practice. Widerøe 1347
Timer for Resistance Welding, A New. Stoddard 1366
Toward the Making of a Profession. Wickenden 1146
Trafford, Counterpoise Tests at. Fortescue, Fielder 1116
Transformer Life, Effect of Overloads on. Nichols 1616
Transformer Reactance and Losses With Nonuniform Windings. Stephens 346
Disc., 1318; clos 1319
Transformer Standards, Recommended. Putman, Clem 1594
Transformers—II, Factors Influencing the Insulation Coördination of. Bellaschi, Vogel 870
Disc., 1401; clos 1406
Transformers for Electric Furnaces. Stephens, Schell 1695
Disc 452, 454
Transformers, Loading a Bank of Dissimilar. Book 1597
Transformers, Measurement of Noise From Power. Fugill 1603
Transformers, Overloading of Power. Montsinger, Dann 1353
Transformers, Reactance and Stray Losses of Power. Cole 338
Transformers, Split Winding. Chase, Garin 914
Disc., 1411; clos 1412
Transients in Magnetic Systems. Wagner 418
Transients in Welding Generators, Control of. Hornby 1598
Transient Voltages in Welding Generators. Miller 1296
(Transmission) A New Porcelain Post Insulator. Lapp 922
Disc., 1531, 1540; clos 1541
(Transmission) An Economic Study of Suburban Distribution. Sweetnam, Corney 97
Disc 489, 610
(Transmission) Attenuation and Distortion of Waves. Bewley 1749
Disc., 471, 595; clos 597
(Transmission) Corona Loss Vs. Atmospheric Conditions. Hegy, Dunlap 272
(Transmission) Corona Losses From Conductors of 1.4-Inch Diameter. Carroll, Cozzens, Blakeslee 1727
Disc., 470, 600; clos 1310
(Transmission) Counterpoise Tests at Trafford. Fortescue, Fielder 1116
(Transmission) Decrement Curves for Power Systems. Dalziel 331
Transmission, Developments in Electric Power. Ryan 712
(Transmission) Dielectric Properties of Cellulose Paper. Parts I and II. Whitehead, Greenfield 1389, 1498
(Transmission) Distance Relay Action During Oscillations. Bancker, Hunter 1073

Disc., 1320; clos. 1822
(Transmission) Effects of Rectifiers on System Wave Shape. Blye, Kent... 54
Disc., 483, 608; clos. 609
(Transmission) Electric Power Switching. Lovell 147
Disc. 456
(Transmission) Equivalent Circuits in Stability Studies. Dahl, Fitzgerald. 1272
(Transmission) Field Tests on Conductor Vibration. Wright, Mini 1123
(Transmission) Flashover Voltages of Insulators and Gaps. (Com. rept.). 882
Disc. 1531, 1537
(Transmission) Fundamentals of Design of Electric Energy Delivery Systems. Johnson, Henry 1704
Disc., 489, 493, 610; clos. 612
(Transmission) High Voltage Insulators. Smith, Lusignan 969
Disc., 1531, 1536; clos. 1536
(Transmission) Insulator Arcover in Air. Maxstadt 1062
(Transmission) Insulator Surface and Radio Effects. Hillebrand, Miller.. 1213
(Transmission) Joint Use of Poles With 6,900-Volt Lines. Bullard, Keyes.. 1763
Disc., 489, 491; clos. 610
(Transmission) Lightning Investigation on a 220-Kv System. Bell 1188
(Transmission) Lightning Performance of 132-Kv Lines. Sporn, Gross 1195
(Transmission) Lightning Performance of 220-Kv Lines. (Com. rept.) 1443
Transmission Line Conductors, Vibration Analysis. Buchanan 1478
Transmission Lines, Auditory Perspective. Affel, Chestnut, Mills 28
Transmission Lines, Coaxial Communication. Schelkunoff 1592
Transmission Lines, Counterpoises for. Fortescue 1781
Disc., 467, 473, 598; clos. 599
Transmission Lines—IV, Lightning Investigation on. Lewis, Foust 1180
Transmission Lines, Power Limits of 220-Kv. Kroneberg, Macferran 1795
Disc., 473, 601; clos. 601
(Transmission) Loading a Bank of Dissimilar Transformers. Bock 1597
(Transmission) Locating Grounds by Distribution Ratio Method. Dunkle, DeShazo 258
(Transmission) Measurement of Noise From Power Transformers. Fugill. 1603
(Transmission) Multiple Lightning Strokes. McEachron 1633
(Transmission) New Laboratory for High Voltage Testing, A. Lusignan, Rorden 1255
(Transmission) Overvoltages on Transmission Lines. Gilkeson, Jeanne.. 1301
(Transmission) Petersen Coil Tests on 140-Kv System. North, Eaton 63
Disc., 462, 612; clos. 614
(Transmission) Radial Versus Primary Network Distribution. Wulfing 38
Disc. 489, 492, 610
(Transmission) Radio Influence Insulator Characteristics. Gilchrest 899
Disc., 1531, 1539; clos. 1539
(Transmission) Recent Developments in Suspension Insulators. Barrow 867
Disc., 1531, 1539; clos. 1540
(Transmission) Resistance and Reactance of 3-Conductor Cables. Salter, Shanklin, Wiseman 1581
(Transmission) Selection and Performance of Suspension Insulators. Sporn, Peterson, Mulford 936
Disc., 1531, 1538; clos. 1538
(Transmission) Simultaneous Control of Voltage and Power Factor. Blume, Woods 1757
Disc. 483, 607
(Transmission) Some Recent Relay Developments. Hunt, Kroneberg 530
(Transmission) Switching at Long Beach Plant No. 3. Kroneberg, Bulkley, Andree 1699
Disc. 456
(Transmission) Switching at Richmond Station. Bailey, Ford 156
Disc., 456; clos. 586
(Transmission) Switching at State Line Station. White 148
Disc., 456; clos. 1312
(Transmission) Switching at the Connors Creek Plant. Fugill 162
Disc., 456; clos. 586
(Transmission) Switching at the Hudson Avenue Station. Gilt 1741
Disc., 456; clos. 585
Transmission System, Power Limit of a. Peterson 1790
Disc., 477; clos. 602
(Transmission) The Insulator String. Sorensen 1221
(Transmission) The Suspension Insulator. Hawley 895
Disc., 1531, 1536; clos. 1536
(Transmission) Theory and Tests of the Counterpoise. Bewley 1163
Transmitter, A Telemeter With Pilot Coil. Lunas, Bernardo 974
Disc., 1660; clos. 1661
(Transportation) Diesel Electric Rail Cars and Locomotives. Storer 1461
(Transportation) Digging in "The Mines of the Motors." Sprague.. 695
(Transportation) Energy Consumption of Multiple Unit Cars. Compton. 280
(Transportation) Energy Consumption on Street Railways. Thomas 326
(Transportation) Investigation of Rail Impedances. Trueblood, Waschek 1771
Disc., 450; clos. 589
(Transportation) Protective Relays on Pa. Locomotives. Luther 261
Trolley Wire Lubrication Improved. Lamson 1690
Disc. 449, 1314
Trolleys I—Design Features, Pantograph. Schaake 182
Disc., 451, 1313; clos. 589
Trolleys II—Operating Features, Pantograph. Pickens 191
Disc. 451, 1313
Tube Controlled Rectifier, A Vacuum. Foos 568
Turbine Generator Rotors, Heat Flow in. Peck 1359
Two Applications of Nonlinear Circuits. Austin, Cooper 293

U

Unique Oscillograph, A. Oplinger 290
Units, Actions on Electric and Magnetic. Kennelly 402
USSR Steel, Electrical Practices in. Fox 1251

V

Vacuum Tube, A 100-Kw. 1266
Vacuum Tube Controlled Rectifier, A. Foos 568
Vacuum Tubes as High Frequency Oscillators. Kelly, Samuel 1504
Vapor Conducting Light Sources. Mailey 1447
Vapor Rectifiers, Voltage Control of. Journeaux 976
Disc., 1396; clos. 1399
Vibration Analysis—Transmission Line Conductors. Buchanan 1478
Vibration, Field Tests on Conductor. Wright, Mini 1123
Voltage and Power Factor, Simultaneous Control of. Blume, Woods 1757
Disc. 483, 607
Voltage Control of Vapor Rectifiers. Journeaux 976
Disc., 1396; clos. 1399
Voltage Regulation and Load Control. Forbes, Searing 903
Disc., 1525; clos. 1528

W

Warble Tone Generator, A New Type of. Bliss 547
Water Power Development. Lee 715
Wave Shape, Effects of Rectifiers on System. Blye, Kent 54
Disc., 483, 608; clos. 609
Weld Metal, A Study of Nitrogen in Metallic Arc 1250
Welding, A New Timer for Resistance. Stoddard 1366
Welding Generators, Control of Transients in. Hornby 1598
Welding Generators, Transient Voltages in. Miller 1296
Welding, Machine Characteristics for Steady. Creedy, Kogge, Danello.. 1268
Welding Rectifier, A High Power. Silverman, Cox 1380
Westinghouse Graduate Program, The Pitt-. Dyche, Hellmund 103
Disc., 466, 587; clos. 588
Wide-Band Open-Wire Program System. Hamilton 550
Wide Band Transmission Over Coaxial Lines. Espenschied, Strieby 1371
Work of the Institute in Standardization, The. Kennelly 676

Division II—Author Index

Ackermann, Otto. Disc. 595
Adams, C. A. Some Major Events in the Life of the Institute *686
Adams, C. A.; Hodge, MacKusick. High Frequency Induction Furnaces 194
Adams, F. J. Disc. 1320
Affel, H. A.; Chesnut, Mills. Auditory Perspective—Transmission Lines.. 28
Albert, A. L.; Wagner. Simplified Measurements of Sound Absorption 1160
Alexanderson, E. F. W.; Mittag. The "Thyratron" Motor 1517
Alfriend, J. V., Jr. Disc. 454
Alger, P. L. Disc. 1316, 1317, 1407, 1411, 1413
Anderson, A. E. Automatic Reclosing of Oil Circuit Breakers 48
Disc. clos. 615
Anderson, J. R.; Seletsky. Cross Current of a 5-Arm Network 1004
Disc. clos. 1660
Andree, J. A.; Kroneberg, Bulkley. Switching at Long Beach Plant No. 3 1699
Arnold, Samuel, 3rd. The 3-Phase Elec-Arc Furnace 1712
Disc. clos. 594
Ashley, C. M. Steam Ejector System for Car Conditioning 406
Austin, T. M.; Cooper. Two Applications of Nonlinear Circuits 293

B

Backus, C. D. Disc. 1418
Bacon, V. R.; Unland, Morton. A 7,000-Ampere Station Bus 994
Disc. clos. 1650
Bailey, Raymond; Ford. Switching at Richmond Station 156
Disc. clos. 586
Baker, E. B. (Letter) Potential Available for Gaseous Discharge in Insulation Voids 363
Ball, D. J. (Letter) Graphical Solution of Star-Delta Transformations 1680
Ball, R. D. (Letter) Shunt Wound Neutralized Phase Advancer 501
Balsbaugh, J. C. Disc. 478

NOTE—An asterisk (*) before a page number denotes publication of author's photograph on that page.

Bancker, E. H.; Hunter. Distance Relay Action During Oscillations..... 1073
Disc. clos..... 1322
Bang, A. F. Disc..... 1651
Barkey, I. H. (Letters) A New Method of Calculating Circuits..... 228
Operational Calculus..... 1681
Barrow, G. M. Recent Developments in Suspension Insulators..... 867
Disc. clos..... 1540
Basberg, A. (Letter) Electrical Characteristics of Impregnated Cable.... 1235
Bassett, W. H., Jr. Disc..... 449
Beck, Edward. Disc.....488, 616
Beckwith, Sterling. Disc..... 487
Bedell, E. H.; Kerney. Auditory Perspective—System Adaptation..... 216
Beeuwkes, Reinier. Disc..... 4349
Bell, Edgar. Lightning Investigation on a 220-Kv System..... 1188
Bellaschi, P. L. Heavy Surge Currents—Generation and Measurement..... 86
Disc. clos..... 623
Bellaschi, P. L. Disc.....1652, 1653
Bellaschi, P. L.; Teague. Impulse and 60-Cycle Strength of Air..... 1638
Bellaschi, P. L.; Vogel. Factors Influencing the Insulation Coördination of Transformers—II..... 870
Disc. clos..... 1406
Bergvall, R. C. Disc..... 601
Bernarde, H. L.; Lunas. A Telemeter With Pilot Coil Transmitter..... 974
Disc. clos..... 1661
Bewley, L. V. Attention and Distortion of Waves..... 1749
Disc. clos..... 597
Theory and Tests of the Counterpoise..... 1163
Bewley, L. V. Disc.....467, 1401
Bewley, L. V.; Kierstead. Shunt Resistors for Reactors—II..... 411
Disc. clos..... 1315
Bibber, H. W. Engineering Education Is Meeting the Challenge..... 1356
Bibber, H. W. Disc.....1416, 1419
Bitter, Francis. Recent Theories of Ferromagnetism..... 1246
Black, H. S. Stabilized Feed-Back Amplifiers..... 114
Blake, D. K. Disc..... 489
Blakeslee, T. M.; Carroll, Cozzens. Corona Losses From Conductors of 1.4-Inch Diameter..... 1727
Disc. clos..... 1310
Bliss, W. H. A New Type of Warble Tone Generator..... 547
Blume, L. F.; Woods. Simultaneous Control of Voltage and Power Factor..... 1757
Blye, P. W. Disc..... 1400
Blye, P. W.; Kent. Effects of Rectifiers on System Wave Shape..... 54
Disc. clos..... 609
Bock, J. A. Loading a Bank of Dissimilar Transformers..... 1597
Bowden, J. D.; Mackeown, Cobine. Reignition of an Arc at Low Pressures..... 1081
Bowen, A. E. Disc..... 1324
Boyajian, A. Disc.....483, 1318, 1412
Brace, P. H. Disc..... 455
Brolly, A. H. Television by Electronic Methods..... 1153
Brooke, F. W..... 453
Brown, H. F. Disc..... 1532
Brown, Harry. Disc.....449, 451
Brownlee, Theodore. Disc..... 480
Buchanan, W. B. Vibration Analysis—Transmission Line Conductors..... 1478
Buck, K. E. (Letter) Rocking Indirect Arc Electric Furnaces..... 1134
Buell, R. C. Disc.....1325, 1520
Bulkley, O. R.; Andree, Kroneberg. Switching at Long Beach Plant No. 3..... 1699
Bullard, W. R. Disc..... 490
Bullard, W. R.; Keyes. Joint Use of Poles With 6,900-Volt Lines..... 1763
Disc. clos..... 610
Burgwin, S. L. An A-C Potentiometer... 108
Burr, G. A.; Hill, Watts. Portable Sobering Bridge for Field Tests..... 176
Disc. clos..... 1311
Butler, J. W. Disc..... 484

C

Calabrese, Giuseppe. Disc.....1321, 1526
Calvert, J. F. Protecting Machines From Line Surges..... 139
Disc. clos..... 608
Calvert, J. F. Disc..... 1409
Carroll, J. S.; Cozzens, Blakeslee. Corona Losses From Conductors of 1.4-Inch Diameter..... 1727
Disc. clos..... 1310
Carson, R. W. Better Instrument Springs..... 282
Charlesworth, H. P. The Institute's Organization..... *671
Chase, P. H. Disc..... 491
Chase, D. D.; Garin. Split Winding Transformers..... 914
Disc. clos..... 1412
Chesney, C. C. Some Contributions to the Electrical Industry..... *726
Chesnut, R. W.; Mills, Affel. Auditory Perspective—Transmission Lines.... 28
Church, E. A. Disc..... 1318
Clarke, Edith. Disc..... 477
Clarke, Edith; Lorraine. Power Limits of Synchronous Machines..... 1802
Disc. clos..... 601
Clem, J. E. Disc....463, 1402, 1537, 1654
Clem, J. E.; Putman. Recommended Transformer Standards..... 1594
Clement, A. W. Line Filter for Program System..... 562
Cobine, J. D.; Mackeown, Bowden. Reignition of an Arc at Low Pressures..... 1081
Cole, H. L. Disc..... 1412
Cole, H. L. Reactance and Stray Losses of Power Transformers..... 338
Compton, F. A., Jr. Energy Consumption of Multiple Unit Cars..... 280
Conrad, A. G.; Haggard. Experiments in Fatal Electric Shock..... 399
Cook, S. S. Disc..... 454
Cooper, F. W.; Austin. Two Applications of Nonlinear Circuits..... 293
Corney, C. A. Disc.....492, 493, 1315
Corney, C. A.; Sweetnam. An Economic Study of Suburban Distribution..... 97
Cowan, F. A. Disc..... 590
Cozzens, Bradley. Disc..... 468
Cox, J. H.; Silverman. A High Power Welding Rectifier..... 1380
Cozzens, Bradley; Blakeslee, Carroll. Corona Losses From Conductors of 1.4-Inch Diameter..... 1727
Disc. clos..... 1310
Crane, J. B. Disc..... 1651
Crary, S. B. Steady State Stability of Composite System..... 1809
Disc. clos..... 594
Crary, S. B. Disc.....473, 475
Crary, S. B.; March, Shildneck. Equivalent Reactance of Synchronous Machines..... 124
Disc. clos..... 605
Creagmile, W. B. Disc..... 1410
Creedy, F.; Easton, Lucas. High Velocity Streams in the Vacuum Arc... 1454
Creedy, F.; Kogge, Danello. Machine Characteristics for Steady Welding.. 1268
Crosby, E. L. Rocking Indirect Arc Electric Furnaces..... 132

D

Dahl, G. C. Disc.....476, 604
Dahl, O. G. C.; Fitzgerald. Equivalent Circuits in Stability Studies..... 1272
Dallye, F. R. Disc..... 1646
Dalziel, C. F. Decrement Curves for Power Systems..... 331
Danello, A. O.; Creedy, Kogge. Machine Characteristics for Steady Welding..... 1268
Dann, W. M.; Montainger. Overloading of Power Transformers..... 1353
Darrow, K. K. Electric Discharges in Gases—II, Ions in Dense Gases..... 388
Davis, R. F. Disc..... 483
Davison, A. E. Disc..... 1539
Dawes, C. L. (Letter) Engineering Schools and the Changed Conditions..... 364
Encouraging Initiative in the Engineering Student..... 910
Disc. clos..... 1417
Electrical Characteristics of Impregnated Cable Papers..... 1235
Dawes, C. L. Disc.....587, 1420, 1534
Dawes, C. L.; Humphries. (Letter) Cable Failure and Deterioration..... 1133
Del Mar, W. A. (Letter) A Theory Regarding Ionization in Cable Fibers..... 500
DeShazo, J. S.; Dunkle. Locating Grounds by Distribution Ratio Method..... 258
Di Toro, M. J. (Letter) A New Method of Calculating Circuits..... 229
Doble, F. C. Disc..... 618
Dow, Alex. On the Schooling of Engineers..... 1589
Dudley, A. M. Disc..... 446
Dudley, C. L. Disc..... 453
Dudley, H. W. Disc..... 462
Dunham, J. M. Disc..... 613
Dunkle, W. F.; DeShazo. Locating Grounds by Distribution Ratio Method..... 258
Dunlap, G. W.; Hegy. Corona Loss Vs. Atmospheric Conditions..... 272
Dunn, Gano. Early Headquarters of the Institute..... *685
Dushman, Saul. Electron Emission..... 1054
Low Pressure Gaseous Discharge Lamps. Parts I and II.....1204, 1283
Dwight, H. B. A Graphical Solution of Steady State Stability..... 566
Disc. clos..... 1316
Dwight, H. B. Disc.....484, 1319, 1646
Dyche, H. E.; Hellmund. The Pitt-Westinghouse Graduate Program..... 103
Disc. clos..... 588

E

Easton, E. C.; Lucas, Creedy. High Velocity Streams in the Vacuum Arc..... 1454
Eaton, G. O. Disc..... 494
Eaton, J. R.; North. Petersen Coil Tests on 140-Kv System..... 63
Disc. clos..... 614
Eby, Eugene D. Disc..... 478
Edgar, R. F. Silicon Steel With A-C and D-C Excitation..... 318
Edson, W. W. (Letter) Graphical Solution of Delta-Star Resistance Transformations..... 1427
Ekvall, H. N. Disc..... 465
Ellyson, D. W. Disc..... 615
Espenschied, Lloyd; Strieby. Wide Band Transmission Over Coaxial Lines..... 1371
Evans, R. D. Disc....473, 474, 476, 487, 608

F

Ferman, R. A. (Letter) Theory of Probability..... 1235
Ferris, L. P. Disc..... 1323
Fielder, F. D. Disc..... 1654
Fielder, F. D.; Fortescue. Counterpoise Tests at Trafford..... 1116
Fitzgerald, A. E.; Dahl. Equivalent Circuits in Stability Studies..... 1272
Fleming, A. P. M. (Letter) Early Development of the Transformer..... 364
Fletcher, Harvey. Auditory Perspective—Basic Requirements..... 9
Floyd, G. D. Disc.....474, 1404, 1655
Foos, C. B. A Vacuum Tube Controlled Rectifier..... 568
Foote, J. H. Disc..... 471

Forbes, H. C. Disc. 1647
Forbes, H. C.; Searing. Voltage Regulation and Load Control 903
Disc. clos. 1528
Ford, F. R. Disc. 586
Ford, F. R.; Bailey. Switching at Richmond Station 156
Disc. clos. 586
Forshee, L. C. Disc. 1323
Fortescue, C. L. Disc. 613, 616, 624, 1403
Fortescue, C. L. G. Counterpoises for Transmission Lines 1781
Disc. clos. 599
Fortescue, C. L.; Fielder. Counterpoise Tests at Trafford 1116
Foust, C. M. Disc. 1537, 1655
Foust, C. M.; Lewis. Lightning Investigation on Transmission Lines—IV 1180
Fox, Gordon. Electrical Practices in USSR Steel 1251
Frear, C. L. Disc. 455
Freiburghouse, E. H. Disc. 484
Frick, C. W.; Stebbins. Output Wave Shape of Controlled Rectifiers 1259
Fugill, A. P. Switching at the Connors Creek Plant 162
Disc. clos. 586
Measurement of Noise From Power Transformers 1603
Fugill, A. P. Disc. 586

G

Gardner, M. F. Operational Calculus 1339
Garin, A. N. Disc. 1319
Garin, A. N.; Chase. Split Winding Transformers 914
Disc. clos. 1412
Garman, G. W. Disc. 1530
George, E. E. Disc. 465, 466, 1413
Gerrell, G. W. Disc. 1320
Gherardi, Bancroft. Communication—Past and Present *745
Gilchrest, G. I. Radio Influence Insulator Characteristics 899
Disc. clos. 1539
Gilkeson, C. L. Disc. 463
Gilkeson, C. L.; Hanks. Iron Armored Aerial Communication Cable 890
Disc. clos. 1325
Gilkeson, C. L.; Jeanne. Overvoltages on Transmission Lines 1301
Gilt, C. M. Switching at the Hudson Avenue Station 1741
Disc. clos. 585
Gilt, C. M. Disc. 495, 585
Goodlet, B. L. Disc. 618
Gorman, L. J. Disc. 1647
Greenfield, E. W.; Whitehead. Dielectric Properties of Cellulose Paper. Parts I and II 1389, 1498
Gross, I. W. Disc. 618
Gross, I. W.; Sporn. Lightning Performance of 132-Kv Lines 1195
Gulliksen, F. H. Electronic Regulator for A-C Generators 877
Disc. clos. 1531

H

Haar, Selby. Disc. 489
Haggard, H. W.; Conrad. Experiments in Fatal Electric Shock 399
Haines, T. H. Disc. 494
Hall, H. Y. Disc. 457
Halperin, Herman; McEachron. Lightning Measured on 4-Kv Overhead Circuits 33
Disc. clos. 617
Hamilton, H. S. Wide-Band Open-Wire Program System 550
Hanks, A. J.; Gilkeson. Iron Armored Aerial Communication Cable 890
Disc. clos. 1325
Hanna, W. M. Disc. 1647
Harder, E. L. Disc. 608
Harding, C. F. Disc. 465, 470, 1421, 1533
Hawley, K. A. The Suspension Insulator 895
Disc. clos. 1536
Hawley, K. A. Disc. 1536, 1537, 1538, 1539, 1540, 1541
Hazen, H. L. Disc. 477
Healey, M. V. Cast Iron and Its Production 120
Heath, L. O. Disc. 1529
Hegy, L.; Dunlap. Corona Loss Vs. Atmospheric Conditions 272
Hellmund, R. E. Disc. 610, 626, 1396, 1409, 1417, 1421, 1654
Hellmund, R. E.; Dyche. The Pitt-Westinghouse Graduate Program 103
Disc. clos. 588
Hellmund, R. E.; Veinott. Irregular Windings in Wound Rotor Induction Motors 342
Disc. clos. 1317
Henderson, S. L. Disc. 1409
Henry, R. T.; Johnson. Fundamentals of Design of Electric Energy Delivery Systems 1704
Disc. clos. 612
Herskind, C. C. Grid Controlled Rectifiers and Inverters 926
Disc. clos. 1401
Herskind, C. C. Disc. 488, 1398
Hertz, Herman. Disc. 469
Herzfeld, Karl F. The Present Theory of Electric Conduction 523
Hibben, S. G. Incandescence—Some Theoretical Aspects 1201
Hickernell, L. F. Disc. 601
Hill, C. F.; Watts, Burr. Portable Schering Bridge for Field Test 176
Disc. clos. 1311
Hillebrand, W. A. Disc. 1535, 1536, 1538, 1539, 1540, 1655
Hillebrand, W. A.; Miller. Insulator Surface and Radio Effects 1213
Hirshfeld, C. F. Engineers of the Next Generation 857
Disc. clos. 1416
Hodnette, J. K. Disc. 616
Hodge, J. C. MacKusick, Adams. High Frequency Induction Furnaces 194
Hollister, F. H. Disc. 456
Holton, J. L. (Ledter) Improving A. I. E. E. Convention Sessions 500
Hornby, F. B. Control of Transients in Welding Generators 1598
Huggins, Maurice L. Structure of Atoms and Molecules, Electronic Theory of Valence 851
Hughes, A. L. Fundamental Laws of Photoelectricity 1149
Hull, A. W. Fundamental Electrical Properties of Mercury Vapor and Monatomic Gases 1435
Humphries, P. H.; Dawes. (Letter) Cable Failure and Deterioration 1133
Hunt, L. F.; Kroneberg. Some Recent Relay Developments 530
Hunter, E. M.; Bancker. Distance Relay Action During Oscillations 1073
Disc. clos. 1322

I

Ireland, G. Disc. 461

J

Jackson, D. C. The Evolution of Electrical Engineering Education *770
Jackson, D. C., Jr. Disc. 588
Jakobsen, B. F. (Letter) Public Versus Private Enterprise 507
James, H. D. (Letter) Engineering Service 1420
Jeanne, P. A.; Gilkeson. Overvoltages on Transmission Lines 1301
Jewett, F. B. Research and Engineering *781
Johnson, J. Allen. An Insight Into the Workings of the Institute 1039
A Message From the President 1142
Another Message From the President 1338
Johnson, J. A.; Henry, R. T. Fundamentals of Design of Electric Energy Delivery Systems 1704
Disc. clos. 612
Johnson, J. B.; Llewellyn. Limits to Amplification 1449
Johnson, T., Jr. Recent Developments in Power Line Carrier 542
Journeaux, Didier. (Letter) A Chart for Complex Quantities 502
Voltage Control of Vapor Rectifiers 976
Disc. clos. 1399

K

Kalb, W. C. Characteristics and Uses of the Carbon Arc 1173
Karapetoff, Vladimir. (Letter) Wine Makers and Bottle Makers—A Parable 1681
Kates, W. A. Disc. 1533, 1538
Keep, A. O. A New High Speed Air Circuit Breaker 322
Kelly, M. J.; Samuel. Vacuum Tubes as High Frequency Oscillators 1504
Kennelly, A. E. Actions on Electric and Magnetic Units 402
The Work of the Institute in Standardization *676
Kent, H. E.; Blye. Effects of Rectifiers on System Wave Shape 54
Disc. clos. 609
Kerney, Iden; Bedell. Auditory Perspective—System Adaptation 216
Keyes, D. H.; Bullard. Joint Use of Poles With 6,900-Volt Lines 1763
Disc. clos. 610
Kidder, A. H. Disc. 495
Kierstead, F. H.; Bewley. Shunt Resistors for Reactors—II 411
Disc. clos. 1315
Kilgore, L. A. Disc. 487, 1648
Kingsley, Charles, Jr. Disc. 603
Koch, C. J. Disc. 1316
Kogge, R.; Danello, Creedy. Machine Characteristics for Steady Welding 1268
Kohman, G. T.; McLean. Measurement of Wetting of Dielectrics 255
Kouwenhoven, W. B. (Letter) A New Method of Calculating Circuits 229
Kouwenhoven, W. B. Disc. 478
Kroneberg, A. A.; Bulkley, Andree. Switching at Long Beach Plant No. 3 1699
Kroneberg, A. A.; Hunt. Some Recent Relay Developments 530
Kroneberg, A. A.; Macferran. Power Limits of 220-Kv Transmission Lines 1795
Disc. clos. 601

L

Lamson, J. V. Trolley Wire Lubrication Improved 1690
Langstaff, H. A. P. Disc. 467
LaPierre, C. W. Disc. 1531
Lapp, G. W. A New Porcelain Post Insulator 922
Disc. clos. 1541
Leader, C. C.; Phillips. Efficiency Tests of Induction Machines 1628
Lee, E. S. Membership Letters 2d cov. Jan., 2d cov. Feb., 2d cov. March, p. 510, 850, 1227, 1328, 1424, 1544, 1664
Lee, E. S. Disc. 479
Lee, W. S. Water Power Development. *715
Levy, C. C. Electrical Equipment for Induction Furnaces 43
Levy, C. C. Disc. 453
Lewis, W. W. Disc. 474
Lewis, W. W.; Foust. Lightning Investigation on Transmission Lines—IV 1180
Lincoln, P. M. Some Reminiscences of Niagara *720
Lincoln, P. M. Disc. 625
Lindvall, F. C. A Glow Discharge Anemometer 1068
Linebaugh, J. J. Disc. 602
Linville, T. M.; Woodward. Selsyn Instruments for Position Systems 953

Little, T. J. Disc. 601
Llewellyn, F. B.; Johnson. Limits to Amplification 1449
Lloyd, W. L., Jr. Disc. 1655
Lorraine, R. G.; Clarke. Power Limits of Synchronous Machines 1802
Disc. clos. 601
Lovell, A. H. Electric Power Switching. 147
Lubkin, Samuel. (Letter) Applications of Nonlinear Circuits 502
Lucas, F. B.; Creedy, Easton. High Velocity Streams in the Vacuum Arc 1454
Ludwig, L. R. Disc. 1399, 1400
Ludwig, L. R.; Maxfield, Toepfer. An Experimental "Ignitron" Rectifier 75
Disc. clos. 602
Ludwig, L. R.; Wagner. The "Ignitron" Inverter 1384
Lunas, L. J. Disc. 1661
Lunas, L. J.; Bernarde. A Telemeter With Pilot Coil Transmitter 974
Disc. clos. 1661
Lusignan, J. R., Jr. Disc. 1656
Lusignan, J. T., Jr.; Rorden. A New Laboratory for High Voltage Testing 1255
Lusignan, J. T., Jr.; Smith. High Voltage Insulators 969
Disc. clos. 1536
Luther, Benjamin. Protective Relays on Pennsylvania Locomotives 261
Lutz, S. G. (Letter) Limiting Reactances of 2-Terminal Reactance Arms 634

M

MacCarthy, D. D. Disc. 465
Macferran, Mabel; Kroneberg. Power Limits of 220-Kv Transmission Lines 1795
Disc. clos. 601
MacGahan, Paul. Disc. 1660
Mackeown, S. S.; Bowden, Cobine. Reignition of an Arc at Low Pressures 1081
MacKusick, M. H.; Adams, Hodge. High Frequency Induction Furnaces 194
Mailey, R. D. Vapor Conducting Light Sources 1447
March, L. A.; Shildneck, Crary. Equivalent Reactance of Synchronous Machines 124
Disc. clos. 605
Mason, R. C. (Letter) Reignition of an Arc at Low Pressures 1679
Mason, R. C.; Slepian. Electric Discharges in Gases—III, Self-Maintained Discharges 511
Mathes, R. C.; Wright. The "Compandor"—An Aid Against Radio Static 860
Maurer, K. L. Disc. 450, 1323, 1324
Maxfield, F. A.; Toepfer, Ludwig. An Experimental "Ignitron" Rectifier 75
Disc. clos. 602
Maxstadt, F. W. Insulator Arcover in Air 1062
McAuley, P. H. Disc. 622
McClellan, William. The Engineer a Creator of Leisure *777
McEachron, K. B. Multiple Lightning Strokes 1633
McEachron, K. B. Disc. 1404, 1537, 1656
McEachron, K. B.; Halperin. Lightning Measured on 4-Kv Overhead Circuits 33
Disc. clos. 617
McGill, C. W. Disc. 1315
McKearin, J. P. Disc. 598
McLean, D. A.; Kohman. Measurement of Wetting of Dielectrics 255
McMains, T. F. (Letter) Engineering Education Should Train 2 Types of Engineers 1678
McMillan, F. O. Disc. 1657
McNicol, Donald. Telegraph Men Founders of the A.I.E.E. *675
Meador, J. R. Calibration of the Sphere Gap 942
Disc. clos. 1659
Mees, C. E. Kenneth. Scientific Thought and Social Reconstruction. 381
Merrill, F. W. Inductor Alternators for Signaling Purposes 78
Meyer, E. B. The Story of the Institute Budget 375
Miller, A. R. Transient Voltages in Welding Generators 1296
Miller, A. R. Disc. 471
Miller, C. J., Jr.; Hillebrand Insulator Surface and Radio Effects 1213
Miller, H. P., Jr. Disc. 469
Mills, R. H.; Affel, Chesnut. Auditory Perspective—Transmission Lines 28
Mini, J., Jr.; Wright. Field Tests on Conductor Vibration 1123
Mittag, A. H.; Alexanderson. The "Thyratron" Motor 1517
Monteith, A. C. Disc. 488
Montsinger, V. M. Disc. 1405
Montsinger, V. M.; Dann. Overloading of Power Transformers 1353
Moore, H. R. Iron Shielding for Telephone Cables 274
Disc. clos. 1324
Moore, W. E. Disc. 590, 591, 593
Morgan, T. H.; Narbutovskih. Stray Load Loss Test on Induction Machines 286
Disc. clos. 1318
Morrow, L. W. W. Industry Demands and Engineering Education 518
Disc. clos. 1422
Morton, W. B.; Bacon, Unland. A 7,000-Ampere Station Bus 994
Disc. clos. 1650
Moser, F. L. Disc. 480
Mulford, V. A.; Sporn, Peterson. Selection and Performance of Suspension Insulators 936
Disc. clos. 1538

N

Naeter, A. (Letter) Graduate Engineering Study Remote from Industrial Centers 501
Narbutovskih, P. M. Power Losses in Induction Machines 1466
Narbutovskih, P. M. Disc. 1318
Narbutovskih, P. M.; Morgan. Stray Load Loss Test on Induction Machines 286
Disc. clos. 1318
Negley, S. R. Disc. 1314
Neher, J. H. Disc. 466
Nichols, L. C. Effect of Overloads on Transformer Life 1616
Norman, H. M. Induction Motor Locked Saturation Curves 536
North, J. R.; Eaton. Petersen Coil Tests on 140-Kv System 63
Disc., clos. 614
Nowacki, L. M. Induction Motors as Selsyn Drives 1721
Nyquist, Harry. Disc. 1311

O

Oesterreich, E. W. Disc. 491, 611
Olmsted, L. M. Disc. 483
Oplinger, K. A. A Unique Oscillograph. 290
Ostrander, J. K. Disc. 458

P

Palmer, H. G.; Rhodes, Roach. (Letter) Appreciation of the "Science Series." 1031
Papst, H. W. Disc. 1649
Park, R. H. Disc. 604
Parsons, J. S. Disc. 490
Peck, C. E. Heat Flow in Turbine Generator Rotors 1359
Peterson, E. L.; Mulford, Sporn. Selection and Performance of Suspension Insulators 936
Disc., clos. 1538
Peterson, T. F. Disc. 600
Peterson, W. S. Power Limit of a Transmission System 1790
Disc., clos. 602
Phillips, F. D.; Leader. Efficiency Tests of Induction Machines 1628
Pickens, B. M. Pantograph Trolleys—II, Operating Features 190
Pidgeon, H. A. Theory of Multielectrode Tubes 1485
Pike, O. W.; Ulrey. Ratings of Industrial Electronic Tubes 1577
Pleasants, Gibson. Electrical Figures on Plates in Air 300
Poritsky, H. Disc. 592
Post, G. G. Port Washington Power Plant Design 264
Powell, G. A. Disc. 1320
Price-Hughes, H. A. (Letter) History of Thomson-Houston Company Name 1133
Pupin, M. I. The Equation of Electrical Propagation *691
Putman, H. V. Disc. 1405
Putman, H. V.; Clem. Recommended Transformer Standards 1594

R

Rah, J. C. Disc. 1541
Randall, K. C. Disc. 458
Reagan, M. E. Some New Developments in Supervisory Control 949
Reagan, M. E. Disc. 1529, 1661
Reed, K. A. Disc. 1408
Reiter, Reuben. Disc. 1534
Rhoads, A. E. (Letter) Rocking Indirect Arc Electric Furnaces 1134
Rhodes, D.; Roach, Palmer. (Letter) Appreciation of the "Science Series." 1031
Rice, E. W., Jr. A Century of Progress in 50 Years *689
Roach, C. L.; Palmer, Rhodes. (Letter) Appreciation of the "Science Series." 1031
Roberts, E. B. Disc. 446
Robertson, B. L.; Rogers. External Impedance Vs. Short-Circuit Currents 252
Robinson, L. N. Disc. 1658
Rogers, T. A.; Robertson. External Impedance Vs. Short-Circuit Currents 252
Roman, W. G. Disc. 622
Rorden, H. L.; Lusignan. New Laboratory for High Voltage Testing, A. 1255
Rutan, E. J. Disc. 1411, 1421, 1529
Ryan, H. J. Developments in Electric Power Transmission *712
Ryan, W. D'Arcy. Lighting "A Century of Progress." *731
Rylander, J. L. Disc. 1411

S

Salter, E. H.; Shanklin, Wiseman. Resistance and Reactance of 3-Conductor Cables 1581
Samuel, A. L.; Kelly. Vacuum Tubes as High Frequency Oscillators 1504
Sanderson, C. H. Disc. 459
Sanford, F. E. Disc. 469
Schaake, W. Pantograph Trolleys I—Design Features 182
Disc. clos. 589
Schelkunoff, S. A. Coaxial Communication Transmission Lines 1592
Schell, L. S.; Stephens. Transformers for Electric Furnaces 1695
Schurig, O. R. Disc. 1649
Schnyder, A. P. Disc. 463
Schwager, A. C. The Expulsion Oil

Circuit Breaker 1108
Scott, C. F. The Institute's First Half Century *645
Scott, J. A. Effect of Oil Pressure on Insulation Strength 308
Scriven, E. O. Auditory Perspective—Amplifiers 25
Seaman, E. F. (Letter) Slide Rule Calculation of Unbalanced 3-Phase Currents 365, 1031
Searing, H. R.; Forbes. Voltage Regulation and Load Control 903
Disc., clos. 1528
Seeley, H. T. A Compensated Automatic Synchroniser 960
Disc., clos. 1538
Seeley, H. T. Disc. 1530
Seeley, W. J. (Letter) Engineering Education for Non-Engineers 1328
Seletzky, A. C. Cross Potential of a 4-Arm Network 1734
Seletzky, A. C.; Anderson. Cross Current of a 5-Arm Network 1004
Disc., clos. 1660
Shanklin, G. B.; Wiseman, Salter. Resistance and Reactance of 3-Conductor Cables 1581
Sharp, C. H. (Letter) Designations of Photo-Electric Devices 1682
Shelton, E. K. Disc. 608
Shildneck, L. P.; Crary, March. Equivalent Reactance of Synchronous Machines 124
Disc., clos. 605
Shuler, William. Disc. 611
Sidler, P. R. Disc. 463
Sills, H. R: (Letter) Jogging the Rotor of an Alternator Electrically 363
Silverman, Daniel; Cox. A High Power Welding Rectifiers 1380
Sinclair, C. T. Disc. 489
Skinner, C. E. The Institute and Industrial Standardization *681
Slepian, Joseph. Disc. 472
Slepian, J.; Mason. Electric Discharges in Gases—III, Self-Maintained Discharges 511
Slinger, R. N. Disc. 607
Smith, B. H. A New Demand Meter 94
Disc., clos. 626
Smith, J. J. Disc. 483
Smith, S. A., Jr. (Letter) Theory of Probability 229
Smith, T. H.; Steinberg. The Theory of Incremental Rates and Their Practical Application to Load Division. Parts I and II 432, 571
Smith, V. G. (Letter) Slide Rule Calculation of $\sqrt{a^2 + b^2}$ 228
Smith, W. A.; Lusignan. High Voltage Insulators 969
Disc., clos. 1536
Snow, W. B.; Steinberg. Auditory Perspective—Physical Factors 12
Sohon, Harry. (Letter) Excitation and Ionisation in Gases 1235
Sorensen, R. W. The Insulator String 1221
Sorensen, R. W. Disc. 1414, 1532, 1537, 1541
Spencer, H. H. Disc. 461, 480
Spooner, Thomas. Characteristics of a Group of Engineers 1571
Sporn, Philip. Disc. 459, 620, 1531
Sporn, Philip; Gross. Lightning Performance of 132-Kv Lines 1195
Sporn, Philip; Peterson, Mulford. Selection and Performance of Suspension Insulators 936
Disc., clos. 1538
Sprague, F. J. Digging in "The Mines of the Motors." *695
Stansel, N. R. Disc. 452
Starr, F. M. Theory of Primary Networks. Parts I and II 310, 426
A New Method of Ground Fault Protection 1472
Starr, F. M. Disc. 492, 1525
Stebbins, F. O. Disc. 1397, 1400
Stebbins, F. O.; Frick. Output Wave Shape of Controlled Rectifiers 1259
Stein, I. M. Disc. 624, 1660
Steinberg, J. C.; Snow. Auditory Perspective—Physical Factors 12
Steinberg, M. J.; Smith. The Theory of Incremental Rates and Their Practical Application to Load Division. Parts I and II 432, 571
Stephens, H. O. Transformer Reactance and Losses With Nonuniform Windings 346
Disc., clos. 1319
Stephens, H. O.; Schell. Transformers for Electric Furnaces 1695
Stewart, H. R. Disc. 1321
Stewart, P. B. Disc. 469
Stillwell, L. B. Alternating Current Versus Direct Current *708
Stinchfield, J. M. Cathode Ray Tubes and Their Application 1608
Stoddard, R. N. A New Timer for Resistance Welding 1366
Storer, N. W. Diesel Electric Rail Cars and Locomotives 1461
Strieby, M. E.; Espenschied. Wide Band Transmission Over Coaxial Lines 1371
Sunde, E. D. Disc. 450
Sweetnam, A. H. Disc. 1525
Sweetnam, A. H.; Corney. An Economic Study of Suburban Distribution 97

T

Taylor, C. W. Disc. 460
Teague, W. L. Disc. 1653
Teague, W. L.; Bellaschi. Impulse and 60-Cycle Strength of Air 1638
Terman, F. E. Resonant Lines in Radio Circuits 1046
Thomas, Benjamin, Jr. Energy Consumption on Street Railways 326
Thomason, J. L. Impulse Generator Circuit Formulas 169
Thomason, J. L. Disc. 482
Thomson, Elihu. Some High Lights of Electrical History *758
Thuras, A. L.; Wente. Auditory Perspective—Loud Speakers and Microphones 17
Timbie, W. H. Disc. 447, 1415
Toepfer, A. H.; Ludwig, Maxfield. An Experimental "Ignitron" Rectifier 75
Disc., clos. 602
Tonks, Lewi. Electric Discharges in Gases, Ionisation, and Excitation 293
Treat, Robert. Disc. 614
Trickey, P. H. Disc. 1312
Trueblood, H. M.; Wascheck. Investigation of Rail Impedances 1771
Disc., clos. 589
Tucker, Carlton E. (Letter) Information on Oliver Heaviside 1554

U

Ulrey, Dayton; Pike. Ratings of Industrial Electronic Tubes 1577
Unland, H. L.; Morton, Bacon. A 7,000-Ampere Station Bus 994
Disc., clos. 1650

V

Van Niekerk, A. Analytical Representation of a Magnetizing Curve 1186
Veinott, C. G. Measurement of Noise From Small Motors 1624
Veinott, C. G.; Hollmund. Irregular Windings in Wound Rotor Induction Motors 342
Disc., clos. 1317
Vogel, F. J. Disc. 1658
Vogel, F. J.; Bellaschi. Factors Influencing the Insulation Coördination of Transformers—II 870
Disc., clos. 1406
Vosburgh, F. J. Electrodes-Carbon and Graphite 1717

W

Wade, P. E. Disc. 1313, 1314
Wagner, C. F. Transients in Magnetic Systems 418
Wagner, C. F.; Ludwig. The "Ignitron" Inverter 1384
Wagner, H. H. Disc. 1319
Wagner, T. B. A Thermionic-Tube Measuring Instrument 1621
Wagner, T. B.; Albert. Simplified Measurements of Sound Absorption 1160
Walker, E. A. (Letter) Arcover Caused by Absorption Current 1680
Wallace, H. A. Social Aspects of the Engineering Approach 395
Wallau, H. L. Disc. 460
Walter, O. W. (Letter) Overcompounded D-C Generators in Parallel Without Equaliser 1553
Warrington, A. R. van C. Control of Distance Relay Potential Connections 206
Disc., clos. 617
Wascheck, George; Trueblood. Investigation of Rail Impedances 1771
Disc., clos. 589
Waterman, A. T. Fundamental Properties of the Electron 3
Watts, T. R.; Burr, Hill. Portable Schering Bridge for Field Tests 176
Disc., clos. 1311
Weber, Ernst. Mapping of Fields 1563
Welch, A. U. Disc. 463
Wente, E. C.; Thuras. Auditory Perspective—Loud Speakers and Microphones 17
Whipple, C. C. Disc. 448
White, T. C. Switching at State Line Station 148
Disc., clos. 1312
Whitehead, J. B. The Life of Impregnated Paper 244
The Fiftieth Anniversary of the A.I.E.E. *643
The Institute on Its 50th Anniversary 1143
Whitehead, J. B.; Greenfield. Dielectric Properties of Cellulose Paper. Parts I and II 1389, 1498
Wickenden, W. E. Toward the Making of a Profession 1146
Wideroe, Rolf. "Thyratron" Tubes in Relay Practice 1347
Wieseman, R. W. Insulation Resistance of Armature Windings 1010
Disc., clos. 1524
Winkler, E. W. (Letter) A New Stroboscope to Study Hunting of a Synchronous Motor 1678
Wiseman, R. J.; Salter, Shanklin. Resistance and Reactance of 3-Conductor Cables 1581
Withington, Sidney. Disc. 1531
Wolf, H. B. Disc. 480
Woods, F. L.; Blume. Simultaneous Control of Voltage and Power Factor 1757
Woodward, J. S.; Linville. Selsyn Instruments for Position Systems 953
Wright, A. M. Disc. 1313
Wright, E. M.; Mini. Field Tests on Conductor Vibration 1123
Wright, S. B.; Mathes. The "Compandor"—An Aid Against Radio Static 860
Wulfing, H. E. Radial Versus Primary Network Distribution 38

Y

Young, W. M. Disc. 587

Z

Zogbaum, F. Load Totalizing in the New York Area 886
Disc., clos. 1529
Zubair, S. M. Disc. 474

Division III—News of A.I.E.E. Activities

Addresses Wanted....235, 370, 506, 639, 848, 1035, 1139, 1242, 1331, 1431, 1559, 1687

B

Board, Urges That Activities of U. S. Bureau of Standards Be Maintained, A.I.E.E. 357
Board of Directors, Report of the.....1095
Branch Activities Summarized in Annual Report for 1933–34, Section and.....1027
Branch Meetings. (See Meetings, Branch)
Branch, Pennsylvania State College, Electronic Show Conducted by Students.. 632
Branches of the Institute (Officers 1934–5).1335
Budget for 1934–35, The Institute.....1542
Budget, The Story of the Institute. Meyer 375

C

(Committee) Annual Reports to Be Made Available.....1022
Committee Reports Postponed, Technical 1129
Committees, National.....1332, 1543

D

Directors' Meetings. (See Meetings, Directors)
District Meetings. (See Meetings, District)
Districts, Technical Committee Activities Proposed for Sections and..... 631

E

Edison Medal for 1933 Presented to Doctor Kennelly.....*353

F

Fiftieth Anniversary
(See Also Under "Technical Subject Index")
Badge, Origin and Adoption of the Institute's..... 838
Branches of the Institute, Sections and.. 835
Branches to Celebrate the Institute's 50th Anniversary in May, Many Sections and..... 496
Celebration of 50th Anniversary.....1227
"Century of Progress" (Photos)..... 737
Charter Members, Formation of the Institute and the Enrolling of Its 787, 822, 824
Cloth Bound Copies of 50th Anniversary Issue.....1023
Committees, Chairmen of the Institute's 828
Committees, Chart of Institute..... 827
Communication Equipment, Some Contrasts in. (Photos).....748, 752
(Communication) Some Contrasts in Radio Equipment..... 784
Engineering Foundation, The..... 837
Formation of the Institute and the Enrolling of Its Charter Members..... .....787, 822, 824
Generating Stations, Some Steam-Electric. (Photos)..... 754
Generators of Various Periods. (Photos) 756
Gilberd, Dr. Wm., Shewing His Experiments on Electricity to Queen Elizabeth and Her Court. (Photo of painting)..... 644
Group of Those Attending the 15th Annual Meeting, Boston, Mass., 1899. (Photo)..... 690
Groups on Which the Institute Is Represented. (Chart)..... 826
Hoboken Station of the Hudson Electric Light Company in 1897, Interior of the..... 767
Honorary Members and Medalists, Other Than Those Who Served Terms as Presidents..... 811
Hydroelectric Power Stations and Equipment, Some. (Photos)..... 716
(Illumination) Some Early Forms of Electric Lamps. (Photos)..... 730
Institute on Its 50th Anniversary, The. Whitehead.....1143
Instruments, Early Electrical. (Photos) 769
International Engineering Congresses... 836
Library, Engineering Societies..... 837
Medalists and Honorary Members, Other Than Those Who Served Terms as Presidents..... 811
Members, Among Long-Standing..... 825
Members in 1897, A Group of Prominent Institute. (Photo)..... 684
Motors, Typical Electrical. (Photos).. 768
Names Behind the Institute; Presidents, Honorary Members, Medalists, Secretaries, Treasurers, Charter Members..... 786
Officers of the Institute, Past and Present..... 834
Past-President's Luncheon, Swampscott, Mass., June 28, 1923, Group in Attendance at. (Photo)..... 674
Past-Presidents in Attendance at the Chicago Convention, June 29, 1911, Group of. (Photo)..... 773
Plans Progressing for Institute's Fiftieth Anniversary Celebration in May..... 358
Queen Elizabeth and Her Court, Dr. Wm. Gilberd Shewing His Experiments on Electricity to. (Photo of painting)..... 644
Radio Equipment, Some Contrasts In. (Photos)..... 784
Secretaries, The Institute's National.... 820
Sections and Branches of the Institute.. 835
Sections and Branches to Celebrate the Institute's 50th Anniversary in May, Many..... 496
Sections, Chairmen of the Institute's.... 831
Significant Electrical Developments.... 840
Standardization, The A.I.E.E. in..... 837
Switchboards, Some Contrasts in Power System. (Photos)..... 839
Switchgear, Some High Lights in the Evolution of. (Photos)..... 780
Thermionic Tube, the Family Tree of the. (Illustration)..... 753
Transformers From Which Modern Power Systems Grew, Some of the. (Photos)..... 779
Transmission Structures, Some. (Photos)..... 711
Transportation, A Few High Lights in Electrical. (Photos)..... 707
Treasurers, The Institute's National.... 821
Women Members of the A.I.E.E., List of 835

G

General Power Applications Committee Appointed.....1543

I

Industrial Power Applications, An Appeal for Papers on..... 358

K

Kennelly, Doctor, Edison Medal for 1933 Presented to.....*353

L

Lamme Medal. (See Medals, Lamme)
Lee, William States, In Memoriam.....1131

M

Medal, Edison, for 1933 Presented to Doctor Kennelly.....*353
Medal, John Fritz for 1935, Awarded Late F. J. Sprague.....1664
Medals, Lamme
Nomination (1934) Due Nov. 1...1022, 1229
Awarded (1933) to L. B. Stillwell..... 1226

MEETINGS, DIRECTORS:

Executive Committee, New York, December 8, 1933..... 222
New York, January 2, 1934..... 356
Executive Committee, New York, March 9, 1934..... 630
New York, May 25, 1934..... 1129
Hot Springs, Va., June 27, 1934..... 1229
New York, August 7, 1934..... 1326
New York, October 10, 1934..... 1544

MEETINGS, DISTRICT:

Middle Eastern District Executive Committee Meets..... 1064
North Central District, Student Conference Held By..... 1132
Executive Committee Meets..... 1664
Southern District Holds Student Conference..... 631
Student Convention at M.I.T. Successful..... 356
Worcester, May 1933.
North Eastern District May 16–18.... 496
To Meet at Worcester..... 627
To Hold Student Convention..... 629
District Meeting, May 16–18..... 844
Holds Tenth Annual Meeting..... 1023

MEETINGS, NATIONAL:

Pacific Coast Convention 1934.
Dates Selected..... 630
Plans Being Made..... 1022
(Temple of Osiris) May Be Visited. (Photo.)..... 1127
Plan Your Vacation to Include the.... 1128
Headquarters..... 1225
Last Call for the..... 1229
Upholds Coast Reputation..... 1423
Group Photo..... 1425
Summer Convention 1934.
Tentative Plans Are Announced..... 630
50th Annual Summer Convention..... 842
To Be Held This Month at Hot Springs, Va..... 1022
Few of Virginia's Many Natural Attractions Near Hot Springs, A. (Photos)..... 1025
To Be Reported in Next Issue..... 1129
Held at Hot Springs, Va..... 1224
Officers, Delegates, and Members Hold Annual Conference at Hot Springs, Va..... 1230
Presidential Group at Hot Springs, Va., June 25–29..... 1232
Winter Convention 1934.
Program Provides Attractive Technical and Social Activities..... 220
May Be Visited. (Photos)..... 225
Marked by Good Attendance..... 350
Demonstration of Music in Auditory Perspective..... 357
Reports of Committee Meetings Held. 498
Winter Convention 1935.
Institute's 1935 Winter Convention, The..... 1543
Technical Program Announced..... 1662
International Music Hall, Radio City, New York. (Photo)..... 1663
Control Board of Radio City Music Hall Stage. (Photo)..... 1669
Membership Letter. Lee. .2d cov. Jan., 2d cov. Feb., 2d cov. March, p. 510, 850, 1227, 1328, 1424, 1544, 1664
Membership, Transfers and Elections... 234, 370, 505, 637, 848, 1034, 1138, ...1242, 1331, 1430, 1558, 1686
Members Planning Trips Abroad, To Institute..... 630

N

(New York Section) What Place the Engineer in the Changing Economic Scene? (Jordan, Chevalier)..... 1546

NOTE—An asterisk (*) before a page number denotes publication of individual's picture on that page.

O

Officers and Committees (1934–35).
Branches ... 1335
District ... 1335
National ... 1332, 1543
Sections ... 1334
Officers Newly Elected for the Year 1934–35, The Institute's National ... 1038
(Officers) Nominating Committee Announces (1934) Candidates ... 222
Officers, Nomination of 1935 A.I.E.E. ... 1425, 1544

P

Pittsfield Section Former Chairman Dies ... 1551
President, Messages From J. Allen Johnson.
An Insight Into the Workings of the Institute ... 1039
A Message From ... 1142
Another Message From ... 1338
Prize Awards Announced for 1933 Papers, Institute ... 1026
Additional Awards for 1933 ... 1234, 1327
Prizes for Technical Papers, Announcement of (1934) ... 1665
Professional Engineers' Committee on Unemployment.
Engineers Urged to Greater Activity in Local Affairs ... 223

R

Ryan, Harris J. (In Memoriam) ... *1327

S

San Francisco Section Stimulates Student Participation ... 227
Science Series for Engineers, A ... 238
Reprints May Be Made Available ... 1545
Will Be Reprinted ... 1665
Section and Branch Activities Summarized in Annual Report for 1933–34 ... 1027
Sections and Districts, Technical Committee Activities Proposed for ... 631
Sections (Officers 1934–35) ... 1334
Sprague, Frank J., Awarded John Fritz Medal for 1935 ... 1664
Sprague, Frank J., (Bust) Presentation, Principal Addresses Given in Connection With ... *351
Standards.
Capacitors, Standards for ... 1135
Constant Current Transformers ... 366
Electrical Installations on Shipboard ... 1135
Electrical Insulating Materials ... 1676
Electrical Measurements, Standard Methods for ... 366
Electronics Field, Report on Definitions in ... 1135
Graphical Symbols Used for Electric Power and Wiring ... 366
Graphical Symbols Used for Electric Traction ... 366
Graphical Symbols Used in Radio ... 366
Mercury Arc Rectifiers ... 1135
Polyphase Induction Machines ... 1677
Rotating Electrical Machinery, Report on ... 366
Transformers ... 1677
Welding Standards, Two ... 366
Standards Be Maintained, A.I.E.E. Board Urges That Activities of U.S. Bureau of ... 357

T

Technical Committee Activities Proposed for Sections and Districts ... 631
(Technical Committee) Annual Reports to Be Made Available ... 1022
Technical Committee Reports Postponed ... 1129
Townley, Calvert, In Memoriam ... *223

Y

Yearbook Now Available, 1934 ... 497

Division IV—News of Non-Institute Activities

Air Conditioner Association, Unit ... 1676
Air Conditioning Analysed, Home Study Course in ... 634
American Association for the Advancement of Science
Annual Science Exhibition ... 1327
American Engineering Council
Census of Engineers ... 1677
Engineering Affairs at Washington ... 1136
Feiker, F. M., Appointed Executive Secretary ... 367
"Following the Flags" at Washington. (Photo) ... 1030
"Integration" of National Activities ... 1677
Its Relation to the Institute ... 1666
Legislation and Administrative Policy Affecting Engineers ... 1029
Mapping and Surveying the United States ... 1031
Officers Elected at Annual Meeting ... 367
Prominent Engineers Named on Federal Aviation Commission ... 1426
Representative on Employment at Washington ... 1677
Salaries for Engineers ... 1031
Secretaries of Engineering Societies Visit Washington ... 1136
Unemployment Among Engineers ... 1677
Wallace, L. W., Leaves ... 367
American Institute of Mining and Metallurgical Engineers
To Meet ... 362
American Physical Society
To Meet in New York ... 362
Meetings ... 1026
Annual Meeting ... 1674
American Society for Testing Materials
To Meet in Washington ... 362
To Hold Meeting in June ... 1026
President Dies ... 1326
Reports on Electrical Research Activities ... 1669
Outdoor Weathering of Metals and Coatings ... 1674
American Society of Civil Engineers
Officers for 1935 Nominated ... 1674
American Society of Mechanical Engineers
Semiannual Meeting ... 497
To Hold Semiannual Meeting ... 1026
Annual Meeting ... 1425
Elects Officers ... 1551
Journal of Applied Mechanics ... 1663
American Standards Association
Letter Symbols Under Revision, Standard ... 1135
Limit of Observable Temperature Rise ... 1676
Membership Increase Reported ... 1426
Noise Measurement Standards Developed ... 1135
Power Switchgear ... 1135
Radio Standardization Sponsorship To Reside Solely in I.R.E. ... 1676
American Transit Association to Meet ... 1131
Applied Mechanics Journal to Be Published ... 1663
Arch Dam Report, Second Volume on ... 1426
Armstrong, Major, Appointed Professor at Columbia University ... 1327
Aviation Commission, Prominent Engineers Named on Federal ... 1426
(Aviation) Flying 60 Tons of Machinery Into the Peruvian Andes. (Photo) ... 584
(Aviation) Modern Transportation's Most Recent Contribution to Speed and Safety ... 349

B

Barker, George Huntington, Pioneer in Electrical Development Dies ... 1027
Bassett, William Hastings, President of A.S.T.M. Dies ... 1326
Bell Telephone System Centralizes Its Researches ... 847
(Board, Samuel S.) "Finding Work" ... 1670
Boiler of New Design, A Steam ... 362
(Bolivian Power Company) Repairing a Conductor Carrying 38,000 Volts ... 1426
Boulder Dam
Generators Being Assembled. (Photo) ... 499, 1551
Power Transformers ... 1132
Throat Liners for Penstocks of the. (Photo) ... 1325
Visited by San Francisco Engineers ... *359

C

Chamber of Commerce, Engineers Active at Meeting of U. S. ... 1136
Chemistry Industry Medal Awarded to J. G. Vail ... 227
Chemists' Medal to Be Presented to Doctor Conant ... 1025
(Chevalier, Col. W. T.) "What Place the Engineer in the Changing Economic Scene?" ... 1549
(Clark, Dr. Walton) Former President of Franklin Institute Dies ... 1551
Code for Engineering Division of Construction Industry, Doctor Whitehead Explains Proposed ... 1234
Columbia University Offers E.E. Scholarships ... 358
Conference Groups in Business Planned ... 1553

E

Edison Monument Erected in Japan. (Photo) ... 1545
(Electric Railway Presidents' Conference Committee) A "Million Dollar Car." ... 1666
Electrical Equipment Orders Placed, Large ... 497
Electronic Show Conducted by Students ... 632
Electronic Tubes in Industry, How to Use ... 1675
Engineer in the Changing Economic Scene? What Place the (Jordan, Chevalier) ... 1546
Engineering Foundation
Annual Report Issued ... 633
Election Held ... 632
Engineers Active at Meeting of U. S. Chamber of Commerce ... 1136
Outline of Joint Engineering Organizations ... 632
Pays Tribute to Founder Swasey ... 1552
Personnel Research Foundation ... 1136
Second Volume on Arch Dam Report ... 1426
Valuable Books in Engineering Societies Library ... 367
Engineers' Council for Professional Development
Committee on Professional Recognition Commented Upon by C. N. Lauer and Dean Barker ... 224
Engineers Urged to Greater Activity in Local Affairs ... 223

F

Finding Work. (By S. S. Board) ... 1670
Ford to Install Second 110,000-Kw Generator ... 1326
Fort Peck Dam, Work Begins on ... 1132
Franklin Institute Former President Dies ... 1551
Fraud, A Warning Against ... 1024

G

Generator, Building the Most Powerful Single-Shaft. (Photo) ... 1031
Great Britain's First Streamlined Rail Car ... 226

Grunsky, Carl Ewald, Prominent Consulting Engineer Dies ... 1234
Guggenheim Medal Awarded to Boeing ... 1027

H

Harvard, Engineering Education to Be Reorganized at ... 1675
Hetch Hetchy Builder Dead, M. M. O'Shaughnessy ... 1545
Historical Information on Engineering Drawing Requested ... 361
Hoover Dam. (See Boulder Dam)

I

Illuminating Engineering Society Meeting 1131
Illumination, Annual Meeting of U. S. Committee on ... 360
(Illumination) Glareless Lights for St. Paul Airport. (Photo) ... 497
(Illumination) Lighting Control, Metropolitan Opera Installs ... 1675
Illumination, Novel Use of Electrical ... 360
Industrial Notes ... 236, 372, 508, 640, 1036, 1140, 1244, 1336, 1432, 1560
Institute of Radio Engineers
Officers Elected ... 361
To Meet at Rochester ... 1426
International Commission on Illumination
Annual Meeting of U. S. Committee on Illumination ... 360
International Congress for Applied Mechanics to Be Held ... 361
International Music Hall, Radio City, New York, N. Y. (Photo) ... 1663

J

(Jehl, Francis) France Honors Early Menlo Park Worker ... 1675
(Jordan, Dr. Virgil) "What Place the Engineer in the Changing Economic Scene?" ... 1546

L

Library Available, Services of Engineering Societies ... 1668
Lightning Storms in Northwest Studied. 1676
Literature, Engineering 235, 371, 507, 639, 1035, 1139, 1242, 1331, 1431, 1559, 1687
Loudspeaker, A 500-Watt ... 1676

M

Medal Awarded to Boeing, Guggenheim ... 1027
Medal to Be Presented Doctor Conant, Chemists' ... 1025
Menlo Park Worker, France Honors Early ... 1675
Metropolitan Opera Installs Lighting Control ... 1675
Middleton, W. Irving, Former Chairman of Boston Section Dies ... 1327
(M.I.T.) Exchange of Professors Being Arranged ... 362
M.I.T., Five-Year Course Added at ... 1132
Montefiore Prize Award Now Open, Triennial ... 1026

N

National Screw Thread Commission Available, Report of ... 362

O

O'Shaughnessy, M. M., Hetch Hetchy Builder Dead ... 1545

P

Pennsylvania Railroad Orders 57 Locomotives ... 1675
(Personnel Research Federation) Conference Groups in Business Planned. 1553
(Phila. Elec. Co.) Building the Most Powerful Single-Shaft Generator. (Photo) ... 1031
"Porphyry Coppers," Development of Mines and Men Traced in ... 227
Power and Mechanical Engineering, Exposition of ... 1551
Psychrometric Charts ... 362
Public Works Expenditures, Referendum on ... 1136

R

Radio City Music Hall Stage, Control Board of ... 1669
Radio Communication, Domestic Short Wave ... 362
Reading List for Junior Engineers, A ... 1667
Refrigerating Machinery Association Meeting ... 1426
Research Projects, Suggestions for ... 1545

S

(Safe Harbor) Large Electrical Equipment Orders Placed ... 497
"Science Makes More Jobs" the Topic of an Interesting Meeting ... 845
Slide Rule Mangifier, New. (Photo) ... 498
Society for the Promotion of Engineering Education
Historical Information on Engineering Drawing Requested ... 361
Standards Be Maintained, A.I.E.E. Board Urges That Activities of U. S. Bureau of ... 357
Standards Reports Electrical Work, Bureau of ... 361
Society of Naval Architects and Marine Engineers To Meet ... 1551
Swasey, Engineering Foundation Pays Tribute to ... 1552

T

T.V.A. Orders Gas-Electric Locomotives. 1667
Traction, Primary Considerations Relating to Steam, Electric and Diesel-Electric ... 227
Transformer Order Placed, Large ... 1676

U

United Engineering Trustees, Inc.
Annual Report Issued ... 634
Election Held ... 633
New Secretary Elected ... 1136

V

Vail, J. G. Chemistry Medal Awarded to ... 227

W

Washington Award, Names Requested for ... 1026
(White, William Porter) Former Chairman of Pittsfield Section Dies ... 1551
Whitehead, Doctor, Explains Proposed Code for Engineering Division of Construction Industry ... 1234
Wind Tunnel Completed at Case, Electrically Controlled ... 228

X

X-Ray Tubes Are Compared, High Voltage ... 227

Division V—Biographical Index

Includes All Personal and Obituary Items.

Adams, Comfort A. ... *803
Adams, Edward D. ... *818
Aiyangar, R. Narayana ... 1101
Allen, A. E. ... 504
Allison, Donald Cameron ... 1330
Allner, F. A. ... 368
Anderson, H. L. ... 1238
Anderson, L. I. ... 1432
Andrews, H. L. ... 1230
Angell, E. L. ... 1239
Anthony, William A. ... *798
Arnold, Bion J. ... *795
Atkinson, George Washington ... 1686
Atkinson, R. W. ... 1032

B

Baker, P. W. ... 1685
Baker, W. R. G. ... 1137
Baldwin, E. A. ... 504, 1329
Banta, L. V. ... 1685
Barclay, R. H. ... 1032
Barnes, D. C. ... 636
Barnes, H. H., Jr. ... 1684
Barre, Herbert Aubrey ... 1330
Barton, J. P. ... 233
Bascome, G. L. ... 1557
Bassett, J. B. ... 1330
Batchelder, W. O. ... 1240
Beall, M. F. ... 1685
Beckjord, W. C. ... 1557
Belinge, R. A. ... 1684
Bell, Alexander Graham ... *791
Bender, L. B. ... 1684
Bergman, S. R. ... 636
Berresford, Arthur W. ... *804, 1239
Betts, Philander ... 1329
Bewley, L. V. ... 625
Bickelhaupt, C. O. ... 368, 1428
Bishop, Nathaniel ... 1685
Black, W. A. ... 1685
Bliss, F. W. ... 1330
Blondel, André E. ... *812
Bohnert, A. M. ... 1330
Brigman, B. M. ... 1557
Brosemer, R. O. ... 1330
Brown, Arthur A. ... 369
Brown, Charles E. L. ... *812
Brush, Charles F. ... *815
Bucher, G. H. ... 1138
Buck, H. W. ... *802
Budde, Emil A. ... *813
Bush, Vannevar ... 636

C

Cady, W. G. ... 368
Caldwell, C. W. ... 1684
Caldwell, O. H. ... 368
Campbell, Allan B. ... 1033
Carraway, T. W. ... 1239
Carty, John J. ... *801
Cavanagh, Gordon ... 1685
Charlesworth, H. P. ... *810
Chawner, W. R. ... 1033
Chesney, C. C. ... *807
Chitty, A. M. ... 1138
Chubb, L. W. ... 1239
Clark, A. B. ... 1237
Clark, F. M. ... 635
Clark, T. C. ... 636
Clarke, Charles L. ... *823
Clegg, T. Herbert ... 234
Clifford, W. R. ... 233
Coe, R. J. ... 1137
Condict, George Herbert ... 1033
Conley, B. L. ... 1557
Conrad, Frank ... 232, *818
Cook, J. A. ... 1556
Coolidge, William D. ... *818
Cooper, A. B. ... 1032
Cooper, L. S. ... 1684
Corney, C. A. ... 1330
Creedy, Frederick ... 1684
Crocker, Francis B. ... *793
Crowdes, G. J. ... 1329
Cullwick, E. G. ... 1684
Currie, Harry Allen ... 1241
Curtis, C. C. ... 1032, 1429
Curtis, H. L. ... 1137
Cushing, Harry C., Jr. ... 1101

D

Dalzell, C. W. ... 1684
Damon, George Alfred ... 1330
Damon, J. C. ... 1329
Darling, J. A. ... 635
Dates, H. B. ... 1032
Davidson, W. F. ... *1556
Davies, J. E. ... 1685
Davis, C. M. ... 1239, *1555
Davis, Minor Meek ... 1138
Dawes, C. L. ... *1238
Dawson, Arthur W. ... 1330
Dean, H. C. ... 1429
Dearborn, R. H. ... 1137
de Ferranti, S. Z. ... *813
Delack, B. L. ... 1556
Dellinger, Floyd Elliott ... 1241
Dellplain, M. O. ... 1684
DeWitt, Paul ... 1101
Dickerson, E. N., Jr. ... 823
Dickinson, Leonard P. ... 1241
Diwan, Jetha N. ... 1101
Dixon, James ... 1685

Dobson, W. P. 1032
Donaldson, R. D. 1557
Dormer, W. J. S. 1329
Doty, Paul 368, 1684
Downing, P. M. 1556
Doyle, E. J. 636
Driscoll, C. C. 1240
Duncan, Louis *792
Dunn, Gano *790
Dunstan, G. H. 1138
Duvoisin, Edward Marc 1430

E

Eastham, Melville 368
Edgar, Harry Thomas 637
Edgar, R. F. *1238
Edison, Thomas A. *814
Egan, L.H. 504
Eldredge, Mark 636
Emmet, William LeRoy *816
Engle, K. D. 1685
Evans, Gomer Louis 1686

F

Faciolli, Giuseppe 368, *819
Farmer, Frank Malcolm 231, 504, *1038, 1555
Farmer, Moses G. *811
Ferguson, Louis A. *798
Ferguson, William A. 1101
Ferry, J. H. 635
Field, Allan Bertram *819
Field, Cyrus W. *811
Fies, John 1557
Finch, H. I. 1329
Finch, W. G. H. 1557
Findley, James G. 505
Finley, James G. 1101
Fisken, J. B. *1329
Fitz, O. R. 1685
Foch, Ferdinand *814
Fondiller, William 1239
Foote, J. H. 1557
Foster, D. E. 1557
Foster, William J. *819
Fowler, G. F. 1330
Fox, E. G. 504
Frederiksen, Victor 1684
Friday, C. D. 1685
Funk, Nevin Elwell 231, 1038

G

Gear, Harry Barnes 232, 1038
Gelin, Lazare 233
Gherardi, Bancroft *807, 1240
Gierisch, Otto Tomas 1138
Gifford, W. S. 1430
Going, L. W. 1032
Goldsmith, A. N. 368
Goldstein, M. K. *1683
Goodwin, Harold, Jr. *1683
Gorsuch, W. S. 1137
Graham, R. W. *1556
Gray, Roy William 1241
Green, D. C. 1685
Green, Norvin *788
Greenland, S. W. 504
Grettum, L. A. 1430
Grissinger, Elwood 1558
Grunfield, Maurice 637
Gulliksen, F. H. *1137

H

Hackett, J. Henry 1101
Hamilton, George A. *816
Hamilton, H. C. 1329
Hammer, William Joseph 636, 847
Hannah, S. W. 1683
Harrell, F. E. 504
Harries, George Herbert 1558
Harris, Grenville A. 1138
Harvey, Dean 1032
Hawkes, C. J. 1324
Hazard, Rowland R. 829
Heath, E. B. 1681
Heaviside, Oliver 815
Heising, R. A. 368
Hellmund, Rudolf E. *819
Henline, H. H. *820
Henrici, Hermann C. 1242
Henyam, G. W. 1033
Hering, Carl *794
Hertz, S. S. 1556
Hewlett, Edward Marriott 1240
Hicks, L. R. 1557
Hill, W. S. 1557
Hillebrand, W. A. 1329
Himes, C. F. 1238, 1329
Hinson, N. B. 1556
Hitchcock, H. W. 233
Hobart, H. M. 1428
Hoen, W. M. 1556
Hogan, J. V. L. 368
Holton, J. L. 1239
Hoover, Herbert *815
Horle, L. C. F. 368
Hosmer, Sidney 1429
Hough, H. W. 1033
Houston, Edwin J. *792
Howell, John W. *817
Hughes, R. H. 1137, 1240
Hull, L. M. 368
Humphries, P. H. *1238
Hunt, L. F. 1683
Hunter, T. M. 635
Hussey, Abram 1684
Hutchinson, F. L. *820

I

Idail, Murray J. 1138
Ilsley, L. C. *1556

J

Jackson, Dugald C. *799
Jacobus, D. S. *1032
Jaehnig, Paul H. 1101
James, H. D. 504
James, T. C. 1032
Jansky, C. M., Jr. 368
Jewett, F. B. 625, *805
Johnson, H. A. 232, 1033
Johnson, J. Allen 230, *1038, 1137, 1428
Joho, Ernest Charles 637
Judy, E. W. 1556

K

Kaesemeyer, Charles F. 1101
Kaighn, Herbert Eugene 1034
Kato, Shizuo 1138
Keel, C. H. 1329
Keese, Foster D. 1430
Keith, Nathaniel S. *820
Kellogg, C. W. 368
Kelly, J. T., Jr. 1685
Kelvin, Lord (William Thomson) *812
Kendall, B. W. 1237
Kennelly, A. E. *232, *793
Kent, P. J. 635
Ker, William Wallace 637
Kikutaro, Nogami 1558
King, C. F., Jr. 1685
Kingston, F. S. 1685
Klauber, L. M. 1429
Knight, F. D. *1683
Knowlton, R. H. 1033
Knox, C. C. 1557
Kobak, Edgar 625, 1032
Kobrock, J. B. 1329
Koiner, C. W. 233
Kolster, F. A. 368
Kouwenhoven, W. B. 1032
Kreindler, Mitchell Aaron 1430
Kron, Gabriel 1137
Kroneberg, A. A. *1683

L

Lackie, W. W. 1138
Lamar, R. W. 636
Lamme, Benjamin G. *817
Lamme, William Fenner 234
Lane, H. S. 1329
Langan, T. R. 1329, 1684
Lawler, E. R. 1032
Laxton, Ralph Roberts 1242
Lee, W. S. 683, *809, *1131
Leihy, C. W. 1329
Lieb, John W. *796
Lillibridge, R. D. 1240
Lincoln, J. C. 1555
Lincoln, Paul M. *801
Lines, Marion Brown 1138
Logan, A. E. 1555
Ludwig, L. R. *1237
Lydall, C. H. 1684
Lyden, Daniel R. 1101
Lyman, James 1033
Lyman, O. B. 1557
Lyons, J. M. 1685

M

Mackness, Cyril Francis 505
Maclachlan, Wills 1032
Magnusson, C. E. 1429
Maillard, A. L. 1137
Mailloux, C. O. *800
Marconi, Guglielmo *814
Martin, C. B. 1032
Martin, H. A. 233
Martin, T. Commerford *789
Mathey, Edward Dubois 1241
May, D. T. 1137
Mayo, C. A. 635
McCarthy, J. B. 1033
McCarty, George Martin 1242
McClellan, William 368, *804
McElheny, George B. 1101
McGraw, J. H. 1430
McKee, E. R. 1684
McKinney, H. R. 1685
McManus, John Hugh 1686
McMeen, Samuel Groenendyke 1330
McMillan, Fred Orville 230, 1038
Mellinger, Edward 1101
Mendenhall, Vestor David 234
Mercier, E. F. H. 1557
Mershon, Ralph D. *800
Mess, C. T. 368
Meyer, E. B. 1239, 1429
Meyer, Frank J. 230, 1038
Milde, E. C. 1684
Miller, Kempster Blanchard 233
Millikan, Robert A. *816
Milne, James 1241
Mitchell, Guy Köchling 1034
Moloney, T. O. 504
Montgomery, L. J. 1684
Montsinger, V. M. 1429
Moody, A. S. 1429
Moon, P. H. 1684
Morecroft, John Harold 504
Morehouse, L. F. 1329
Moreland, E. L. *1683
Morrill, Edward F. 1101
Morris, H. W. 1685
Morrow, L. W. W. 1428
Morse, John 1329
Morss, Everett 369
Morss, H. A. 636
Mortensen, Niels L. 1101
Moulton-Redwood, W. J. *1238
Moultrop, I. E. 1239
Muir, R. C. 1239
Murray, J. M. 1330
Myers, Ord 1101
Myler, P. J. 636

N

Nelson, A. R. 1685
Nelson, E. L. 368
Newton, George Johnson 1035
Nitschke, Charles Wells 505
Noble, P. O. 1330
Nogami, Kikutaro 1558

O

Oehler, A. G. 1033
Oldacre, M. S. 1430
Osgood, Farley *806

P

Pacinotti, Antonio *813
Parkhurst, Charles W. 1686
Partridge, Warren 1686
Patten, I. A. 1684
Perry, O. M. 1032
Peters, Joseph Dufferin 369
Phelps, George M. *821
Phelps, J. E. B. 1033
Pope, Franklin L. *788
Pope, Ralph W. *820
Porras, M. Alfonso 1101
Porter, J. F. 1329
Post, George Gilbert 230, 1038
Potter, William Bancroft 369
Powell, A. L. *1239
Preece, Sir William *811
Price, Charles Wilson 1034
Proutt, Frederick George 1241
Pupin, M. I. *806

Q

Quinn, E. A. 1240

R

Rae, Frank B. 824
Reagan, M. E. *1555
Reid, Thorburn 234
Rhodes, Donald 1329
Rice, Calvin Winsor 1557
Rice, E. W., Jr. *802
Ripple, Paul W. 1242
Robert, Jr., L. W. 635
Rodey, Jr., B. S. 636
Rogers, J. O. 1557
Roper, M. L. 1686
Ross, J. D. 1033
Ross, Norman Nelson 637
Roth, Arnold 368
Royer, J. E. 1429
Rutan, E. J. 1557
Ryan, Harris Joseph *805, 1240, *1327
Ryan, Walter D'Arcy 636
Ryan, W. T. 1429

S

Samuels, M. M. 1329
Scattergood, E. F. 1429
Schamberger, S. O. 1239
Schiller, A. R. 1556
Schleicher, G. B. 1237
Schmid, C. F. 1033
Schneider, W. G. 1557
Schreiber, H. V. 233
Schuchardt, R. F. *808
Schum, Charles H. 1101
Scott, Carl F. 1557
Scott, Charles F. *795
Scott, J. A. 1137
Scott, William Morton 1242
Selden, Paul Bernard 1430
Sessions, Edson Oliver 1033
Shaad, G. C. 1329
Shand, Robert 1101
Sheldon, Samuel *797
Shibusawa, Motoji *815
Shields, C. R. 1685
Shoemaker, G. T. 1329
Shreve, E. O. 1240
Shute, E. R. 368
Siegfried, Victor 504
Simon, Arthur 1684
Skinker, M. F. 1033
Skinner, C. E. *809, 1032
Sleeper, H. P. 1428
Slepian, Joseph *1237
Slichter, Walter Irvine 232, *821
Sloan, M. S. 1032
Smalley, D. D. 1329
Smedburg, M. W. 1685
Smith, Carleton W. 505
Smith, D. L. 1137
Smith, F. W. 1429
Smith, H. A. 1330
Smith, Harold B. *808

Smith, J. C. 504
Smith, L. W. 504
Smith, W. R. 1137, *1682
Spector, M. 504
Spencer, H. H. 1239
Sperry, Elmer A. *818
Sporn, Philip *635
Sprague, Frank Julian *791, 1557, 1685
Spring, E. W. *1137
Squier, George Owen 636, 848
Stacy, J. D. 1684
Stahl, E. C. M. 1684
Stanley, William *817
Stannard, Clare Nowien 369
Stansel, N. R. *1555
Stauffacher, E. R. 233
Stearns, W. G. 1330
Steinmetz, Charles P. *794
Stephens, C. E. 368
Stevens, John Franklin 234
Stewart, H. R. 1430
Stillwell, L. B. *503, *798
Stott, Henry G. *797
Streuli, W. R. 1684
Strong, J. R. 1685
Susman, Paul 1138
Sutherland, George 1429
Sutton, L. V. 1240
Swasey, Ambrose *815
Swope, Gerard 1429

T

Tait, F. M. 1685
Tapscott, Ralph Henry 231, 1038, 1428
Taylor, T. S. 1429, 1557
Teckoe, J. E. 1032
Tesla, Nikola *817
Thompson, S. P. *813
Thomson, Elihu *790
Thomson, Wm. (Lord Kelvin) *812
Timbie, W. H. 231, 1038
Timoshenko, G. S. 1557
Tolman, C. M. 1685
Townley, Calvert *223, 233, *803
Tullar, C. E. 1239
Turner, H. M. 368, *1555

U

Underwood, C. M. 1684

V

Vassar, H. S. 1033, 1239
von Siemens, E. W. *812

W

Waddell, J. D. 1557
Wagner, T. B. *1237
Walls, J. A. 368
Way, S. B. 504
Weber, F. D. 636, 1032
Weber, H. H. 1032
Welch, A. F. 1330
West, John 504
Westinghouse, George *816
Weston, Edward *789
Wheatlake, B. C. J. 504
Wheeler, Schuyler Skaats *796
White, Bryant 233
Whitehead, J. B. 504, *810, 1032
Willis, C. H. 1237
Wilson, C. E. 1330
Wilson, Charles H. 1558
Wilson, J. M. 1033
Wilson, Richard Little 1430
Wilson, William 368
Winter, W. L. 368
Wolfe, C. M. 1685
Wolfrom, C. A. 504
Wood, L. A. S. 1240
Wood, Walter 1430
Woodruff, W. W. 1685
Wright, E. M. 1330
Wyatt, K. S. *1137

Y

Yamamota, Kiyosho 1684
Yambert, D. W. 1685
Yorke, George Marshall 636

Published Monthly by

American Institute of Electrical Engineers

(Founded May 13, 1884)

Electrical Engineering

Registered U. S. Patent Office

January 1934
Volume 53
No. 1

The Official Monthly Journal and Transactions of the A.I.E.E.

J. B. Whitehead, President
H. H. Henline, National Secretary

Publication Committee
E. B. Meyer, Chairman
R. N. Conwell — **H. H. Henline**
W. S. Gorsuch — **H. R. Woodrow**

Publication Staff
G. Rom Hannigan, Editor
C. A. Graef, Advertising Manager

PUBLICATION OFFICE, 20th and Northampton Streets, Easton, Pa.

EDITORIAL AND ADVERTISING OFFICES, 33 West 39th Street, New York, N. Y.

ENTERED as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918.

SUBSCRIPTION RATES—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii and the Philippine Islands, Central America, South America, Haiti, Spain and Spanish Colonies; $13 to Canada; $14 to all other countries. Single copy $1.50.

CHANGE OF ADDRESS—requests must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered due to incorrect address cannot be replaced without charge. Be sure to specify both old and new addresses and any change in business affiliation.

ADVERTISING COPY—changes must be received by the fifteenth of the month to be effective for the issue of the month succeeding.

STATEMENTS and opinions given in articles appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters.

REPUBLICATION from "Electrical Engineering" of any Institute article or paper (unless otherwise specifically stated) is hereby authorized provided full credit be given.

COPYRIGHT 1934 by the American Institute of Electrical Engineers.

ELECTRICAL ENGINEERING is indexed in Industrial Arts Index and Engineering Index.

Printed in the United States of America. Number of copies this issue—

17,500

This Month—*Winter Convention Issue*

Front Cover

Electric Furnace in Operation

Special Educational Series—No. 2

Fundamental Properties of the Electron 3
By ALAN T. WATERMAN

Communication

★Auditory Perspective—Basic Requirements 9
By HARVEY FLETCHER

★Auditory Perspective—Physical Factors 12
By J. C. STEINBERG and W. B. SNOW

★Auditory Perspective—Loud Speakers and Microphones . . . 17
By E. C. WENTE and A. L. THURAS

★Auditory Perspective—Amplifiers 25
By E. O. SCRIVEN

★Auditory Perspective—Transmission Lines 28
By H. A. AFFEL, R. W. CHESNUT, and R. H. MILLS

★Stabilized Feed-Back Amplifiers 114
By H. S. BLACK

★Auditory Perspective—System Adaptation 216
By E. H. BEDELL and IDEN KERNEY

Education

★The Pitt-Westinghouse Graduate Program 103
By H. E. DYCHE and R. E. HELLMUND

—Turn to Next Page

Electric Furnaces

★Electrical Equipment for Induction Furnaces . . 43
By C. C. LEVY

★Cast Iron and Its Production 120
By M. V. HEALEY

★Rocking Indirect Arc Electric Furnaces . . . 132
By E. L. CROSBY

★High Frequency Induction Furnaces 194
By C. A. ADAMS, J. C. HODGE, and M. A. MacKUSICK

Electric Power Switching

★Electric Power Switching 147
By A. H. LOVELL

★Switching at State Line Station 148
By T. C. WHITE

★Switching at Richmond Station 156
By RAYMOND BAILEY and F. R. FORD

★Switching at the Connors Creek Plant 162
By A. P. FUGILL

Electrical Machinery

★Effects of Rectifiers on System Wave Shape . . 54
By P. W. BLYE and H. E. KENT

★An Experimental Ignitron Rectifier 75
By L. R. LUDWIG, F. A. MAXFIELD, and A. H. TOEPFER

★Inductor Alternators for Signaling Purposes . . 78
By F. W. MERRILL

★Equivalent Reactance of Synchronous Machines . 124
By S. B. CRARY, L. A. MARCH, and L. P. SHILDNECK

★Protecting Machines From Line Surges 139
By J. F. CALVERT

Electrical Measurements

★Heavy Surge Currents—Generation and Measurement 86
By P. L. BELLASCHI

★A New Demand Meter 94
By B. H. SMITH

★An A-C Potentiometer 108
By S. L. BURGWIN

★Impulse Generator Circuit Formulas 169
By J. L. THOMASON

★Portable Schering Bridge for Field Tests . . . 176
By C. F. HILL, T. R. WATTS, and G. A. BURR

Power Distribution

★Radial Versus Primary Network Distribution . . 38
By H. E. WULFING

★An Economic Study of Suburban Distribution . . 97
By A. H. SWEETNAM and C. A. CORNEY

Protective Devices

★Lightning Measured on 4-Kv Overhead Circuits . 33
By HERMAN HALPERIN and K. B. McEACHRON

★Automatic Reclosing of Oil Circuit Breakers . . 48
By A. E. ANDERSON

★Petersen Coil Tests on 140-Kv System 63
By J. R. NORTH and J. R. EATON

★Control of Distance Relay Potential Connections . 206
By A. R. van C. WARRINGTON

Transportation

★Pantograph Trolleys I—Design Features . . . 182
By W. SCHAAKE

★Pantograph Trolleys II—Operating Features . . 190
By B. M. PICKENS

News of Institute and Related Activities 220

Winter Convention Program Provides Attractive Technical and Social Activities 220
A.I.E.E. Executive Committee Meets 222
Nominating Committee Announces Candidates . 222
In Memoriam—Calvert Townley 223
E.C.P.D. Committee on Professional Recognition Commented Upon by C. N. Lauer and Dean Barker 224

Letters to the Editor 228
Membership 234
Engineering Literature 235
Industrial Notes 236
Employment Notes . . (See Advertising Section)
Officers and Committees (For complete listing see p. 658–81, September 1933 issue of ELECTRICAL ENGINEERING)

★ These papers are to be discussed at the forthcoming A.I.E.E. winter convention to be held in New York, N. Y., January 23–26, 1934. For final announcements concerning the convention, see p. 220–2.

The Annual Reference Index to ELECTRICAL ENGINEERING for 1933 Is Now Available

Fundamental Properties of the Electron

By ALAN T. WATERMAN
FELLOW Am. Phys. Soc.
Yale University,
New Haven, Conn.

Presenting clearly and concisely a story of the evolution of the electron, as seen from the viewpoint of modern theoretical physics, this article reveals that the electron in many respects is following the "trend of the times." A review of the status of the electron reveals clearly that its properties have been extended well beyond those contemplated by its discoverer; also that, in following the simple and apparently necessary expedient of endowing the electron with such properties as a wave aspect and a change of mass with velocity, the vividness of the mental conception of an electron has been dulled. The author indicates that, in addition to the mental picture of fundamental atomic processes having become more difficult or even impossible, the intrinsic precision of the processes themselves is called into question by the most recent theories. This is the second in a series of special articles developed under the sponsorship of the A.I.E.E. committee on education.—Editor

THE ATOMIC NATURE of electricity, the realization that an electric charge or current consists of minute electrons, may be considered to be the second vindication of the atomist school of Greek philosophy which so earnestly and ably argued against the continuity of matter or its infinite divisibility. Although ordinary matter already had been shown to consist of atoms and molecules, the physicists of the eighteenth and the early nineteenth centuries had come to regard electricity as a continuous fluid and possibly not like matter at all in the ordinary sense. This conception lent itself readily to theoretical development, even to the extent of explaining in the expert hands of Maxwell the nature of light as electromagnetic wave motion. The picture of the ultimate nature of electricity, however, remained vague in spite of this progress. The first evidence as to its atomic nature was implicit in the laws of electrolysis discovered by Faraday in 1834, although Faraday seems not to have stressed this conclusion. Maxwell himself refers to the possibility, but it remained for Stoney in 1874 to make use of this hypothetical particle which he christened the "electron."

The laws of electrolysis become almost self-evident if a definite electrical charge, or some multiple thereof, is carried by atoms in electrolytic solution. What then is more natural than to assume the existence of a universal particle of electricity? The size of this charge evidently is the total charge passed through the solution, divided by the number of carriers. Unfortunately, although the charge transported may be measured easily, the number of carriers is more difficult to ascertain. However, the mass of substance liberated along with the electricity is measurable; it should be equal to the desired number multiplied by the mass of each. Thus, simple observations of the mass of substance M and the total electrical charge E liberated at a given electrode, since each involves the same number of particles, yield at once by their quotient E/M the ratio e/m of the charge on *each* particle to its mass. (Strictly speaking, of course, only the average value is obtained.) The stage then is all set for progress in two directions: an independent determination of m will determine e, and *vice versa*. Thus, in an experiment that may be performed quickly by an elementary student, we find ourselves on the road toward knowledge both of the atom and of electricity.

Electric Discharges in Gases

The next step in the isolation of the electron came from the study of electrical discharges in gases. At low pressures mysterious rays were seen to proceed, apparently from the cathode, hence called "cathode rays." Traveling as they did, away from the negative terminal, these rays, if particles, should bear a negative charge. It was necessary however to prove that they were not some form of ray like light, and this was difficult because of their straight paths and the fluorescent effects they caused, as well as from the obvious light effects present during the discharge at higher pressures. That they were electrified became evident when they were found to be deflected by a magnetic field, precisely as the armature of a simple electric motor is propelled by the magnetic influence of the field magnet (for electricity in motion should constitute an electric current and be subject to the same laws). The direction of their deflection and also their deviation by an electrostatic field, in conjunction with their source, confirmed their electric charge as negative. From their mechanical and heating effects upon impact they were seen to possess mass. Assuming by analogy with electrolysis, therefore, that the cathode rays were negatively charged particles of definite mass and velocity, Schuster found in 1870 that the velocity and the charge-to-mass ratio e/m could be determined from the amount of deflection in electrostatic and magnetic fields. This ratio turned

out to be about 1,850 times as large as the corresponding value for the hydrogen ion in electrolysis. Evidently either the charge on each particle would have to be enormously greater than ionic charges in electrolysis, or the mass of the particle should be correspondingly smaller; perhaps both.

Sir J. J. Thomson in a series of masterly studies of the conduction of electricity through gases beginning in 1895, showed that, although the speeds of the cathode rays depended to a certain extent upon the conditions of the experiment, the value of the charge-to-mass ratio was the same regardless of the kind of (rarefied) gas used in the tube and regardless of the material of the electrodes. The presumption, therefore, was that the cathode rays were streams of new *universal* negatively charged particles. Upon making the reasonable assumption that the charge carried by each cathode particle was equal to the elementary unit-charge involved in electrolysis, the mass of each particle should be about $^1/_{1,850}$ of the mass of the lightest known atom, hydrogen. In this way the existence of Stoney's "electrons" seemed to be demonstrated. Incidentally, the mass of this electron was so small that the difference in weight of a positively and a negatively charged body would escape detection.

Charge and Mass of an Electron

It remained for Millikan, between the years 1908 and 1917, by perfecting a method originated by Townsend in 1897 and improved by J. J. Thomson and H. A. Wilson at Cambridge, to measure to an accuracy of 1 part in 1,000 the electrical charge ($e = 1.59 \times 10^{-19}$ coulombs) carried by a single electron. From the known value of e/m its mass could then be found in *grams*, this proving to be 9×10^{-28} grams. At once the mass of every atom was known in terms of ordinary units, instead of merely with reference to that of oxygen as in the chemical atomic weights. Off hand, the measurement of any quantity as small as the electronic charge would seem to be out of the question. In principle, Millikan's method consists essentially in the use of a strong electric field to support a minute electrically charged oil drop in the space between 2 condenser plates where it may be observed through a microscope. The force on a charge q in a field E is Eq and, if the particle is to remain suspended, this force must equal its weight w. Hence, in equilibrium, $Eq = w$ and q is computed by a knowledge of E and w. The ingenuity of the device consisted in applying an electric field large enough to make up for the smallness of the charge and thus produce a force sufficient to equal the weight of the drop, which weight could be determined in several ways. In practice it was found expedient not to hold the drop stationary, but to measure its upward and its downward drift with the field on and off, respectively. The charge on the drop was obtained by allowing it to pick up ions from the air, which was ionized by exposing it to X rays or to a radioactive source. It was found that practically all drops bore the same charge no matter what the gas, its ionizing agent, or the size or nature of the drop; none carried less than this charge; a few carried exactly twice as much or, rarely, exactly 3 or 4 times as much. The electron thus was established as a particle of definite mass and electric charge; presumably it was the fundamental unit in electrical phenomena.

Change of Electronic Mass With Velocity

Paralleling this advance there came, from the then new field of radioactivity in the study of the β rays isolated by Rutherford, evidence of the new particles as an integral constituent of the atom. In 1902 Kaufmann, by deflection methods similar to those used for cathode rays, determined the value of e/m for β rays. Their speeds proved to be much higher than those of cathode rays, approaching in some cases the speed of light (186,000 miles per second). For all except the fastest β rays the value of e/m agreed with that for cathode rays, and the β rays thus were identified as electrons. For the case of an electron, the fastest rays proceeded to furnish a striking verification of a proposal made by Lorentz that mass might be electromagnetic in nature; a proposal later generalized by the theory of relativity to the effect that mass and energy are equivalent and connected by the relation (in CGS units): $mass = energy/c^2$, where c is the velocity of light in a vacuum. Lorentz first showed that by virtue of its charge alone an electron would have to possess inertia, and hence mass, even if not endowed with mass as ordinarily conceived. That this is true may be understood from the fact that when an electron is accelerated its surrounding magnetic field caused by its motion is increased. Now, a magnetic field represents energy; to increase this field requires the expenditure of energy; consequently a force is required to accelerate the electron *because of its electrical charge alone;* therefore, a pure electrical charge must have the property of mass. For ordinary speeds, and for a charged sphere of radius a and total charge e, this electromagnetic mass is computed to be $2\,e^2/3\,ac^2$. In passing, it is interesting to note that, subject to its verification, this hypothesis makes possible a rough estimate of the dimensions of an electron. If the electron is a charged sphere possessing only electromagnetic mass, its radius would be 1.85×10^{-13} cm, roughly $^1/_{50,000}$ the diameter of an atom. Lorentz and others

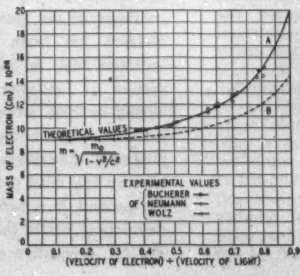


Fig. 1. Variation of electronic mass with velocity. Curve A, theoretical values; Curve B, assuming half the mass invariable

(From "Atomic Physics," Physics Staff, University of Pittsburgh)

further showed that the electron's mass (transverse), although constant for ordinary speeds, should increase rapidly as its velocity approached the speed of light, according to the expression $m = m_0/(1 - \beta^2)^{1/2}$ where $\beta = v/c$ the ratio of the speed of the electron to that of light and m_0 is the "rest-mass" of the electron. The same result is obtained more directly and more generally from relativity theory. This matter was put to experimental test by Bucherer, who found by an ingenious application of the deflection method that this law was obeyed closely for fast electrons from radium fluoride. The mass of an electron moving with 98 per cent of the speed of light, for instance, proved to be more than 5 times its rest-mass, although the difference is not detectable for speeds less than $^1/_{10}$ that of light.

Thermionic and Photoelectric Emission; The Quantum Theory

Along with the investigation of the electron, and contributing to its establishment, came an investigation the application of which was destined to be of the greatest importance, both commercially and in research. Chiefly as a result of the efforts of O. W. Richardson and his coworkers for a period of years beginning about 1900, the phenomenon of thermionic emission was analyzed and its laws discovered. Substances, especially metals, when heated were observed to emit electricity which proved to consist of these same electrons. A quite satisfactory theory of this behavior assumed the electrons to exist within the hot body somewhat as a gas which "evaporated" from the surface when heated. The analogy holds further for, corresponding to the heat of vaporization, the electron has to do work w in order to escape. Very soon Fleming in England saw in this effect the possibility of using a hot and a cold electrode in an evacuated tube to operate as a unidirectional valve, or rectifier, for electric currents. The current, in the form of electrons, will pass only from hot to cold electrode. De Forest added a third electrode in the form of a grid between the others, thus adding flexibility, control, and the possibility of amplification. The subsequent sensational development of the vacuum tube as radio detector, amplifier, oscillator, and for other uses is well known.

In the meantime Max Planck in 1900 had set the scientific world agog with his radical but undeniably successful quantum theory of radiation, a theory which has revolutionized thought in physical science. It was not long before the theory was linked with the electron. In 1905 Einstein proposed a simple quantum theory explanation for a phenomenon long known but little understood—the photoelectric effect, or the emission of electrons from bodies under the action of light. Among the known facts regarding this effect was the observation that the speed or the *kinetic energy* with which the electrons were emitted depended upon the *frequency of the light, but not upon its intensity.* This fact proved impossible to reconcile with any imaginable mechanism for the effect based upon classical laws. The striking nature of this apparent paradox becomes more evident when it is considered that the light from the feeblest possible source, such as a faint star, will eject from a substance electrons having the same kinetic energy as those produced by the most intense arc light. There can be no question of gradual absorption of the light until the requisite energy has been obtained, for in either case emission immediately follows illumination. The only difference is that the arc light produces *more* electrons per second. To a physicist with the viewpoint of the last century it is as though the ripples produced by a raindrop falling in a pond were to cause drops of water to be shot up here and there from the pond to a height of 100 ft, say, and all to the same height no matter how far they happened to be from the source of the ripples. In explanation, Einstein proposed an equation innocent enough when stated in words: that the kinetic energy with which the electron emerges is equal to the energy received from the light minus the work done to escape. The novelty consisted in identifying the energy received from the light with Planck's "quantum" of energy, a discrete bundle of energy. The latter is written as $h\nu$, where h is a universal constant (6.55×10^{-27} erg sec) and ν is the frequency of the light. The amount of energy contained in a quantum then depends only upon the *frequency* of the light, whereas according to the wave theory of radiation it also depends upon the amplitude of the wave (intensity of light). Furthermore, the electron must accept or reject this energy as a unit; it may ignore the quantum completely, but it cannot use part only. The photoelectric effect then could be interpreted rationally in terms of this theory. As added confirmation, the work done by an electron in escaping, on the basis of the Einstein equation, proved to be identical within experimental error with the work w already mentioned as deducible from thermionic emission. Einstein's equation then reads: *kinetic energy* $= h\nu - w$.

The Atomic Model of Bohr

In the hands of Planck and Einstein the phenomena of radiation and photoelectricity thus were explained by the quantum theory, but this theory appeared completely irreconcilable with the wave theory of light which had reached an apparently impregnable position of security during the nineteenth century. How can light radiation consist of waves continuously spreading in all directions and at the same time consist of a collection of bundles of energy, each of which is capable of being delivered intact at any given point? Before a way out of this dilemma could be found, the champions of the wave theory were dismayed to find that overwhelming evidence began to appear in the atomic realm in further support of the quantum theory. In 1913 Niels Bohr put forward a theory of the emission and absorption of light by atoms that explained in remarkable detail the spectrum of hydrogen and ionized helium. His model of the atom as a miniature solar system in which the massive nucleus is the sun and the electrons the planets, now is well known. Although, as a pic-

ture, Bohr's atom has faded almost into a mathematical abstraction in the light of present-day quantum mechanics, his fundamental postulate has remained; namely, that the total energy of an atom can change only by an amount equal to a quantum of energy $h\nu$. If the atomic energy increases, an energy $h\nu$ is absorbed; if it decreases, an energy $h\nu$ is liberated. In either case the frequency of radiation absorbed or emitted is perfectly definite and calculable from the relation: $h\nu$ = change in atomic energy. Since the atom then obviously could exist only in discrete "stationary" states of energy, Bohr pictured each electron as having various separate possible orbits of different energies. When an electron jumped from one orbit to another, a definite frequency of radiation corresponding to the resulting change in atomic energy might thus be absorbed or emitted. Confirmation of this idea received support also from the more directly measurable energy required to detach an electron completely from an atom (i. e., to ionize the atom) which energy on the Bohr theory, is calculable as an electron jump from a normal orbit to a very great distance from its nucleus. It was found soon that Bohr's model was inadequate in the case of more complicated atoms; in fact, the atom has shown greater and greater reluctance toward being portrayed in any such simple guise. Of interest here is the fact that a careful study of apparently single spectral lines has exposed a "fine structure" explicable on the quantum basis by attributing to each electron a spin of determinable amount.

Waves Regarded as Particles; The Compton Effect

Probably the most striking application of the quantum theory is shown in the Compton effect. If a homogeneous beam of X rays (which can be shown to consist of waves of equal length and frequency) is allowed to fall upon a solid, a block of carbon for instance, the beam is "scattered" in all directions like a beam of sunlight on paraffin. Analysis of the X rays scattered in a particular direction discloses the curious fact that although a part of the scattered rays retain their original wave length and frequency the remainder are found to possess a definite longer wave length (lower frequency) than the primary rays. (As in all waves, the product of wave length and frequency is equal to the velocity of the wave; hence a longer wavelength has a lower frequency of vibration, and *vice versa*.) These "modified" rays, in the process of being deflected through the scattering angle, have had their quanta of energy reduced in amount. A. H. Compton in 1922 boldly postulated that the fundamental scattering process consisted of a collision between a primary quantum of radiation and an electron, in which collision the usual laws of impact were maintained; namely, conservation of momentum and of energy. As a result of the impact, regarded like that of two billiard balls, the electron is set into motion and thus acquires kinetic energy. This kinetic energy must be furnished by the original quantum, which then leaves the scene of action with less energy; i. e., as a smaller quantum, which in turn means a lower frequency, since the amount of energy in a quantum is proportional solely to its frequency. Thus there is established a remarkable sequence: (1) at the start the frequency of the primary X rays is obtained by measuring their wave length, thus establishing their wave nature; (2) during impact the X ray is treated as a material particle colliding with an admittedly material electron; (3) after impact the frequency again is measured by wave methods. By this method is found complete justification for the assumed character of the impact process, for the theoretical change in frequency observed should depend only (and in a calculable manner) upon the angle of scattering—conclusions which are exactly confirmed by experiment. Furthermore the "recoil" electrons can be detected and shown to have acquired kinetic energy. The question previously asked might now be worded: "When is a wave not a wave?" And the answer, in all seriousness, is: "When it is a particle."

Electric Waves; Wave Mechanics

Considerations such as these led L. de Broglie in 1924 to speculate concerning a possible conception of matter in terms of waves, which idea in any other age would have seemed highly fantastic and metaphysical. Nevertheless, he arrived at a consistent hypothesis, though it required the postulation of waves of a sort different from any which have been observed directly—so-called phase or ψ-waves. This notion was developed by Schrödinger in 1926 into precise mathematical form with noticeable improvement over the Bohr-Sommerfeld theory in the interpretation of spectra. Briefly the "wave-mechanical" theory sets up a second-order differential equation applying to an atom, for instance, that in form resembles a wave equation in sound or in mechanics. Subject to appropriate boundary conditions, solutions of this equation are possible only for certain discrete values of the energy of the atom; for example, the stationary states of Bohr. Thus essentially the scheme is one for determining these same atomic energy states by means of an equation. The equation, be it noted, is a *wave* equation, whereas

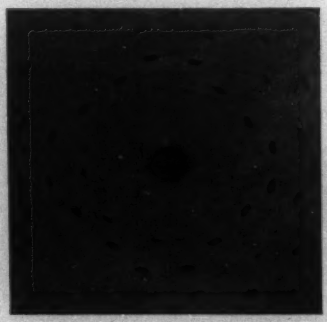


Fig. 2. Diffraction pattern of a narrow beam of X rays on passing through a ZnS crystal

(Friedrich and Knipping)

hitherto only particles had been postulated in an atom. Development in another direction, laying emphasis upon strictly observable quantities such as frequencies instead of hypothetical orbits, led to Heisenberg's matrix theory which is entirely mathematical, using the unusual form of mathematics responsible for its name, and which was shown to agree entirely with the wave-mechanical scheme.

Proof of Wave Aspect of Electrons

Now, on the de Broglie wave-mechanical basis, there should be associated with an electron a wave the length of which should be Planck's constant h divided by the momentum of the electron. No direct evidence for such a contention had appeared at that time. The first experimental verification of this property of electrons came, curiously enough, as the result of an accident. In 1927 Davisson and Germer, of the Bell Telephone Laboratories in New York City, were engaged in studying the manner in which electrons were reflected from metal surfaces. A beam of electrons of a given velocity was directed against the face of a piece of nickel in a vacuum and the proportion of electrons reflected at different angles was studied. The electrons were found to be reflected much as might be expected—a large percentage being reflected like perfectly elastic balls (in the manner of rays of light from a mirror) and the number decreasing continuously for angles on either side of the maximum—in other words a fuzzy sort of mirror-like reflection. In preparing for one of the tests, while the nickel specimen was being heated to a high degree in a vacuum to drive out any gases it might contain, the glass container broke and the surface of the nickel was oxidized. After the nickel was treated to remove this oxide layer this particular sample showed a curious type of electron reflection. The reflection was a maximum at the usual angle, to be sure, but there were subsidiary maxima of reflection at other angles on both sides of the usual one. Soon it was shown that this property was occasioned by a crystallization of the nickel, and could be reproduced with any nickel crystal or with crystals of several other metals. Now such a phenomenon is known to occur when light is reflected from the finely ruled surface of a diffraction grating, and it also had been shown by Sir William Bragg to occur when X rays are reflected from the face of a crystal. In the latter case the effect is caused by interference between X ray beams reflected from successive layers of atoms in the crystal. In the cases cited the experiment establishes respectively the wave nature of light and of X rays. The similarity in the case of electron reflection from a metal crystal was striking.

Davisson and Germer, assuming therefore that their discovery was an effect caused by waves, calculated from the angles at which the secondary maxima appeared and from the spacing of the atomic planes in the crystal (known from X ray analysis) the wave length of the hypothetical waves. This wave length agreed accurately with that demanded by de Broglie's theory for electrons; i. e., Planck's constant divided by the electron momentum. Shortly after this discovery G. P. Thomson, the son of J. J. Thomson, obtained a similar effect for electrons shot through thin metallic films. Some of the electrons in the beam were deviated from their straight course, but only in certain preferential directions, so that the resulting pattern of the transmitted beam (in Thomson's experiment registered on a photographic plate) consisted of a central spot about which appeared concentric rings like halos, or in certain cases smaller spots symmetrically arranged at definite distances. Similar patterns produced by X rays had been obtained by Friedrich and Knipping in 1912 and were the first experiments to prove the wave nature of X rays. When E. Rupp in 1929 ruled fine scratches on a plane metal surface and obtained diffraction effects for electrons reflected from this artificial diffraction grating, there was no room for further doubt. Electrons may exhibit the properties of waves, and to the conundrum already propounded concerning radiation must be added a corresponding one. To the question as to when a particle is not a particle comes the answer: when it is a wave.

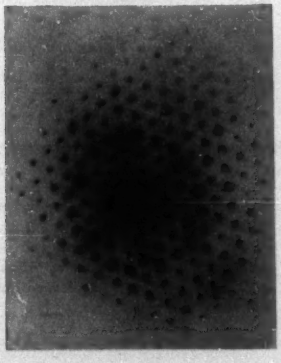


Fig. 3. Diffraction pattern of a narrow beam of electrons on passing through mica

(Kikuchi)

Present Status of Electronic Theory

There is after all a sense of relief in finding that both radiation and material particles are consistent in having this dual and mutual aspect. The puzzle raised by the quantum theory in the field of matter is, if not fully understood, at least consistent. We are forced to conclude that the wave and the particle aspects are inseparable and fundamental in nature. In fact, to a high degree of presumption, they are 2 different aspects of the same thing. The question: "Is an electron a wave or a particle?" implies a mutual exclusiveness that does not exist; the electron is both. A similar question would be "Is a musical note in the soprano register or is it pleasing?" Both pitch and quality are attributes of a musical tone. C. G. Darwin suggests that the wave aspect and the particle aspect may bear the same sort of relation to each other as color bears to wave length of light; both are different aspects of the same thing.

Bizarre as this conception of matter and of radiation appears, wave-mechanics have shown its ability to assist in solving many baffling problems regarding the behavior of electrons in addition to its success in spectroscopy. The most successful theory of electrical conduction in solids to date, by Bloch, treats an electric current as the passage of electron waves through the substance. Similarly, Fowler and Nordheim have shown that the laws of thermionic emission may be deduced on the assumption of electron waves breaking through the surface of a body. A signal success of this method was the explanation, hitherto entirely lacking, of electron currents obtained from cold metals by the agency of very intense electric fields, a phenomenon studied experimentally by Millikan and others. A novel property of electron waves that developed in this connection is that there exists a finite chance that an electron wave may escape through a surface barrier even though from the usual standpoint its energy apparently is not equal to the task. This last property of electron waves has within recent years been utilized by Gamov and others to explain radioactive disintegration. Electron waves within a nucleus may have a finite chance of breaking through the bonds that hold them—bonds which would sentence a classical electron particle to the nucleus for life.

In reviewing the status of the electron, it is clear that its properties have been extended considerably beyond those contemplated by its discoverers. It is clear also that in endowing the electron with a spin, a change of mass with velocity, and a wave aspect (although these developments have appeared to be necessary) the mental conception of an electron has lost its vividness. It is no longer, for much of the time at least, simply a tangible unit of electricity. In the light of quantum mechanical theory it shows signs of rapidly becoming a mathematical abstraction. In these respects it is following the trend of the times. Not only has a mental picture of fundamental atomic processes become difficult or even impossible, but the intrinsic precision of the process itself is called into question by the most recent theories. The principle of uncertainty or indeterminism proposed by Heisenberg frankly acknowledges this fact. This principle states that it is impossible simultaneously to determine with perfect exactness both the position and the momentum of an electron. At present the logic behind the *experimental* reasoning in support of this principle is unassailable. The electron is so small that any attempt to determine its position will change its momentum and *vice versa*. For instance, in order to "see" an electron's position accurately it would be necessary to use waves comparable in size to an electron. If longer waves were used an uncertainty in the position would appear, since the position could be determined only to the nearest wave length of the light used. This would necessitate the use of very short waves, such as γ-rays from radioactive substances. Such waves have a large quantum of energy, and upon striking an electron would impart to it a momentum according to the Compton effect; thus an uncertainty would appear in the momentum. It develops that the product of the uncertainty in position and the uncertainty in momentum is of the order of magnitude of Planck's constant h. As a result of this principle and as an inherent property of the present quantum mechanics, in fundamental processes only probabilities can be inferred, never a prediction of certainty. It is believed in some quarters that in this discovery a new fundamental law of nature has been disclosed. Whether this is the case or whether present theories are deficient in this respect is a matter for future investigation to determine. In the meantime, however, no criticism can be offered as to the utility of the new ideas and methods. As theories they are designed to explain and to correlate observed facts and to point the road for further progress. This purpose they are fulfilling admirably.

Books of Reference

Quantum Mechanics, E. U. Condon and P. M. Morse. McGraw-Hill Book Company, New York, N. Y., 1930.

Ions, Electrons, and Ionising Radiations, J. A. Crowther. Longmans Green and Co., Lond., 1929.

Introduction to Contemporary Physics, K. K. Darrow. D. Van Nostrand Co., New York, N. Y., 1926.

The New Conceptions of Matter, C. G. Darwin. Macmillan Co., New York, N. Y., 1931.

Matter, Electricity and Energy, W. Gerlach and F. J. Fuchs. D. Van Nostrand Co., New York, N. Y., 1928.

Wave Mechanics and the New Quantum Theory, A. Haas. Constable and Co., Lond., 1928.

Modern Physics, G. E. M. Jauncey. D. Van Nostrand, New York, N. Y., 1932.

The Electron, R. A. Millikan. Ginn and Co., New York, N. Y., 1924.

An Outline of Atomic Physics, Physics Staff, Univ. of Pittsburgh. Wiley and Sons, New York, N. Y., 1933.

Introduction to Modern Physics, F. K. Richtmyer. McGraw-Hill Book Company, New York, N. Y., 1928.

Atoms, Molecules and Quanta, A. E. Ruark and H. C. Urey. McGraw-Hill Book Company, New York, N. Y., 1930.

The foregoing article is the second in a special series developed under the auspices of the A.I.E.E. committee on education and scheduled for publication month-by-month during 1934. The purpose of the series is to provide, to members of the Institute who are interested in improving their time, some general guidance for contemporary reading and study in several important and rapidly advancing fields of science that are of special significance to electrical engineers. Each of the articles will deal with a specific topic, will present a digest of historical and recent developments and references to current literature, and will be prepared by one of the foremost authorities in its field.

A Symposium on

Wire Transmission of Symphonic Music and its Reproduction in Auditory Perspective

On April 27, 1933, another milestone in the development of the communication art was passed when the music of the Philadelphia Symphony Orchestra was picked up in the Academy of Science Hall in Philadelphia and reproduced in Constitution Hall in Washington, D. C., with a fidelity, depth, and spatial effect that effectively created the illusion of the orchestra's presence behind the stage curtain. To achieve this effect it was necessary that the frequency, intensity, and phase relations of the sound in each ear of each listener be reproduced so accurately as to convey not only the sounds of the various instruments, but also their spatial relations with respect to each other. In this experiment a close approximation to complete facsimile reproduction of symphonic music was obtained by using a 3-channel system, each channel involving its own microphone, amplifier control, transmission, and reproducing equipment. With such a system the auditory illusion was substantially complete and the effect upon the listening audience in the distant hall was essentially the same as though the orchestra had been behind the stage curtains there instead of miles away in another city. Details of the various principles and apparatus involved in the auditory perspective system used in the Philadelphia-Washington experiment are treated in the 6 papers of this symposium appearing on this and the following 23 pages, and on p. 214–19, inclusive, of this issue.

Auditory Perspective —Basic Requirements

The fundamental requirements involved in a system capable of picking up orchestral music, transmitting it a long distance, and reproducing it in a large hall, are discussed in this first paper of the symposium.

By
HARVEY FLETCHER
FELLOW A.I.E.E.

Bell Tel. Labs., Inc.,
New York, N. Y.

IN THIS ELECTRICAL ERA one is not surprised to hear that orchestral music can be picked up in one city, transmitted a long distance, and reproduced in another. Indeed, most people think such things are commonplace. They are heard every night on the radio. However, anyone who appreciates good music would not admit that listening even to the best radio gives the emotional thrill experienced in the concert hall. Nor is it evident that a listener in a small room ever will be able to get the same effect as that experienced in a large hall, although it must be admitted that such a question is debatable. The proper answer will involve more than a consideration of only the physical factors.

This symposium describes principles and apparatus involved in the reproduction of music in large halls, the reproduction being of a character that may give even greater emotional thrills to music lovers than those experienced from the original music. This statement is based upon the testimony of those who have heard some of the few concerts reproduced by the apparatus which will be described in the papers of this symposium.

It is well known that when an orchestra plays, vibrations which are continually changing in form are produced in the air of the concert hall where the orchestra is located. An ideal transmission and reproducing system may be considered as one that produces a similar set of vibrations in a distant concert hall in which is executed the same time-sequence of changes that takes place in the original hall. Since such changes are different at different positions in the hall, the use of such an ideal system implies that at corresponding positions in the two halls this time-sequence should be the same. Obviously, this never can be true at every position unless the halls are the same size and shape; corresponding positions would not otherwise exist. Let us consider the case where the two halls are the same size and shape and also have the same acoustical properties. Let us designate the first hall in which the music originates by O, and the second one in which the music is reproduced by R. What requirements are necessary to obtain perfect reproduction from O into R such that any listener in any part of R will receive the same sound effects as if he were in the corresponding position in O?

Suppose there were interposed between the orches-

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 31, 1933; released for publication Dec. 4, 1933. *Not published in pamphlet form.*

tra and the audience a flexible curtain of such a nature that it did not interfere with a free passage of the sound, and which at the same time had scattered uniformly over it microphones which would pick up the sound waves and produce a faithful electrical copy of them. Assume each microphone to be connected with a perfect transmission line which terminates in a projector occupying a corresponding position on a similar curtain in hall *R*. By a perfect transmission line is meant one that delivers to the projector electrical energy equal both in form and magnitude to that which it receives from the microphone. If these sound projectors faithfully transform the electrical vibrations into sound vibrations, the audience in hall *R* should obtain the same effect as those listening to the original music in hall *O*.

Theoretically, there should be an infinite number of such ideal sets of microphones and sound projectors, and each one should be infinitesimally small. Practically, however, when the audience is at a considerable distance from the orchestra, as usually is the case, only a few of these sets are needed to give good auditory perspective; that is, to give depth and a sense of extensiveness to the source of the music. The arrangement of some of these simple systems together with their effect upon listeners in various parts of the hall is described in the paper by Steinberg and Snow. (Page 12)

In any practical system it is important to know how near these ideal requirements one must approach before the listener will be aware that there has been any degradation from the ideal. For example, it is well known that whenever a sound is suddenly stopped or started, the frequency band required to transmit the change faithfully is infinitely wide. Theoretically, then, in order to fulfill these ideal requirements for transmitting such sounds, all 3 elements in the transmission system should transmit all possible frequencies without change. Practically, because of the limitations of hearing, this is not necessary. If the intensities of some of the component frequencies required to represent such a change are below the threshold of audibility it is obvious that their elimination will not be detected by the average normal ear. Consequently, for high-grade reproduction of sounds it is obvious that, except in very special cases, the range of frequencies that the system must transmit is determined by the range of hearing rather than by the kind of sound that is being reproduced.

Tests have indicated that, for those having normal hearing, pure tones ranging in frequency from 20 to 20,000 cycles per second can be heard. In order to sense the sounds at either of these extreme limits, they must have very high intensity. In music these frequencies usually are at such low intensities that the elimination of frequencies below 40 cps and those above 15,000 cps produces no detectable difference in the reproduction of symphonic music. These same tests also indicated that the further elimination of frequencies beyond either of these limits did begin to produce noticeable effects, particularly on a certain class of sounds produced in the orchestra. For example, the elimination of all frequencies above 13,000 cps produced a detectable change in the reproduced sound of the snare drum, cymbals, and castanets. Also, the elimination of frequencies below 40 cps produced detectable differences in reproduced music of the base viol, the bass tuba, and particularly of the organ.

Within this range of frequencies the system (the combination of the microphone, transmission line, and loud speaker) should reproduce the various frequencies with the same efficiency. Such a general statement sounds correct, but a careful analysis of it would reveal that when any one tried to build such a system or tried to meet such a requirement he would have great difficulty in understanding what it meant.

For example, for reproducing all the frequencies within this band, a certain system may be said to have a uniform efficiency when it operates between two rooms under the condition that the pressure variation at a certain distance away from the sound projector is the same as the pressure variation at a certain position in front of the microphone. It is obvious, however, that in other positions in the 2 rooms this relation would not in general hold. Also, if the system were transferred into another pair of rooms the situation would be entirely changed. These difficulties and the way they were met are discussed in the papers of this symposium that deal with loud speakers and microphones (p. 17) and with methods of applying the reproducing system to the concert hall (p. 216). It will be obvious from these papers that the criterion for determining the ideal frequency characteristics to be given to the system is arbitrary within certain limits. However, solving the problem according to criteria adopted produced a system that gave very satisfactory results.

Besides the requirement on frequency response just discussed, the system also must be capable of handling sound powers that vary through a very wide range. If this discussion were limited to the type of symphonic music that now is produced by the large orchestras, this range would be about 10,000,000 to 1, or 70 decibels. To reproduce such music then, the system should be capable of handling the smallest amount of power without introducing extraneous noises approaching it in intensity, and also reproduce the most intense sounds without overloading any part of the transmission system. However, this range is determined by the capacities of the musical instruments now available and the man power that conveniently can be grouped together under one conductor. As soon as a system was built that was capable of handling a much wider range, the musicians immediately took advantage of it to produce certain effects that they previously had tried to obtain with the orchestra alone, but without success because of the limited power of the instruments themselves. For these reasons it seems clear that the desirable requirements for intensity range, as well as those for frequency range, are determined largely by the ear rather than by the physical characteristic of any sound. An ideal transmission should, without introducing an extraneous audible sound, be capable of reproducing a sound as faintly as the ear can hear and as loudly as the ear can tolerate. Such

a range has been determined with the average normal ear when using pure tones. The results of recent tests are shown in Fig. 1.

The ordinates are given in decibels above the reference intensity which is 10^{-16} watts per square centimeter. The values are for field intensities existing in an air space free from reflecting walls. The most intense peaks in music come in the range between 200 and 1000 cps. Taking an average for this range it may be seen that there is approximately a 100-db range in intensity for the music, provided about 10 db is allowed for the masking of sound in the concert hall even when the audience is quietest.

The music from the largest orchestra utilizes only

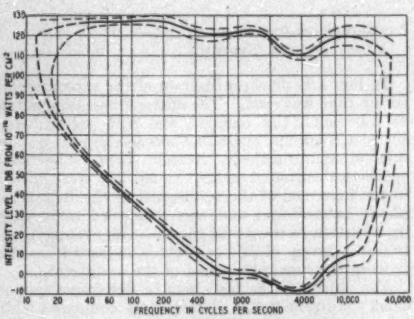


Fig. 1. Limits of audible sound as determined by recent tests

70 db of this range when it plays in a concert hall of usual size. To utilize the full capabilities of the hearing range the ideal transmission system should add about 10 db on the *pp* side and 20 db on the *ff* side of the range. The capacity of the sound projectors necessary to reach the maximum allowable sound that the ear can tolerate varies with the size of the room. A good estimate can be obtained by the following consideration.

If T is the time of reverberation of the hall in seconds, E the power of the sound source in watts, I the maximum energy density per cubic centimeter in joules, and V the volume of the hall in cubic centimeters, then it is well known teat

$$I = \frac{1}{6 \log_e 10} \cdot \frac{ET}{V} \qquad (1)$$

Measurements have shown that when the sound intensity in a free field reaches about 10^{-4} watts per square centimeter, the average person begins to *feel* the sound. This maximum value is approximately the same for all frequencies in the important audible range. Any higher intensities, and for some persons somewhat lower intensities, become painful and may injure the hearing mechanism. This intensity corresponds to an energy density I of 3×10^{-9} joules. Using this figure as the upper limit to be tolerated by the human ear, then, the maximum power of the sound source must be given by

$$E = 4.1 \times 10^{-4} \frac{V}{T} \qquad (2)$$

For halls like the Academy of Music in Philadelphia and Carnegie Hall in New York City, in which the volume V is approximately 2×10^{10} cubic centimeters and the reverberation time about 2 sec, E, the power of the sound source, is approximately 400 watts. For other halls it may be seen that the power required for this source is proportional to the volume of the hall and inversely proportional to the reverberation time. A person would experience the sense of *feeling* when closer than about 10 meters to such a source of 400 watts power, even in free open space. Hence it would be unwise to have seats closer than 10 or 15 meters from the stage when such powers are to be used.

These, then, are the general fundamental requirements for an ideal transmission system. How near they can be realized with apparatus that we now know how to build will be discussed in the papers included in this symposium.

A system approximately fulfilling these requirements was constructed and used to reproduce the music played by the Philadelphia Orchestra. The first public demonstration was given in Constitution Hall, Washington, D. C., on the evening of April 27, 1933, under the auspices of the National Academy of Sciences. At that time, Dr. Stokowski, Director of the Philadelphia Orchestra, manipulated the electric controls from a box in the rear of Constitution Hall while the orchestra, led by Associate Conductor Smallens, played in the Academy of Music in Philadelphia.

Three microphones of the type described in the paper by Wente and Thuras (p. 17) were placed before the orchestra in Philadelphia, one on each side and one in the center at about 20 ft in front of and 10 ft above the first row of instruments in the orchestra. The electrical vibrations generated in each of these microphones were amplified by voltage amplifiers and then fed into a transmission line which was extended to Washington by means of telephone cable. The construction of these lines, the equipment used with them, and their electrical properties, are described in the paper by Affel, Chesnut, and Mills (p. 28). In Constitution Hall at Washington, D. C., these transmission lines were connected to power amplifiers. The type of power amplifiers and voltage amplifiers used are described in the paper by Scriven (p. 25). The output of these amplifiers fed 3 sets of loud speakers like those described in the paper by Wente and Thuras. They were placed on the stage in Constitution Hall in positions corresponding to the microphones in the Academy of Music, Philadelphia.

Judging from the expression of those who heard this concert, the development of this system has opened many new possibilities for the reproduction and transmission of music that will create even a greater emotional appeal than that obtained when listening to the music coming directly from the orchestra through the air.

Auditory Perspective —Physical Factors

In considering the physical factors affecting it, auditory perspective is defined in this paper as being reproduction which preserves the spatial relationships of the original sounds. Ideally, this would require an infinite number of separate microphone-to-speaker channels; practically, it is shown that good auditory perspective can be obtained with only 2 or 3 channels. This is the second paper in the symposium.

By
J. C. STEINBERG
MEMBER ACOUS. SOC. OF AMERICA

W. B. SNOW
ASSOCIATE A.I.E.E.

Bell Tel. Labs., Inc.,
New York, N. Y.

ABILITY to localize the direction, and to form some judgment of the distance from a sound source under ordinary conditions of listening, are matters of common experience. Because of this faculty an audience, when listening directly to an orchestral production, senses the spatial relations of the instruments of the orchestra. This spatial character of the sounds gives to the music a sense of depth and of extensiveness, and for perfect reproduction should be preserved. In other words, the sounds should be reproduced in true *auditory perspective*.

In the ordinary methods of reproduction, where only a single loud speaking system is used, the spatial character of the original sound is imperfectly preserved. Some of the depth properties of the original sound may be conveyed by such a system,[1] but the directional properties are lost because the audience tends to localize the sound as coming from the direction of a single source, the loud speaker. Ideally, there are 2 ways of reproducing sounds in true auditory perspective. One is binaural reproduction which aims to reproduce in a distant listener's ears, by means of head receivers, exact copies of the sound vibrations that would exist in his ears if he were listening directly. The other method, which was described in the first paper of this series, uses loud speakers and aims to reproduce in a distant hall an exact copy of the pattern of sound vibration that exists in the original hall. In the limit, an infinite number of microphones and loud speakers of infinitesimal dimensions would be needed.

Far less ideal arrangements, consisting of as few as 2 microphone-loudspeaker sets, have been found to give good auditory perspective. Hence, it is not necessary to reproduce in the distant hall an exact copy of the vibrations existing in the original hall. What physical properties of the waves must be preserved then, and how are these properties preserved by various arrangements of 2- and 3-channel loudspeaker reproducing systems? To answer these questions, some very simple localization tests have been made with such systems. Perhaps attention can be focused more easily on their important properties by considering briefly the results of these tests.

Localization Afforded by Multichannel Systems

In Fig. 1 is shown a diagram of the experimental set-up that was used. The microphones, designated as *LM* (left), *CM* (center), and *RM* (right), were set on a "pick-up" stage that was marked out on the floor of an acoustically treated room. The loud speakers, designated as *LS*, *CS*, and *RS*, were placed in the front end of the auditorium at the Bell Telephone Laboratories and were concealed from view by a curtain of theatrical gauze. The average position of a group of 12 observers is indicated by the cross in the rear center part of the auditorium.

The object of the tests was to determine how a caller's position on the pick-up stage compared with his apparent position as judged by the group of observers in the auditorium listening to the reproduced speech. Words were uttered from some 15 positions on the pick-up stage in random order. The 9 positions shown in Fig. 1 were always included in the 15, the remaining positions being introduced to minimize memory effects. The reproducing system was switched off while the caller moved from one position to the other.

In the first series of tests, the majority of the observers had no previous experience with the set-up. They simply were given a sheet of coördinate paper with a single line ruled on it to indicate the line of the gauze curtain and asked to locate the apparent position of the caller with respect to this line. Following these tests, the observers were permitted to listen to speech from various announced positions on the pick-up stage. This gave them some notion of the approximate outline of what might be called the "virtual" stage. These tests then were repeated. As there was no significant difference in results, the data from both tests have been averaged and are shown in Fig. 1.

The small diagram at the top of Fig. 1 shows the caller's positions with respect to the microphone positions on the pick-up stage. The corresponding average apparent positions when reproduced are shown with respect to the curtain line and the loudspeaker positions. The type of reproduction is indicated symbolically to the right of the apparent position diagrams.

With 3-channel reproduction there is a reasonably

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 31, 1933; released for publication Dec. 4, 1933. *Not published in pamphlet form.*

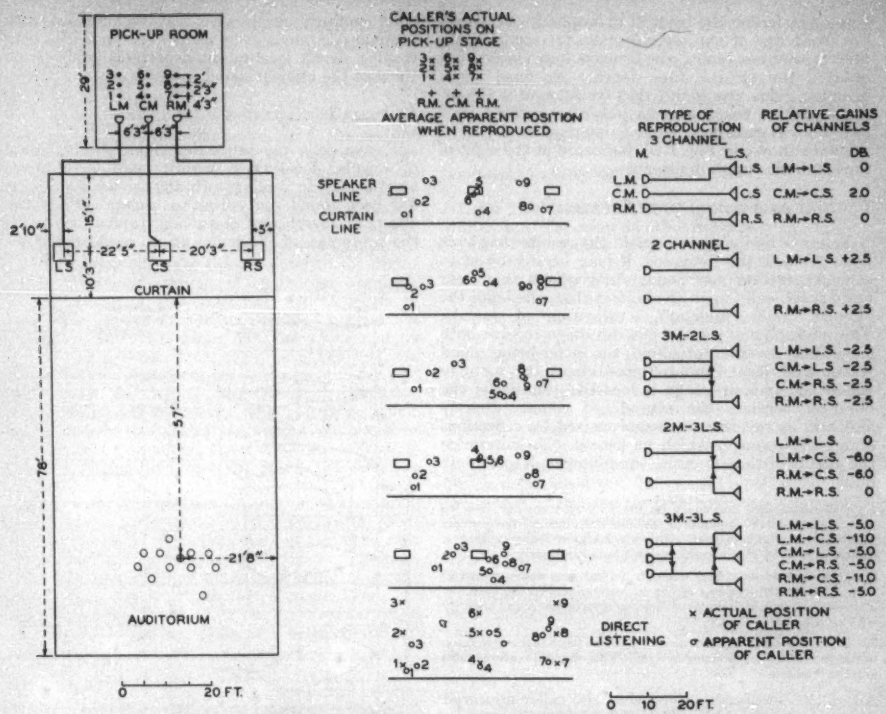


Fig. 1. Diagram of arrangement (left) for sound localization tests and (right) the results obtained

good correspondence between the caller's actual position on the pick-up stage and his apparent position on the virtual stage. Apparent positions to the right or left correspond with actual positions to the right or left, and apparent front and rear positions correspond with actual front and rear positions. Thus the system afforded lateral or "angular" localization as well as fore and aft or "depth" localization. For comparison, there is shown in the last diagram the localization afforded by direct listening. The crosses indicate a caller's position in back of the gauze curtain and the circles indicate his apparent position as judged by the observers listening to his speech directly. In both cases, as the caller moved back in a straight line on the left or right side of the stage, he appeared to follow a curved path pulling in toward the rear center; e. g., compare the caller positions 1, 2, 3, with the apparent positions 1, 2, 3. This distortion was somewhat greater for 3-channel reproduction than for direct listening.

The results obtained with the 2-channel system show 2 marked differences from those obtained with 3-channel reproduction. Positions on the center line of the pick-up stage (i. e., 4, 5, 6) all appear in the rear center of the virtual stage, and the virtual stage depth for all positions is reduced. The virtual stage width, however, is somewhat greater than that obtained with 3-channel reproduction.

Bridging a third microphone across the 2-channel system had the effect of pulling the center line positions 4, 5, 6, forward, but the virtual stage depth remained substantially that afforded by 2-channel reproduction, while the virtual stage width was decreased somewhat. In this and the other bridged arrangements the bridging circuits employed amplifiers, as represented by the arrows in Fig. 1, in such a way that there was a path for speech current only in the indicated direction.

Bridging a third loud speaker across the 2-channel system had the effect of increasing the virtual stage depth and decreasing the virtual stage width, but positions on the center line of the pick-up stage appeared in the rear center of the virtual stage as in 2-channel reproduction.

Bridging both a third microphone and a third loud speaker across the 2-channel system had the effect of reducing greatly the virtual stage width. The width could be restored by reducing the bridging

gains, but fading the bridged microphone out caused the front line of the virtual stage to recede at the center, whereas fading the bridged loud speaker out reduced the virtual stage depth. No fixed set of bridging gains was found that would enable the arrangement to create the virtual stage created by 3 independent channels. The gains used in obtaining the data shown in Fig. 1 are indicated at the right of the symbolic circuit diagrams.

Factors Affecting Depth Localization

Before attempting to explain the results that have been given in the foregoing, it may be of interest to consider certain additional observations that bear more specifically upon the factors that enter into the "depth" and "angular" localization of sounds. The microphones on the pick-up stage receive both direct and reverberant sound, the latter being sound waves that have been reflected about the room in which the pick-up stage is located. Similarly, the observer receives the reproduced sounds directly and also as reverberant sound caused by reflections about the room in which he listens. To determine the effects of these factors, the following 3 tests were made:

1. Caller remained stationary on the pick-up stage and close to microphone, but the loudness of the sound received by the observer was reduced by gain control. This was loudness change without a change in ratio of direct to reverberant sound intensity.

2. Caller moved back from microphone, but gain was increased to keep constant the loudness of the sound received by the observer. This was a change in the ratio of direct to reverberant sound intensity without a loudness change.

3. Caller moved back from microphone, but no changes were made in the gain of the reproducing system. This changed both the ratio and the loudness.

All of the observers agreed that the caller appeared definitely to recede in all 3 cases. That is, either a reduction in loudness or a decrease in ratio of direct to reverberant sound intensity, or both, caused the sound to appear to move away from the observer. Position tests using variable reverberation with a given pick-up stage outline showed that increasing the reverberation moved the front line of the virtual stage toward the rear, but had slight effect upon the rear line. When the microphones were placed outdoors to eliminate reverberation, reducing the loudness either by changing circuit gains or by increasing the distance between caller and microphone moved the whole virtual stage farther away. It is because of these effects that all center line positions on the pick-up stage appeared at the rear of the virtual stage for 2-channel reproduction.

It has not been found possible to put these relationships on a quantitative basis. Probably a given loudness change, or a given change in ratio of direct to reverberant sound intensity, causes different sensations of depth depending upon the character of the reproduced sound and upon the observer's familiarity with the acoustic conditions surrounding the reproduction. Since the depth localization is inaccurate even when listening directly, it is difficult to obtain sufficiently accurate data to be of much use in a quantitative way. Because of this inaccuracy, good auditory perspective may be obtained with reproduced sounds even though the properties controlling depth localization depart materially from those of the original sound.

Angular Localization

Fortunately, the properties entering into lateral or angular localization permit more quantitative treatment. In dealing with angular localization, it has been found convenient to neglect entirely the effects of reverberant sound and to deal only with the properties of the sound waves reaching the observer's ears without reflections. The reflected waves or reverberant sounds do appear to have a small effect on angular localization, but it has not been found possible to deal with such sound in a quantitative way. One of the difficulties is that, because of differences in the build-up times of the direct and reflected sound waves, the amount of direct sound relative to reverberant sound reaching the observer's ears for impulsive sounds such as speech and music is much greater than would be expected from steady state methods of dealing with reverberant sound.

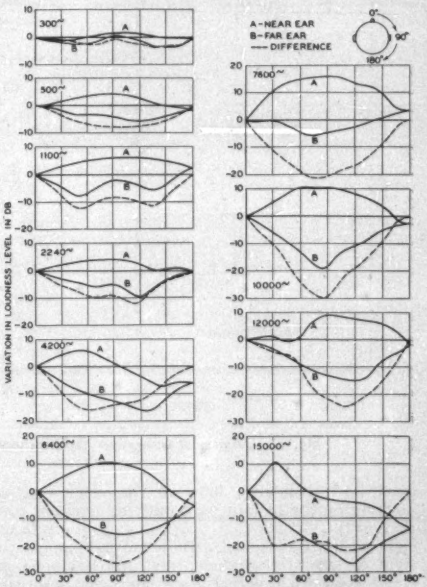


Fig. 2. Variation in loudness level as a sound source is rotated in a horizontal plane around the head

For the case of a plane progressive wave from a single sound source, and where the observer's head

is held in a fixed position, there are apparently only 3 factors that can assist in angular localization: namely, phase difference, loudness difference, and quality difference between the sounds received by the 2 ears.

In applying these factors to the localization of sounds from more than one source, as in the present case, the effects of phase differences have been neglected. It is difficult to see how phase differences in this case can assist in localization in the ordinary way. The 2 remaining factors, loudness and quality differences, both arise from the directivity of hearing. This directivity probably is due in part to the shadow and diffraction effects of the head and to the differences in the angle subtended by the ear openings. Measurements of the directivity with a source of pure tone located in various positions around the head in a horizontal plane have been reported by Sivian and White.[2] From these measurements, the loudness level differences between near and far ears have been determined for various frequencies. These differences are shown in Fig. 2 from which, using the pure tone data given, similar loudness level differences for complex tones may be calculated. Such calculated differences for speech are shown in Fig. 3.

As may be inferred from the varying shapes of the curves of Fig. 2, the directive effects of hearing introduce a frequency distortion more or less characteristic of the direction from which the sound comes. Thus the character or quality of complex sounds varies with the angle of the source. There are quality differences at each ear for various angles of source, and quality differences between the two ears for a given angle of source. In Fig. 4 is shown the frequency distortion at the right ear when a source of sound is moved from a position on the right to one on the left of an observer. It is a graph of the "difference" values of Fig. 2 for an angle of 90 deg. Frequencies above 4,000 cycles per second are reduced by as much as 15 to 30 decibels. This amount of distortion is sufficient to affect materially the quality of speech, particularly as regards the loudness of the sibilant sounds.

Reference to the difference curve of Fig. 3 shows that if, for example, a source of speech is 20 deg to the right of the median plane the speech heard by the right ear is 3 db louder than that heard by the left ear. A similar difference exists when the angle is 167 deg. Presumably, when the right ear hears speech 3 db louder than the left, the observer localizes the sound as coming from a position 20 deg or 167 deg to the right, depending upon the quality of the speech. If this be assumed to be true, even though the difference is caused by the combination of sounds of similar quality from several sources, it should be possible to calculate the apparent angle.

Loudness Theory of Localization

Upon this assumption the apparent angle of the source as a function of the difference in decibels between the speech levels emitted by the loud speakers of the 2- and 3-channel systems has been calculated. Each loud speaker contributes an amount of direct sound loudness to each ear, depending upon its distance from, and its angular position with respect to, the observer. These contributions were combined on a power basis to give a resultant loudness of direct sound at each ear, from which the difference in loudness between the 2 ears was determined. The calculated results for the 2- and 3-channel systems are shown by the solid lines in Fig. 5. The y axis shows the apparent angle, positive angle being measured in a clockwise direction. The x axis shows the difference in decibels between the speech levels from the right and left loud speakers. The points are observed values taken from Fig. 1. The observed apparent angles were obtained directly from the average observer's location and the average apparent positions shown in Fig. 1. The speech levels from each of the loud speakers were calculated for each position on the pick-up stage. This was done by assuming that the waves arriving at the microphone had relative levels

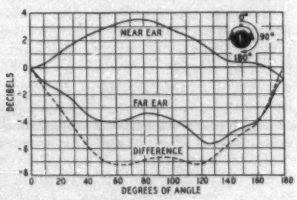


Fig. 3. Variation in loudness as a speech source is rotated in a horizontal plane around the head

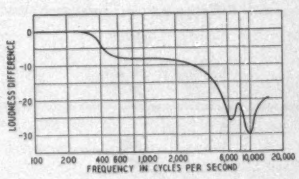


Fig. 4. Loudness difference produced in the right ear when a source of pure tone is moved from a position on the right to the left of an observer

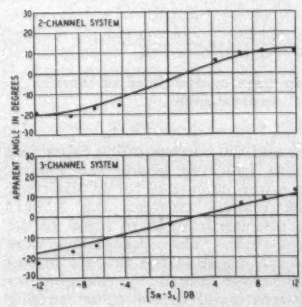


Fig. 5. Calculated and observed apparent angles for 2- and 3-channel reproduction

inversely proportional to the squares of the distances traversed. By correcting for the angle of incidence and for the known relative gains of the systems, the speech levels from the loud speakers were obtained.

A comparison of the observed and calculated results seems to indicate that the loudness difference at the 2 ears accounts for the greater part of the apparent angle of the reproduced sounds. If this is true, the angular location of each position on the virtual stage results from a particular loudness difference at the 2 ears produced by the speech coming from the loud speakers. When 3 channels are used a definite set of loud speaker speech levels exists for each position on the pick-up stage. To create these same sets of loud speaker speech levels with the bridging arrangement of 3-microphones 3-loud speakers already discussed, it would be necessary to change the bridging gains for each position on the pick-up stage. Hence it could not be expected that the arrangement as used (i. e., with fixed gains) would create a virtual stage identical with that created by 3-channel reproduction. However, with proper technique, bridging arrangements on a given number of channels can be made to give better reproduction than would be obtained with the channels alone.

Experimental Verification of Theory

Considerations of loudness difference indicate that all caller positions on the pick-up stage giving the same relative loud speaker outputs should be localized at the same virtual angle. The solid lines of Fig. 6 show a stage layout used to test this hypothesis with the 2-channel system. All points on each line have a constant ratio of distances to the microphones. The resulting direct sound differences in pressure ex-

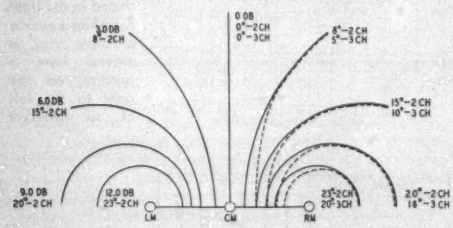


Fig. 6. Pick-up stage contour lines of constant apparent angle

pressed in decibels and the corresponding calculated apparent angles are indicated beside the curves. The apparent angles were calculated for an observing position on a line midway between the 2 loud speakers but at a distance from them equal to the separation between them. The microphones were turned face up at the height of the talker's lips to eliminate quality changes caused by changing incidence angle. It was found that a caller walking along one of these lines maintained a fairly constant virtual angle. For caller positions far from the microphones the observed angles were somewhat greater than those computed. For highly reverberant conditions, the tendency was toward greater calculated than observed angles. Reverberation also decreased the accuracy of localization.

A change of relative channel gain caused a change in virtual angle as would be expected from loudness difference considerations. For instance, if the caller actually walked the left 3-db line, he seemed to be on the 6-db line when the left channel gain was raised 3 db. Many of the effects of moving about the pick-up stage could be duplicated by volume control manipulation as the caller walked forward and backward on the center path. With a bridged center microphone substituted for the 2 side microphones similar effects were possible and, in addition, the caller by speaking close to the microphone could be brought to the front of the virtual stage.

For observing positions near the center of the auditorium the observed angles agreed reasonably well with calculations based only upon loudness differences. As the observer moved to one side, however, the virtual source shifted more rapidly toward the nearer loud speaker than was predicted by the computations. This was true of reproduction in the auditorium, both empty and with damping simulating an audience, and outdoors on the roof. Computations and experiment also show a change in apparent angle as the observer moves from front to rear, but its magnitude is smaller than the error of an individual localization observation. Consequently, observers in different parts of the auditorium localize given points on the pick-up stage at different virtual angles.

Because the levels at the 3 microphones are not independent, and because the desired contours depend upon the effects at the ears, a 3-channel stage is not as simple to lay out as a 2-channel stage. For a given observing position, however, a set of contour lines can be calculated. The dashed lines at the right of Fig. 6 show 4 contours thus calculated for the circuit condition of Fig. 1 and the observing position previously mentioned. The addition of the center channel reduces the virtual angle for any given position on the pick-up stage by reducing the resultant loudness difference at the ears. Although the 3-channel contours approach the 2-channel contours in shape at the back of the stage, a given contour results in a greater virtual angle for 2- than for 3-channel reproduction.

Similar effects were obtained experimentally. As in 2-channel reproduction, movements of the caller could be simulated by manipulation of the channel gains. From an observing standpoint the 3-channel system was found to have an important advantage over the 2-channel system in that the shift of the virtual position for side observing positions was smaller.

Effects of Quality

If the quality from the various loud speakers differs, the quality of sound is important to localiza-

tion. When the 2-channel microphones were so arranged that one picked up direct sound and reverberation while the other picked up mostly reverberation, the virtual source was localized exactly in the "direct" loud speaker until the power from the "reverberant" loud speaker was from 8 to 10 db greater. In general, localization tends toward the channel giving most natural or "close-up" reproduction, and this effect can be used to aid the loudness differences in producing angular localization.

Principal Conclusions

The principal conclusions that have been drawn from these investigations may be summarized as follows:

1. Of the factors influencing angular localization, loudness difference of direct sound seems to play the most important part; for certain observing positions the effects can be predicted reasonably well from computations. When large quality differences exist between the loudspeaker outputs, the localization tends toward the more natural source. Reverberation appears to be of minor importance unless excessive.

2. Depth localization was found to vary with changes in loudness, the ratio of direct to reverberant sound, or both, and in a manner not found subject to computational treatment. The actual ratio of direct to reverberant sound, and the change in the ratio, both appeared to play a part in an observer's judgment of stage depth.

3. Observers in various parts of the auditorium localize a given source at different virtual positions, as is predicted by loudness computations. The virtual source shifts to the side of the stage as the observer moves toward the side of the auditorium. Although quantitative data have not been obtained, qualitative data on these effects indicate that the observed shift is considerably greater than that computed. Moving backward and forward in the auditorium appears to have only a small effect on the virtual position.

4. Because of these physical factors controlling auditory perspective, point-for-point correlation between pick-up stage and virtual stage positions is not obtained for 2- and 3-channel systems. However, with stage shapes based upon the ideas of Fig. 7, and with suitable use of quality and reverberation, good auditory perspective can be produced. Manipulation of circuit conditions probably can be used advantageously to heighten the illusions or to produce novel effects.

5. The 3-channel system proved definitely superior to the 2-channel by eliminating the recession of the center-stage positions and in reducing the differences in localization for various observing positions. For musical reproduction, the center channel can be used for independent control of soloist renditions. Although the bridged systems did not duplicate the performance of the physical third channel, it is believed that with suitably developed technique their use will improve 2-channel reproduction in many cases.

6. The application of acoustic perspective to orchestral reproduction in large auditoriums gives more satisfactory performance than probably would be suggested by the foregoing discussions. The instruments near the front are localized by every one near their correct positions. In the ordinary orchestral arrangement, the rear instruments will be displaced in the reproduction depending upon the listener's position, but the important aspect is that every auditor hears differing sounds from differing places on the stage and is not particularly critical of the exact apparent positions of the sounds so long as he receives a spatial impression. Consequently 2-channel reproduction of orchestral music gives good satisfaction, and the difference between it and 3-channel reproduction for music probably is less than for speech reproduction or the reproduction of sounds from moving sources.

References

1. Some Physical Factors Affecting the Illusion in Sound Motion Pictures, J. P. Maxfield. *Jl.*, Acous. Soc., July 1931.

2. Minimum Audible Sound Fields, L. J. Sivian and S. D. White. *Jl.*, Acous. Soc., April 1933.

Auditory Perspective —Loud Speakers and Microphones

In ordinary radio broadcast of symphony music, the effort is to create the effect of taking the listener to the scene of the program, whereas in reproducing such music in a large hall before a large gathering the effect required is that of transporting the distant orchestra to the listeners. Lacking the visual diversion of watching the orchestra play, such an audience centers its interest more acutely in the music itself, thus requiring a high degree of perfection in the reproducing apparatus both as to quality and as to the illusion of localization of the various instruments. Principles of design of the loud speakers and microphones used in the Philadelphia-Washington experiment are treated at length in this, the third paper of this symposium.

By
E. C. WENTE
MEMBER ACOUS. SOC. OF AMERICA

A. L. THURAS
MEMBER ACOUS. SOC. OF AMERICA

Bell Tel. Labs., Inc., New York, N. Y.

As early as 1881 a large scale musical performance was reproduced by telephone instruments at the Paris Electrical Exhibition. Microphones were placed on the stage of the Grand Opera and connected by wires to head receivers at the exposition. It is interesting to note that separate channels were provided for each ear so as to give to the music perceived by the listener the "character of relief and localization." With head receivers it is necessary to generate enough sound of audible intensity to fill only a volume of space enclosed between the head receiver and the ear. As no amplifiers were available, the production of enough sound to fill a large auditorium would have been entirely outside the range of possibilities. With the advent

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 31, 1933; released for publication Dec. 5, 1933. *Not published in pamphlet form.*

1. Bell Telephone Laboratories, Inc.

of telephone amplifiers, microphone efficiency could be sacrificed to the interest of good quality where, as in the reproduction of music, this was of primary interest. When amplifiers of greater output power capacity were developed, loud speakers were introduced to convert a large part of the electrical power into sound so that it could be heard by an audience in a large auditorium. Improvements have been made in both microphones and loud speakers, resulting in very acceptable quality of reproduction of speech and music; as is found, for instance, in the better class of motion picture theaters.

In the reproduction, in a large hall, of the music of a symphony orchestra the approach to perfection that is needed to satisfy the habitual concert audience undoubtedly is closer than that demanded for any other type of musical performance. The interest of the listener here lies solely in the music. The reproduction therefore should be such as to give to a lover of symphonic music esthetic satisfaction at least as great as that which would be given by the orchestra itself playing in the same hall. This is more than a problem of instrument design, but this paper will be restricted to a discussion of the requirements that must be met by the loud speakers and microphones, and to a description of the principles of design of the instruments used in the transmission of the music of the Philadelphia Orchestra from Philadelphia to Constitution Hall in Washington. Some of the requirements are found in the results of measurements that have been made on the volume and frequency ranges of the music produced by the orchestra.

General Considerations

The acoustic powers delivered by the several instruments of a symphony orchestra, as well as by the orchestra as a whole, have been investigated by Sivian, Dunn, and White. Figure 1 was drawn on the basis of the values published by them.[1] The ordinates of the horizontal lines give the values of the peak powers within the octaves indicated by the positions of the lines. For a more exact interpretation of these values the reader is referred to the original paper, but the chart here given will serve to indicate the power that a loud speaker must be capable of delivering in the various frequency regions, if the reproduced music is to be as loud as that given by the orchestra itself. However, it was the plan in the Philadelphia-Washington experiment to reproduce the orchestra, when desired, at a level 8 or 10 db higher, so that with 3 channels each loud speaking system had to be able to deliver 2 or 3 times the powers indicated in Fig. 1. Sivian, Dunn, and White also found that for the whole frequency band the peak powers in some cases reached values as high as 65 watts. In order to go 8 db above this value, each channel would have to be capable of delivering in the neighborhood of 135 watts.

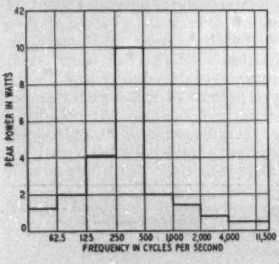


Fig. 1. Peak powers delivered by an orchestra within various frequency regions

The chart (Fig. 1) shows that the orchestra delivers sound of comparable intensity throughout practically the whole audible range. Although it is conceivable that the ear would not be capable of detecting a change in quality if some of the higher or lower frequencies were suppressed, measurements published by W. B. Snow[2] show that for any change in quality in any of the instruments to be undetectable the frequency band should extend from about 40 to about 13,000 cps. The necessary frequency ranges that must be transmitted to obviate noticeable change in quality for the different orchestral instruments are indicated in the chart of Fig. 2, which is taken from the paper by Snow.

Thus far only the sound generated by the orchestra itself has been considered. However, it is well known that the esthetic value of orchestral music in a concert hall is dependent to a very great extent upon the acoustic properties of the hall. At first thought one might be inclined to leave this out of account in considering the reproduction by a loud speaking system, as one should normally choose a hall known to have satisfactory acoustics for an actual orchestra. There would be no further problem in this if the orchestral instruments and the loud speaker radiated the sound uniformly in all directions, but some of the important instruments are quite directive; i. e., they radiate much the greater portion of their sound through a relatively small angle. As an example, a polar diagram giving the relative intensities of the sound radiated in various directions by the violin is given in Fig. 3, which is taken from a paper published by Backhaus.[3] The directional characteristics of some of the instruments is one of the chief reasons why the music from an orchestra does not sound the same in all parts of a concert hall. The music which we hear comes to us in part directly and in part indirectly; i. e., after one or more reflections from the walls. Both contribute to the esthetic value of the music. The ratio of the direct to the indirect sound, which has been designated by Hughes[4] as the *acoustic ratio*, is to a first approximation inversely proportional to the product of the reverberation time and the angle through which the sound is radiated.[5] For a steady tone by far the greater part of the intensity at a given point in a hall remote from the source is attributable to the indirect sound. However, inasmuch as many of the tones of a musical selection are of short duration, the direct sound is of great importance; it is this sound alone which enables us to localize the source. So far as this ratio is concerned, a decrease in the radiating angle of a loud speaker is equivalent to a reduction in the reverberation time of the hall. The effect on the music, however, is not entirely equivalent, for the rate of decay of sound in the room

is unaltered by a change in directivity of the source, as this depends only on the reverberation time.

As already pointed out, some of the instruments of the orchestra are quite directive and others are nondirectional. In general, it may be said that the instruments of lower register are less directive than those of higher register. To have each instrument as reproduced by the loud speaker sound just as the instrument itself would sound in the same hall, the loud speaker would have to reproduce the music from each instrument with a directivity corresponding to that of the instrument itself. This manifestly is impossible. The best that can be hoped for is a compromise. Let the loud speaking system be designed so that it is nondirective for the lower frequencies, and at the higher frequencies it will radiate the sound through a larger angle than the most directive of the instruments and through a smaller angle than the least directive. Although this compromise means that the individual instruments will not sound exactly like the originals, it carries with it one advantage: At all the seats in the hall included in the radiating angle and at a given distance from the loud speaker the music may be heard to equal advantage, whereas with the orchestra itself the most desirable seats comprise only a certain portion of the hall. The optimum radiating angle is largely a matter of judgment; if it is too small the music will lack the spatial quality experienced at indoor concerts; if it is too large there will be a loss in definition.

There is another respect in which the directivity of the source can greatly affect the tone quality. Most loud speakers radiate tones of low frequency

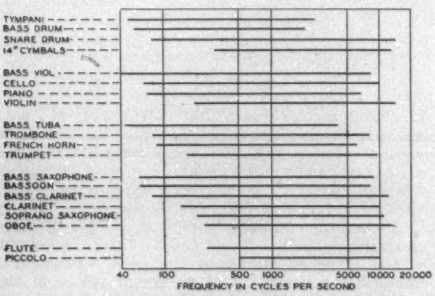


Fig. 2. Frequency transmission range required to produce no noticeable distortion for orchestral instruments

through a relatively large angle, but as the frequency is increased this angle becomes smaller and smaller. Under this condition the relation between the intensities of the high and low frequency tones as received directly will be different for almost all parts of the hall. Hence, even with equalization by electrical networks, the reproduction at best can be good only at a few places in the hall. Therefore, the sound radiated not only should be contained within a certain solid angle, but the radiation throughout this angle should be uniform at all frequencies.

The Loud Speaker

At present 2 kinds of loud speakers are in wide commercial use, the direct radiating and the horn types. Each has its merits, but the latter was used in the Philadelphia-Washington experiment because it appears to have definite advantages where such large amounts of power are to be radiated. The horn type can be given the desired directive properties more readily, and higher values of efficiency throughout a wide frequency range are more easily realized. In consideration of the large power requirements, high efficiency is of special importance because it will keep to the lowest possible value the power capacity requirements of the amplifiers and because, with the heating proportional to one minus the efficiency, the danger of burning out the receiving units is reduced.

For efficiently radiating frequencies as low as 40 cps, a horn of large dimensions is required. In order that the apparatus may not become too unwieldy the folded type of horn is preferable, but a large folded horn transmits high frequency

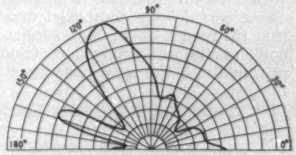


Fig. 3. Variation of intensity with direction of the sound radiated by a violin (660 cps)

tones very inefficiently. As actually used, therefore, the loud speaker was constructed in 2 units: one for the lower and the other for the higher frequencies, an electrical network being used to divide the current into 2 frequency bands, the point of division being about 300 cps.

The Low Frequency Horn

When moderate amounts of power are transmitted through a horn the sound waves will suffer very little distortion, but when the power per unit area becomes large, second-order effects, usually neglected in considering waves of small amplitude, must be taken into account. The transmission of waves of large amplitude through an exponential horn has been investigated theoretically by M. Y. Rocard.[6] His investigation shows that if W watts are transmitted through the throat of an exponential horn a second harmonic of intensity RW will be generated, where R is given by the relation

$$R = \frac{(\gamma + 1)^2 f^2 \times 10^7 W}{2\rho c^3 f_0^2 A}, \qquad (1)$$

in which f is the frequency of the fundamental, f_0

the cut-off frequency of the horn, c the velocity of sound, ρ the density of air, and A the area of the throat of the horn, all expressed in cgs units. It may be noted that the intensity of the harmonic increases with the ratio of the frequency to the cut-off frequency of the horn; this is another argument against attempting to cover too wide a range of frequencies with a single horn. In Fig. 1 it is shown that in the region of 200 cps the orchestra gives peak powers of about 10 watts. If, therefore, 30 watts be set as the limit of power that the horn is to deliver at 200 cps, 32 cps as the cut-off frequency of the horn, and 30 db below the fundamental be assumed as the limit of tolerance of a second harmonic, from eq 1 a throat diameter of about 8 in. is determined.

If the radiation resistance at the throat of a horn is not to vary appreciably with frequency, the mouth opening must be a substantial fraction of a wave length. This condition calls for an unusually large horn if frequencies down to 40 cps and below are to be transmitted. However, the effect of variations in radiation resistance on sound output can be kept down to a relatively small value if the receiving unit is properly designed. This will be explained in the next section. The low frequency horn used in these reproductions has a mouth opening of about 25 sq ft. As computed from well-known formulas [7] for the exponential horn the impedance of this horn with a throat diameter of 8 in. is shown in Fig. 4. These curves were computed under the assumption that the mouth of the horn is surrounded by a plane baffle of infinite extent, a condition closely approximated if the horn rests on a stage floor.

Low Frequency Receiving Unit

When a moving coil receiving unit, coupled to a horn, is connected to an amplifier having an output resistance equal to $n-1$ times the damped resistance R of the driving coil, it can easily be shown that the sound power output is

$$P = \frac{\left(\frac{EBLT}{nR}\right)^2 r \times 10^{-9}}{\left[T^2 r + \frac{B^2L^2 \times 10^{-9}}{nR}\right]^2 + [x_d + T^2 x]^2} \text{ watts} \tag{2}$$

where E is the open circuit voltage of the amplifier, L the length of wire in the receiver coil, T the ratio of the area of the diaphragm to the throat area of the horn, $r + jx$ the throat impedance of the horn, and x_d the mechanical reactance of the diaphragm and coil, the mechanical resistance of which is assumed to be negligibly small. From Fig. 4 it may be seen that the mean value of x increases as the frequency decreases to a value below 40 cps, and that x is smaller than r except at the very lowest frequencies. If, therefore, the stiffness of the diaphragm be adjusted so that x_d is equal to T^2 times the mean value of x at 40 cps, the second term in the denominator may be neglected without much error because it will have but little effect upon the sound output except at the higher frequencies, where the mass reactance of the coil and diaphragm may have to be taken into account.

If minimum variations in sound output are desired for variations in r,

$$\frac{B^2L^2 10^{-9}}{nRT^2} = r_0 \tag{3}$$

where r_0 is equal to the geometric mean value of r, which is approximately equal to $A\rho c$.

If α is the ratio of the resistance at any frequency to the mean value, and if the second term in the denominator is neglected, eq 2 becomes

$$P = \frac{E^2}{nR}\frac{\alpha}{(1+\alpha)^2} \tag{4}$$

In Fig. 4 it is shown that above 35 cps α has extreme values of 2.75 and 0.36, at which points there will

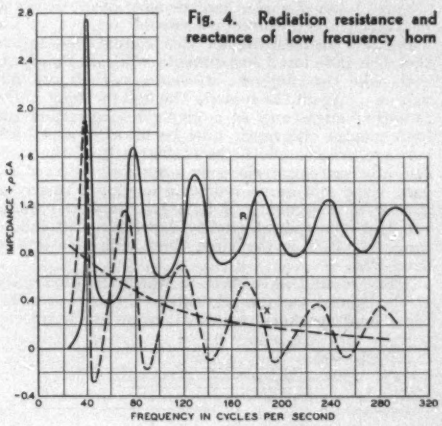


Fig. 4. Radiation resistance and reactance of low frequency horn

be minimum values in P, but these minimum values will not lie more than 1 db below the maximum values. Hence, if the receiver satisfies the condition of eq 3, the extreme variations in the sound output will not exceed 1 db, although the horn resistance varies by a factor of 7.5. Also it may be stated here that when the condition of eq 3 is satisfied the horn is terminated at the throat end by a resistance equal to the surge resistance of the horn. Thus eq 3 establishes a condition of minimum values in the transient oscillations of the horn.

The mean motional impedance of the loud speaker is $\frac{B^2L^2 \times 10^{-9}}{T^2 r_0}$ which, from eq 3, is equal to nR. The condition of eq 3 therefore specifies that the efficiency of the loud speaker shall be $\frac{n}{n+1}$. The maximum power that an amplifier can deliver without introducing harmonics exceeding a specified value is a function of the impedance into which it operates. Therefore, to obtain the maximum acoustic power for a specified harmonic content, the load impedance should have the value for which the prod-

uct of the loud speaker efficiency and the power capacity of the amplifier has a maximum value. This optimum value of load impedance for the amplifier and loud speaker used in the Philadelphia-Washington experiments was found to be about 2.25 times the output impedance of the amplifier; the corresponding value of n then is 2.6 and the required efficiency 72 per cent. For best operating condition a definite value of receiver efficiency thus is specified.

The receiver may be made to satisfy the foregoing conditions regardless of the value of T, the ratio of diaphragm area to throat area. The area of the diaphragm has, however, a definite relation to the

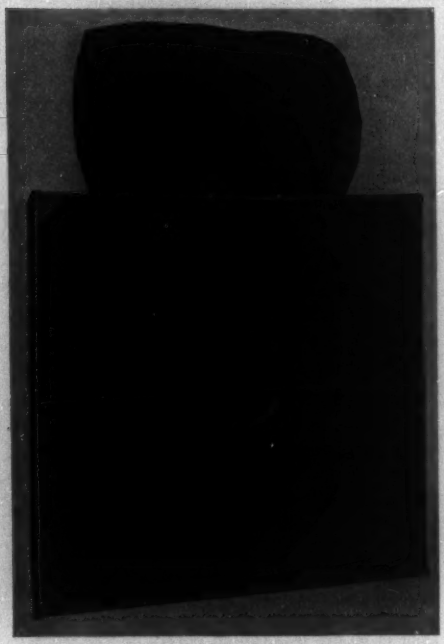


Fig. 5. Special loud speaker developed for auditory perspective experiment

maximum power that the receiver can deliver at the low frequencies. The peak power delivered by the receiver is equal to $T^2 \alpha r_s \xi^2 \omega^2 \times 10^{-7}$ peak watts where ξ is the maximum amplitude of motion of the diaphragm. Figure 1 shows that in the region lying between 40 and 60 cps, peak powers reach a value of from 1 to 2 watts. However, the low frequency tones of an orchestra are undesirably weak and may advantageously be reproduced at a relatively higher level. Therefore it was decided to construct the loud speaker to be able to deliver 25 watts in this region.

As the coil moves out of its normal position in the air gap, the force factor varies. Harmonics thus will be generated, the intensities of which increase with increasing amplitude. A limit to the maximum value of the amplitude ξ thus is set by the harmonic distortion that one is willing to tolerate. In this receiver the maximum value of ξ was taken equal to 0.060 in. Figure 4 shows that $\alpha\omega^2$ has a minimum value at about 50 cycles, where α is equal to about 0.4. These values give a ratio of 4.5 for T.

Inasmuch as $R = \frac{\sigma L^2}{v}$, where σ is the resistivity of the wire used for the coil and v the volume of the coil, from eq 3 is obtained

$$B^2 v = n\sigma T^2 r_0 10^9 \tag{5}$$

The first member gives the total magnetic energy that must be set up in the region occupied by the driving coil. This value is fixed by the fact that all factors in the second member are specified. The same performance is obtained with a small coil and high flux density as with a large coil and low flux density, provided $B^2 v$ is held fixed, but the coil in any case should not be made so small that it will be incapable of radiating the heat generated within it without danger of overheating, nor so large that the mass reactance of the coil will reduce the efficiency at the higher frequencies.

This receiver unit, when constructed according to the above principles and when connected to an amplifier and a horn in the specified manner, should be capable of delivering power 3 or 4 times that delivered by the orchestra in the frequency region lying between 35 and 400 cps, with an efficiency of about 70 per cent, and with a variation in sound output for a given input power to the amplifier of not more than 1 db throughout this range.

The High Frequency Horn

It is well known that a tapered horn of the ordinary type has a directivity which varies with frequency. Sound of low frequency is projected through a relatively large angle. As the frequency is increased this angle decreases progressively until, at frequencies for which the wave length is small compared with the diameter of the mouth opening, the sound beam is confined to a very narrow angle about the axis of the horn.

If we had a spherical source of sound (i. e., a source consisting of a sphere, the surface of which has a radial vibratory motion equal in phase and amplitude at every point of the surface), sound would be radiated uniformly outward in all directions; or, if we had only a portion of a spherical surface over which the motion is radial and uniform, uniform sound radiation still would prevail throughout the solid angle subtended at the center of curvature by this portion of the sphere, provided its dimensions were large compared with the wave length. Throughout this region the sound would appear to originate at the center of curvature. Hence, for the ideal distribution of a spherical source within

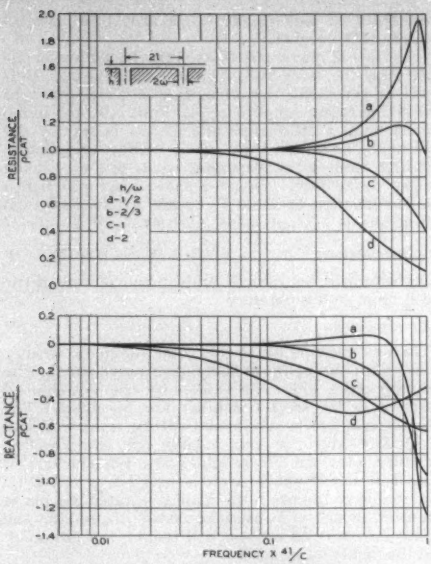


Fig. 6. Load impedance of speaker diaphragm

a region to be defined by a certain solid angle, it is necessary and sufficient that the radial motion be the same in amplitude and phase over the part of a spherical surface intercepted by the angle and having its center of curvature at the vertex and located at a sufficient distance from the vertex to make its dimensions large compared with the wave length. If, further, these conditions are satisfied for this surface at all frequencies, all points lying within the solid angle will receive sound of the same wave form. A horn was designed to meet these requirements for the high frequency band.

The horn, shown in the upper part of Fig. 5, comprises several separate channels, each of which has substantially an exponential taper. Toward the narrow ends these channels are brought together with their axes parallel, and are terminated into a single tapered tube which at its other end connects to the receiver unit. Sound from the latter is transmitted along the single tube as a plane wave and is divided equally among the several channels. If the channels have the same taper, the speed of propagation of sound in them is the same. The large ends are so proportioned and placed that the particle motion of the air will be in phase and equal over the mouth of the horn. This design gives a true spherical wave front at the mouth of the horn at all frequencies for which the transverse dimensions of the mouth opening are a large fraction of a wave length.

As the frequency is increased, the ratio of wave length to transverse width of the channels becomes less, and the sound will be confined more and more to the immediate neighborhood of the axis of each channel. The sound then will not be distributed uniformly over the mouth opening of the

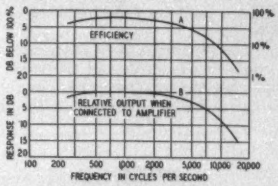


Fig. 7. Relative computed sound output of high frequency receiver

horn, but each channel will act as an independent horn. To have a true spherical wave front up to the highest frequencies, the horn would have to be divided into a sufficient number of channels to make the transverse dimension of each channel small compared with the wave length up to the highest frequencies. If it is desired to transmit up to 15,000 cps, it is not very practical to subdivide the horn to that extent. Both the cost of construction and the losses in the horn would be high if designed to transmit also frequencies as low as 200 cps, as is the case under consideration. However, it is not important that at very high frequencies a spherical wave front be established over the whole mouth of the horn. For this frequency region it is perfectly satisfactory to have each channel act as an independent horn, provided that the construction of the horn is such that the direction of the sound waves coming from the channels is normal to the spherical wave front.

The angle through which sound is projected by this horn is about 60 deg, both in the vertical and in the horizontal direction. For reproducing the orchestra 2 of these horns, each with a receiving unit, were used. They were arranged so that a horizontal angle of 120 deg and a vertical angle of 60 deg were covered. These angular extensions were sufficient to cover most of the seats in the hall with the loud speaker on the stage. The vertical angle determines to a large extent the ratio of the direct to the indirect sound transmitted to the audience. The vertical angle of 60 deg was chosen purely on the basis of judgment as to what this ratio should be for the most pleasing results.

The High Frequency Receiving Unit

In the design of the low frequency receiver one of the main objectives was to reduce to a minimum the variations in sound transmission resulting from variations in the throat impedance of the horn. However, the high frequency horn readily can be made of a size such that the throat resistance has relatively small variations within the transmitting region. On the other hand, whereas the diameter of the diaphragm of the low frequency unit is only

a small fraction of the wave length, that of the high frequency unit must be several wave lengths at the higher frequencies in order to be capable of generating the desired amount of sound. Unless special provisions are made there will be a loss in efficiency because of differences in phase of the sound passing to the horn from various parts of the diaphragm. The high frequency receiver therefore was constructed so that the sound generated by the diaphragm passes through several annular channels. There are enough of these channels to make the distance from any part of the diaphragm to the nearest channel a small fraction of a wave length. These channels are so proportioned that the sound waves coming through them have an amplitude and phase relation such that a substantially plane wave is formed at the throat of the horn.

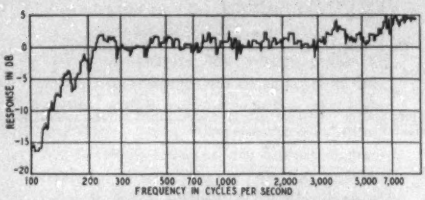


Fig. 8. Output-frequency characteristic of high frequency receiver as measured in a small room

In the appendix it is shown that, for the higher frequencies where the impedance of the horn may be taken as equal to ρc times the throat area and for the type of structure adopted, the radiation resistance is equal to

$$\rho c a T^2 \left[\frac{1}{k^2 h^2 T^2 + k^2 l^2 \cot^2 kl}\right] \tag{6}$$

and the reactance

$$-j\frac{\rho c a}{kh} T \left[1 - \frac{1}{kl \cot kl + \left(\frac{hT}{l}\right)^2 kl \tan kl}\right] \tag{7}$$

where a is the area of the throat of the horn, T the ratio of the area of the diaphragm to the throat area, $k = \frac{\omega}{c}$, and the other designations are those indicated in Fig. 11. At the lower frequencies the resistance is $T^2 r$ and the reactance $T^2 x$ where r and x are, respectively, the resistance and reactance of the throat of the horn.

Equation 6 shows that at a given frequency, other conditions remaining the same, the radiation resistance will have a maximum value when l is approximately equal to $\frac{\pi}{2k} = \frac{c}{4f}$. In Fig. 6 the resistances as computed from eq 6 are plotted as a function of frequency for several values of $\frac{h}{w}$. It is seen from these curves that the resistance at the higher frequencies is determined very largely by the relation of $\frac{h}{w}$ but is independent of it at the lower frequencies, where it is equal to $\rho c a T^2$. At the lower frequencies where the mechanical impedance of the diaphragm is negligible, the efficiency, as was the case for the low frequency receiver, depends upon the value of $B^2 v$ where v is the volume of the coil, but at the higher frequencies the efficiency decreases with increasing mass of the coil. It is advantageous, therefore, to keep v small and to make B as large as is practically possible. Values were selected to give the receiver an efficiency of 55 per cent at the lower frequencies. For these conditions the relative sound power output was computed by eq 2 on the assumption that the receiver was connected to an amplifier having an output impedance equal to 0.45 times that of the receiver at the lower frequencies. Figure 7 shows the values so obtained. Corresponding values obtained experimentally when the receiver was connected to the horn previously described are shown in Figs. 8 and 9, where the sizes of the rooms in which the values were obtained were, respectively, 5,000 and 100,000 cu ft. Both of these curves differ considerably from the computed curve, particularly as regards loss at high frequencies. The curve of Fig. 8 shows less, and that of Fig. 9 more, loss at high frequencies. The computed curve, however, refers to the total sound output, whereas the measured curves give average values of sound intensity in a certain part of the room, values dependent upon the acoustic characteristics of the room.

Fig. 9. Output-frequency characteristic of combined low and high frequency receivers as measured in a large room

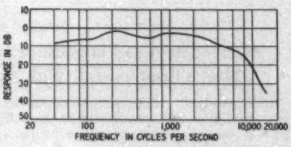
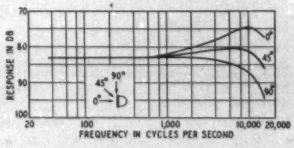


Fig. 10. Output-frequency characteristic of moving coil microphone



The number of high frequency receivers that must be used for each transmitting channel is governed largely by the amount of power that the system is to deliver before harmonics of an objectionable intensity are introduced. The generation of harmonics in a horn when transmitting waves of large amplitude already has been discussed. Let it suffice here to say that, for a given percentage harmonic distortion, the power that can be transmitted through the horn is proportional to the area of the throat and inversely proportional to the square of the ratio of the frequency to the cut-off frequency.

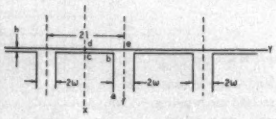
Inasmuch as the moving coil microphones used for the transmission of music in acoustic perspective have been described previously[8] they will not be discussed here at length. Their frequency response characteristic as measured in an open sound field for several different angles of incidence of the sound wave on the diaphragm are shown in Fig. 10 where it is seen that the response at the higher frequencies becomes less as the angle of incidence is increased. In general, this is not a desirable property, but with the instruments as used in this experiment the sound observed as coming from each loud speaker is mainly that which is picked up directly in front of each microphone; sound waves incident at a large angle do not contribute much.

At certain times the sound delivered by the orchestra is of very low intensity. Therefore it is important that the microphones have a sensitivity as great as possible, so that the resistance and amplifier noises may readily be kept down to a relatively low value. At 1,000 cps these microphones, without an amplifier, will deliver to a transmission line 0.05 microwatt when actuated by a sound wave having an intensity of 1 microwatt per sq cm. This sensitivity is believed to be greater than that of microphones of other types having comparable frequency response characteristics, with the possible exception of the carbon microphone.

Appendix—Load Impedance of a Diaphragm Near a Parallel Wall With Slot Openings

First assume a diaphragm and a parallel wall of infinite extent separated by a distance h, and that the wall is slotted by a series of equally spaced openings as shown in Fig. 11. From symmetry it

Fig. 11. Schematic diagram of diaphragm and parallel slotted wall of infinite length



is known that when the diaphragm vibrates there will be no flow perpendicular to the plane of the paper or across the planes indicated by the dotted lines. Therefore only one portion of unit width, such as *abcdef* need be considered. Let the x and y reference axes be located as shown. If the general field equation

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} + k^2\varphi = \xi \tag{8}$$

is applied when the diaphragm has a normal velocity equal $\dot{\xi}e^{i\omega t}$ the following boundary conditions are obtained:

When $x = 0$, $\quad \dfrac{\partial\varphi}{\partial x} = -\dot{\xi}$

$x = h$, $\quad \dfrac{\partial\varphi}{\partial x} = 0$

$y = 0$, $\quad \dfrac{\partial\varphi}{\partial y} = 0$

and when $y = l$, the pressure is equal to the product of acoustic impedance and volume velocity or

$$\frac{\rho}{h}\int_0^h \left(\frac{\partial\varphi}{\partial t}\right)_{y=l} dx = \frac{c\rho}{w}\int_0^h \left(\frac{\partial\varphi}{\partial y}\right)_{y=l} dx$$

where φ is the velocity potential, $k = \dfrac{\omega}{c}$, and c is the velocity of sound.

The appropriate solution of eq 8 then is

$$\varphi = \frac{\dot{\xi}}{k}\left[\frac{\cos ky}{kh\left(\cos kl + i\dfrac{h}{w}\sin kl\right)} - \frac{\cos k(x-h)}{\sin kh}\right]$$

The average reacting force per unit area of the diaphragm is

$$\frac{ik\rho c}{l}\int_0^l (\varphi)_{x=0}\, dy$$

Thus, for the impedance per unit area, which is equal to the force divided by the velocity, is obtained

$$\frac{\rho c l}{w}\left\{\left[\frac{\sin^2 kl}{k^2 l^2}\,\frac{1}{\cos^2 kl + \left(\dfrac{h}{w}\right)^2 \sin^2 kl}\right] - j\frac{w}{h}\left[\frac{\dfrac{kh\cos kh}{\sin kh}\,kl - \dfrac{\sin kl\cos kl}{\cos^2 kl + \left(\dfrac{h}{w}\right)^2\sin^2 kl}}{k^2 l^2}\right]\right\} \equiv r' + jx'$$

In all practical types of loud speakers $\dfrac{kh\cos kh}{\sin kh}$ would be very nearly equal to 1; then

$$r' = \frac{\rho c l}{w}\left[\frac{1}{k^2 l^2\left(\left(\dfrac{h}{w}\right)^2 + \cot^2 kl\right)}\right]$$

$$x' = -\frac{\rho c l}{h}\left[\frac{kl - \dfrac{1}{\cot kl + \left(\dfrac{h}{w}\right)^2\tan kl}}{k^2 l^2}\right]$$

If the total area of the diaphragm is A and that of the corresponding channels a, then $\dfrac{A}{a} = \dfrac{l}{w}$, approximately, and the total impedance becomes

$$= \frac{\rho c A^2}{a}\cdot\frac{1}{\left(\dfrac{kh}{a}\right)^2 A^2 + k^2 l^2\cot^2 kl}$$

$$x = -j\frac{\rho c A}{kh}\left[1 - \frac{1}{kl\cot kl + \left(\dfrac{h}{l}\dfrac{A}{a}\right)^2 kl\tan kl}\right]$$

References

1. ABSOLUTE AMPLITUDES AND SPECTRA OF CERTAIN MUSICAL INSTRUMENTS AND ORCHESTRA, L. J. Sivian, H. K. Dunn, and S. D. White. *Jl.*, Acous. Soc. Am., v. 2, Jan. 1931, p. 330.

2. AUDIBLE FREQUENCY RANGES OF MUSIC, SPEECH, AND NOISE, W. B. Snow. *Jl.*, Acous. Soc. Am., v. 3, July 1931, p. 155.

3. Backhaus, *Zeits. f. Tech. Physik*, v. 9, 491, 1928.

4. "Engineering Acoustics," L. E. C. Hughes, p. 47. Benn, London.

5. W. J. Albersheim and J. P. Maxfield, similar relations were presented in a paper before the Acoustical Society in May 1932.

6. SUR LA PROPAGATION DES ONDES SONORES D'AMPLITUDE FINIE, M. Y. Rocard. *Comptes Rendus*, Jan. 16, 1933, p. 161.

7. "Theory of Vibrating Systems and Sound," Crandall. P. 163 ff. D. Van Nostrand, New York.

8. MOVING COIL TELEPHONE RECEIVERS AND MICROPHONES, E. C. Wente and A. L. Thuras. *Jl.*, Acous. Soc. Am., v. 3, 1931, p. 44.

Auditory Perspective —Amplifiers

Appreciable care is required in the design of a system which must amplify with great fidelity practically the whole range of audible frequencies and be capable of delivering a high level while at the same time providing a wide volume range. Some of the problems involved are discussed, particularly as applying to the equipment used in the reproduction in Washington, D. C., of the Philadelphia Symphony Orchestra playing in Philadelphia. This is the fourth paper in this symposium.

By
E. O. SCRIVEN
ASSOCIATE A.I.E.E.

Bell Tel. Labs., Inc.,
New York, N. Y.

VACUUM TUBE AMPLIFIERS have been closely identified with the extension of the channels of communication since, with completion of the initial transcontinental telephone line 20 years ago, they first enabled New York to converse with San Francisco. There are now thousands of audio frequency amplifiers in telephone circuits and in sound picture theaters, public address systems, and other similar services as well as in the millions of radio receiving sets.

Along with the extension of the field of usefulness of audio amplifiers there has been continuing progress toward more faithful reproduction, better transmitters, better receivers, and better amplifiers. Those first telephone repeaters, although quite adequate for their immediate purpose, transmitted a frequency band only a few octaves wide. Very few radio sets even now cover a range above 3,000 cps without distortion, and the most up-to-date sound picture installation rarely can be depended upon for accurate reproduction of frequencies above 7,000 or 8,000 cps. The requirements as to frequency range and freedom from distortion for any particular service are, in the last analysis, determined by public demand.

However, when one undertakes to reproduce an orchestra like the Philadelphia Symphony and to reproduce it in such a manner as to satisfy the critical ear of the director, or that of the devotee of symphonic concerts, one has to provide something out of the ordinary in audio amplifiers.

In his paper, which forms a part of this symposium, Dr. Fletcher has pointed out that "only the elimination of those frequencies below 40 cps and those above 15,000 cps produces no detectable difference in the reproduction of symphonic music." This, then, is the frequency spectrum that the amplifier must be designed to handle. Also, it is important that there shall be uniform amplification of all parts of the frequency range and that no extraneous frequencies shall be introduced.

Of importance commensurate with the distortionless amplification of the complete frequency range of the orcehstra is the provision of an equivalent volume of sound. The amplifier must be capable of supplying to the loud speakers without distortion an amount of energy that will produce a sound volume at least equivalent to that produced by the orchestra (the Philadelphia-Washington installation was designed to produce about 10 times this amount). And equally important, the amplifier must be so free from internal disturbances and from self-induced electrical fluctuations that the softest music, the weakest input to the microphone, can be reproduced without appreciable background noise. According to Fletcher the ratio of the heaviest playing of a large orchestra such as the Philadelphia Symphony Orchestra to the softest music such as that of a violin is about 10,000,000 to 1, or 70 db. Thus it is required that any noise be at least 75 db below the loudest tones; that is, there must be at least a 75-db volume range.

The sources of noise may be divided into 2 groups. In the first group are included the 60-cycle alternating current power supply, vibration or jar of mechanically unstable vacuum tubes, contact and thermoelectric potentials, and similar disturbances, which may be reduced to practically any degree depending upon the lengths to which one is willing to go to reduce them. In the second group are those electronic irregularities intimately associated with the operation of the vacuum tube and which depend somewhat upon the design, manufacture, and method of operation of the vacuum tube; and which, when sufficiently amplified and fed into a loud speaker, may be heard as noise. In general, the maximum volume range of an amplifier is reached when all other disturbances are reduced to the level of this tube noise.

It is evident, then, that under ordinary circumstances the limiting volume range of an amplifier is a function of the amount of amplification following the first tube. In other words, the magnitude of the signal voltage with respect to the noise voltage in the plate circuit of the first tube in a multistage amplifier determines the limiting volume range obtainable with that amplifier.

It will appear that in a sound reproduction system a highly efficient microphone simplifies the amplifier volume range requirements, and that loud speakers of high efficiency reduce the volume required from the amplifier.

Perhaps it is in order to inquire as to what makes an amplifier free from frequency distortion over a

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 31, 1933; released for publication Dec. 4, 1933. *Not published in pamphlet form.*

wide range. The answer might well be: attention to impedance relations. A compact, efficient amplifier requires several pieces of reactive apparatus such as transformers, retardation coils, and capacitors. One must remember that an inductance of one henry is equivalent to an impedance of 250 ohms at 40 cps but that it is nearly 100,000 ohms at 15,000 cps; that the grid circuit of the vacuum tube is not actually an open circuit even though the grid is maintained negative with respect to the cathode, but has a reactance which becomes important at high frequencies or with large ratio input transformers. Many years of development in this field have advanced the art to the point where transformers transmitting extremely wide bands now can be designed. The commercial production of such designs requires rigid inspection including shop transmission measurements under the actual conditions of use. The transformer must be designed for the particular type of vacuum tube with which it is to be used. First, however, the tube must be designed to permit its use under the proposed conditions and then it must be manufactured to close limits, every tube of a type like every other tube of that type.

This is, then, the general requirement for a wide frequency range amplifier: (1) attention to impedance relations; (2) meticulous design of each component for the particular job it has to do, and rigid inspection to insure that it does that job.

One might suppose that when the tube designer and the coil designer each had done his part the job was done. Such is not the case. The various pieces of apparatus have to be gathered together into a unit (often a current supply set for supplying anode, cathode, and grid potential is assembled with the amplifier) and out of this electrical and physical association is apt to arise "feed-back" and "noise."

When there is coupling between 2 parts of the amplification circuit which are at different potential or different phase there is feed-back. Feed-back sometimes is employed designedly to modify an amplifier characteristic, but, feed-back which may arise as a result of a particular arrangement of apparatus or wiring ordinarily will cause more or less severe frequency distortion. It may be induced due to stray electromagnetic or electrostatic fields, which must be eliminated by rearrangement of apparatus or by shielding; or it may be caused by common circuit impedance, requiring circuit modifications. In general, a low gain amplifier or one with limited frequency range presents no feed-back problems, but a study of a high-gain wide-range equipment usually is necessary in order to determine the best arrangement. Often modifications of tentative circuit or apparatus must be made to obtain satisfactory operation.

The provision of a volume range of some 75 db on an energy basis became largely a matter of the suppression of a-c hum. The low inherent electronic noise effect of the Western Electric No. 262A vacuum tube and the relatively high level from the microphones kept electronic tube noise well in the background. Careful and in some cases rather elaborate shielding of audio transformers and leads and the segregation of the 60-cycle power equipment coupled with the use of vacuum tubes having indirectly heated cathodes and specially designed to have small stray fields prevented a-c hum trouble in the early stages. However, the Western Electric No. 242A vacuum tubes used in the push-pull final

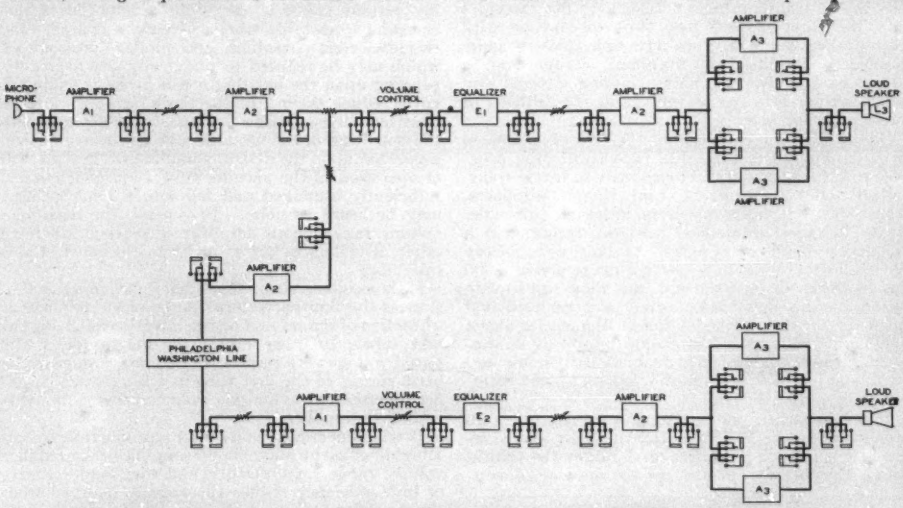


Fig. 1. Schematic diagram of the amplification system used in conveying Philadelphia symphonic music to Constitution Hall in Washington, D. C., and there reproducing it in auditory perspective

stage have filamentary cathodes, and when such tubes have raw a-c filament supply, a very appreciable 120-cycle component appears in the space current. Although theoretically in a perfectly balanced push-pull amplifier this component would be eliminated, in practice an exact balance cannot be obtained. As a final step in noise elimination, advantage was taken of the fact that each channel employed 2 amplifiers in parallel. Under such conditions and with proper phasing of the power supply to the 2 amplifiers the net a-c noise output of the 2 amplifiers in parallel will be less than that of either one alone.

Having reduced feed-back and noise to tolerable values, it remains to determine the operating conditions for maximum output. The vacuum tube is not strictly a linear device, but, when properly used, the total harmonic content can be held to a low figure. For a high quality system the total harmonics produced in the system should not exceed one per cent of the fundamental. This requires that impedance and potential relations in the vacuum tubes should be adjusted to give approximately linear operation; and also that the design of audio transformers, particularly those carrying considerable levels, must be scrutinized carefully to insure that they operate over an essentially linear portion of the magnetization curve of the core material.

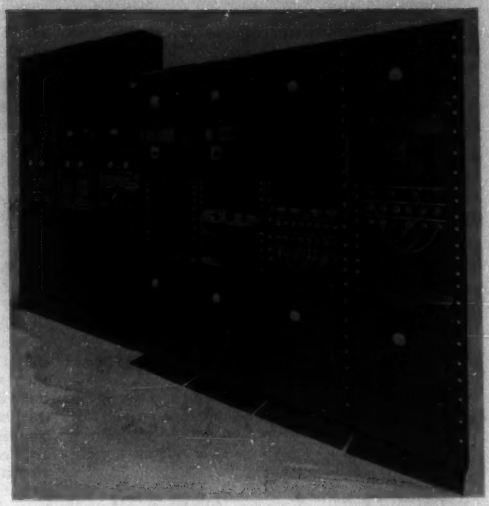


Fig. 2. Amplifying equipment used at Philadelphia. The taller racks are 8 ft high and contain A_1 and A_2 amplifiers, volume indicators, and various controls

An instrument really essential to the design of high quality amplifiers is a high sensitivity harmonic analyzer that is capable of quickly and accurately resolving a complex wave into its simple components. By this means the effect of variations in circuit relations can be evaluated and the optimum condition for maximum distortionless power output determined.

It may be desirable at this point to examine the make-up of the audio amplification system used in the Philadelphia-Washington experiments. It should be noted that the arrangement of equipment provided for simultaneous reproduction at both Philadelphia and Washington. There were 3 complete and essentially equivalent channels of equipment actually in use and a fourth complete channel held in reserve as a spare.

Several stages of so-called voltage amplification were required preliminary to the final or power stage. There is, of course, no essential difference between a voltage amplifier and a power amplifier, the term "voltage amplifier" being applied to those preliminary stages of an amplification system the function of which is so to amplify the output of the pick-up device as to supply adequate driving voltage to the grids of the power stage. Theoretically, inasmuch as no energy is absorbed in the ideal grid circuit, this voltage increase might be supplied entirely by a high ratio input transformer. However, there are practical difficulties to the design of such a single stage amplifier and therefore multistage vacuum tube amplification is employed.

As a matter of convenience the voltage amplification for this system was obtained through the use of several separate amplifier units in tandem. This arrangement not only enabled the ready replacement of any unit of the system in case of failure, but it also facilitated the insertion of a pad, control potentiometer, or other network at any desired point. Several of these devices were required, and of course each introduced a loss. Thus the gross amplification of the system used for reproduction at Philadelphia was approximately 160 db and for Washington 240 db, although the actual difference in level between microphone output and loud speaker input was but from 80 to 90 db.

The general scheme of the amplification system is shown in Fig. 1. A_1 is a single-stage, single-tube Western Electric No. 80A amplifier slightly modified to meet the particular conditions of use; it has a gain of 30 db, and employs a Western Electric No. 262A vacuum tube. This tube has an equipotential cathode, the heater being operated on 10-volt 60-cycle alternating current and the anode being supplied from rectified alternating current. A_2 is a 2-stage amplifier having a single Western Electric No. 262A vacuum tube in the first stage and push-pull Western Electric No. 272A tubes in the second stage. It has a gain of 50 db. The cathodes of the tubes are energized with low-voltage 60-cycle alternating current and the anodes with rectified alternating current. A_3, the final or power amplifier, is a single stage amplifier employing 2 Western Electric No. 242A vacuum tubes in parallel on each side of a push-pull circuit, thus having 4 tubes per amplifier.

Two of the A_3 amplifiers were used in parallel on each channel, and were capable of supplying 60 watts each, or a total of 120 watts, to the loud speakers. These are rms values. The instantaneous peaks of power of course could equal twice this value, or 720 watts, for the 3 channels. E_1 and E_2 are equalizers to compensate for any amplitude distortion that would cause a listener to obtain a different tone effect from the loud speakers than he would from the actual orchestra. These equalizers are loss networks and principally equalize for the acoustic characteristic of the loud speakers in the particular hall, but they are placed in a low energy part of the amplification circuit so as not to waste the energy of the final power stage.

In view of the inclusion of the equalizers in the amplification system, and particularly because of the fact that the amplification of the A_3 amplifier deliberately was made to increase with frequency in order to compensate in part for acoustic losses in the overall system, the actual amplification-frequency curves of the amplifiers are of little importance. The equalizers of the system are discussed in a paper by Bedell and Kerney. (See page 216.)

Auditory Perspective —Transmission Lines

Describing methods whereby high quality sound reproduction in auditory perspective can be accomplished over long distances, this discussion centers largely upon a description of the exact technique employed in providing communication transmission circuits for the Philadelphia-Washington demonstration. Problems that might be involved in carrying out such transmission on a more widespread scale also are touched upon. This is the fifth paper in this symposium.

By
H. A. AFFEL
MEMBER A.I.E.E.
Am. Tel. and Tel. Co., New York, N. Y.

R. W. CHESNUT
ASSOCIATE A.I.E.E.
Bell Tel. Labs., Inc., New York, N. Y

R. H. MILLS
ASSOCIATE A.I.E.E.
Bell Tel. Labs., Inc., New York, N. Y.

MICROPHONES have been described that will pick up without noticeable distortion all the sounds given forth by a symphony orchestra. Loud speakers and amplifiers also have been described that will accurately reproduce this highest quality music in its full range of tone quality and volume. Therefore, the situation obviously requires connecting transmission paths so perfect in their characteristics that reproduction 100 or 200 miles away may not suffer in comparison with reproduction which may be only 100 or 200 ft from the source of music.

There are several respects in which a long line circuit possibly may distort the speech or music passed over it, unless considerable effort is expended to overcome these tendencies. For example, there may be frequency-amplitude distortion; i. e., all the notes and overtones may not be transmitted with the proper relative volumes. Similarly there may be phase or delay distortion, the different frequencies may not arrive at the receiving end of the line circuit in the same time relationships in which they originated. A line circuit is subject also to possible inductive disturbances from other communication circuits ("crosstalk"), or from power or miscellaneous circuits which cause "noise" at the receiving terminal. If the circuit contains amplifiers, transformers, and inductances having magnetic cores, it is subject to possible nonlinearity effects; i. e., the current at the receiving end of the line may not follow exactly the amplitude variations of the current applied to the transmitting end or, what is more important, spurious intermodulation frequencies may be generated within the transmission circuit and mar the purity of the musical tones. The problem of reproduction in auditory perspective, using 2 or 3 paralleling channels, also adds the requirement that these channels must be substantially identical in their transmission characteristics.

With the exception of the last, all these aspects of the problem are, of course, not peculiar to symphony music transmission. They exist as part of the problem of satisfactorily transmitting any telephone message. However, the requirements of this new high quality transmission have set a new high standard of refinement, even as compared with that required for ordinary radio chain broadcasting. For example, ordinary telephone message transmission commonly is carried out by circuits having a frequency range not exceeding 200 to 3,000 cycles per second. Much present-day radio broadcasting involves a transmission band only from about 100 to 5,000 cps. This new high quality transmission,

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 31, 1933; released for publication Dec. 4, 1933. *Not published in pamphlet form.*

however, requires a range from approximately 40 to 15,000 cps. Further, with reference to the required freedom from interference, ordinary radio broadcasting seldom exceeds a volume range greater than 30 decibels. The new high-quality system, however, requires a volume range of at least 65 db, which is more than 3,000,000 to 1 expressed as a power ratio.

In considering the specific problem of transmitting from Philadelphia to Washington for the demonstration given on April 27, 1933, several alternative methods of providing the required transmission paths presented themselves. The arrangement chosen consisted in bridging the distance between the 2 cities by means of carrier channels over cable conductors. From the telephone toll office in Philadelphia to the toll office in Washington, 3 carrier transmission paths were provided in which the music frequencies were stepped up from their normal position in the audible range to considerably higher frequencies. The frequency range from 40 to 15,000 cps picked up by the microphones was transmitted over line circuits in a range from 25,000 to 40,000 cps. After being thus stepped up in frequency, the high frequency currents were applied to 3 nonloaded pairs in an all-underground cable which was equipped with repeaters at approximately 25-mile intervals. At Washington, step-down or demodulation apparatus restored the frequencies to their normal position in the spectrum.

For transmission between the auditorium in Philadelphia and the toll office there, a distance of approximately 3 miles, and for transmission in Washington between the telephone toll office and the auditorium, about half this distance, normal frequency transmission over small-gauge pairs in ordinary exchange cables was employed.

The use of the carrier method for the long distance transmission has several advantages. In general, it permits multiplex operation; i. e., more than one message or program on the same pair of wires. As a matter of expediency in this particular case this feature of operation was not used, and 3 separate pairs were employed, one for each channel. In the future the same technique undoubtedly would permit 2 or possibly more of these extra-broad-band transmission paths to be obtained on the same pair of conductors. The most important reason for choosing the carrier method rather than transmission in the natural audio-frequency range in this particular case was that, because all other transmission circuits in the same cable were at a considerably lower frequency and because the lead sheath of the cable acts efficiently at the high frequencies to shield the pairs from induced disturbances from the outside, it offered a special freedom from crosstalk and noise.

With these arrangements, which will be described in somewhat greater detail in what follows, requirements of transmission were met very satisfactorily and the reproduction of the symphony music in Washington with the orchestra playing in Philadelphia suffered not the least in comparison wiht the reproduction of the same program in an auditorium in Philadelphia located but a few feet from the hall in which the orchestra played. It is believed that, if necessary, by the use of the same principles, line circuits may be set up and comparable quality reproduction given throughout the country. However, as will be evident from part of the discussion which follows, in some respects the problem of meeting the requirements in transmission between Philadelphia and Washington was not as difficult as might be encountered in other localities. Hence even more complex arrangements might be necessary if it were desired to establish such transmission circuits to other points, and particularly for greater distances.

Line Circuits

There are several all-underground cables between Philadelphia and Washington. As described in a paper[1] by Clark and Green given before the A.I.E.E. in 1930, recently laid cables contain several 16-gauge conductors distributed throughout the cross section of the cable for possible use as program circuits in chain broadcasting. These pairs, however, ordinarily are loaded and equipped with repeaters at approximately 50-mile intervals so that they transmit a frequency range up to about 8,000 cps.

In one of the cables several pairs of this type had not yet been loaded, and these pairs were used for this newer transmission. Because of the higher frequencies employed and the greater attenuation encountered, it was necessary to install repeaters at more frequent intervals. As may be noted in Fig. 1, the normal cable layout between Philadelphia and Washington includes 2 intermediate repeater stations, one at Elkton and one at Baltimore. Additional repeater stations were established accordingly at in-between points—Holly Oak, Abingdon, and Laurel. One of these repeater points, Holly Oak,

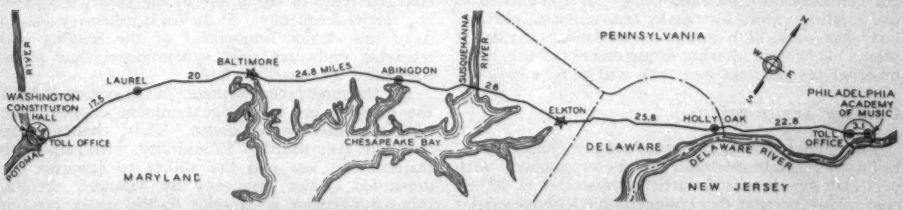


Fig. 1. Geographical layout of 3-circuit communication line used to carry Philadelphia symphony music to Washington, D. C., for reproduction in auditory perspective

was established in a local telephone office. No such convenient housing existed at the other 2 points, and it was necessary to establish new repeater stations. These were small metal structures large enough to house only the repeaters, their power supply, and

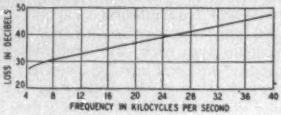


Fig. 2. Line attenuation characteristic of typical repeater section

testing equipment. This apparatus was arranged to be normally nonattended, various switching actions being remotely controlled from the nearest regular repeater station.

The line attenuation between repeater points is shown in Fig. 2. It may be noted that the attenuation is approximately 50 db for the highest carrier frequency involved. A diagram showing the variations in power level as the carrier waves traverse the complete circuit is shown in Fig. 3. Because of the variation in attenuation over the frequency range employed it was necessary, of course, to use equalizers at the input of each repeater; i. e., networks having an attenuation variation with frequency approximately the inverse of that of the line circuit.

Noise

In setting up these circuits various tests, including measurements of noise currents picked up by the conductors to be employed, were made prior to the actual installation of the apparatus. It was discovered that on the cable circuits north of Baltimore these pairs were picking up sufficient noise even at the higher frequencies to constitute a possible limitation in the volume range that might be delivered. This noise was generated chiefly as a by-product of relay and other similar operations within the Baltimore office and was propagated over the longitudinal circuits of various pairs in the cable from which, by induction, it entered the special selected pairs. As a remedial measure, longitudinally acting choke coils applied to all but the specially selected pairs in the cable greatly reduced the noise. Shielding and physical separation were employed in the Baltimore office to prevent induction between the repeaters and the connection to the main cable. If it is desired to use existing cables for carrier transmission, particularly for such high grade transmission circuits, it seems likely that filtering arrangements of this kind, or other precautions, generally will be required.

Carrier Apparatus

The carrier system employed may be characterized briefly as single-sideband carrier-suppressed, with perfectly synchronized carrier frequencies of 40,000 cps. Most present-day commercial telephone carrier systems are of the single-sideband carrier-suppressed type. Suppressing one sideband saves frequency space and suppressing the carrier reduces the load on the line amplifiers or repeaters. Ordinarily the exact synchronization of the carrier frequencies at the sending and receiving ends is not required for message telephone service.

Obtaining a single sideband after modulation commonly is carried out by providing band filters which transmit the desired sideband and suppress the unwanted sideband. For the requirements of message telephone transmission this does not impose severe requirements in the design of filters because audio frequencies less than about 100–200 cps ordinarily are not transmitted, in which case, if the filter in suppressing the unwanted sideband tends to cut off the lower frequencies of the desired sideband, it is not important.

For the requirements of this new high quality system, however, where it was desired to transmit

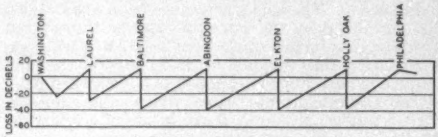


Fig. 3. Transmission level diagram

all frequencies to at least as low as 40 cps, the problem was considerably more difficult. Two alternatives presented themselves in the design of the required filters. The first consisted in attempting to provide the required selectivity in the filters themselves, perhaps supplementing the actions of inductance coils and condensers (which normally make up such a filter structure) by quartz crystals to provide the sharp selectivity required on the sides of the band. The other alternative consisted in providing a filter of moderate selectivity so that in the neighborhood of the carrier frequency the unwanted sideband is not completely suppressed, and in arranging that the resultant reproduced music at the receiving terminal is obtained by the proper coördination of the desired and the vestige of the unwanted sideband. The "vestigial" sideband method was decided upon. Although this does not require filters having particularly sharp selectivity on the sides of the band, it does, however, impose more severe requirements upon the control of the phase characteristics of the filters in the neighborhood of the carrier frequency. It makes it necessary also to have the carrier frequencies at the sending and receiving ends not only synchronized, but phase controlled as described later.

For the modulating elements in the system at both the sending and receiving terminals, copper oxide rectifying disks were chosen. These elements can be made very simple. In stability, with respect to transmission loss and the ability to suppress the unwanted carrier frequency by balanced circuits, this arrangement is superior to the usual vacuum tube circuits.

In Fig. 4 is shown schematically the arrangements

of the carrier circuit at the transmitting and receiving ends. At the transmitting terminal the circuit from the microphones is led first through low- and high-pass filters to limit the bands to the desired width; i. e., 40 cps to 15,000 cps. The 40-cycle limiting filter was included because tests had demonstrated that lower frequencies are not required for the satisfactory transmission of music of symphony character, and because it was feared that occasional high energy pulses of subaudible frequency might cause overloading. When these 40-cycle filters are omitted, as was done in tests, the carrier channels are capable of transmitting frequencies down to and including zero frequency, a characteristic which could not possibly be obtained in a single sideband system by other than such a vestigial sideband technique.

As may be noted further in Fig. 4, carrier current is supplied to the rectifying disks of the modulator along with the incoming music frequencies. The balancing connection of the 4 rectifying disks making up the modulator is arranged to suppress the carrier frequency, the final degree of suppression being adjusted by means of the variable condenser and resistance shown, which were included to make up for slight dissimilarities in the characteristics of the individual copper disks. A very high degree of carrier suppression can be achieved by this means. No difficulty was experienced in maintaining a ratio of at least 60 db between the carrier voltage applied to the unit and the residual carrier current not completely balanced out. Over short periods an even higher degree of balance can be readily obtained.

There is a certain amount of electrical noise generated in the rectifying disks over and above that caused by thermal agitation[2,3] effects. The amount of this noise compared with the maximum permissible modulation output determines the volume range possibilities of a modulator of this type. Measurements indicated that this range was approximately 90 db, which obviously was more than sufficient to meet the requirements desired.

The circuit includes a relay and a meter through both of which flows the d-c component produced by the rectification of the carrier frequency. These supplementary units give a check on the magnitude of the carrier supply and afford an alarm in case of failure. From the modulator unit the circuit is connected to the band filter which transmits only the lower sideband lying between approximately 25,000 and 40,000 cps and the vestige of the upper sideband. From the band filter the currents are led to an amplifier and thence to the line circuit leading to the farther terminal.

It may be noted that at the transmitting terminal the 40,000-cycle carrier current is derived from a 20,000-cycle oscillator by passing its output through a series of copper oxide rectifiers connected to form a frequency doubler. Part of the originally generated 20,000 cycles also is connected to the input of the transmitting amplifier and sent over the line to be used in producing the 40,000-cycle carrier supply for demodulation.

At the receiving terminal a similar modulation or demodulation process occurs through the use of copper oxide disk circuits. A relay and meter also are included in the circuit to check the carrier supply,

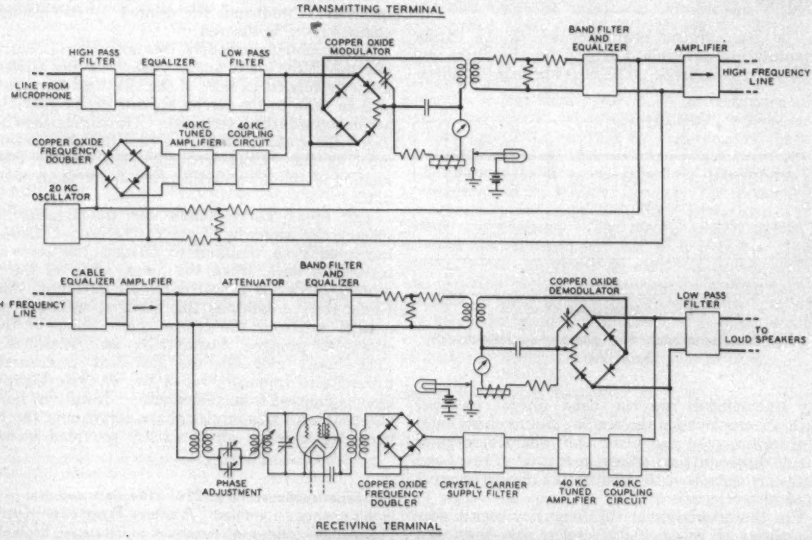


Fig. 4. Schematic diagram of carrier terminal circuits

in this case providing also a check or pilot of the transmission over the long line circuit. The 20,000-cycle synchronizing current is selected at the receiving terminal, amplified and applied to a frequency doubler, and thence applied to the demodulator circuit. The input of this carrier supply circuit includes also a phase adjusting variable condenser arrangement so that the phase of the carrier supplied to the demodulator may be adjusted properly in relation to that of the carrier supplied to the modulator at the sending end. An interesting feature of the receiving terminal carrier supply is the quartz crystal filter employed to select the 40,000-cycle carrier after frequency doubling. The transmission characteristic of this extremely selective filter is shown in Fig. 5.

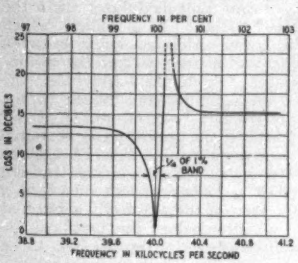


Fig. 5. Transmission characteristic of carrier supply crystal filter

Filters

The transmission characteristics of the carrier channels are determined largely by the filters and associated equalizers. The filters principally affecting transmission are the band filters. Identical units are employed at the sending and receiving ends. The transmission and phase shift characteristics of one of these units are shown in Fig. 6. These band filters are equalized to produce the desired squared band characteristic.

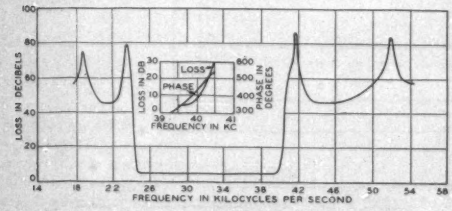


Fig. 6. Transmission and phase characteristics of band filter

The characteristics in the frequency region near the carrier (i. e., at 40,000 cycles) are shown on a large scale. This region is of particular interest because it is here that the degree of success in the application of the vestigial sideband method, for the purpose of insuring the satisfactory transmission of the low music frequencies, is determined. If for a given frequency interval above the carrier the phase change is arranged to be equal and opposite to that of the same frequency interval below the carrier, then in the action of demodulation the demodulated current produced by the action of one sideband adds itself arithmetically to that produced by the other sideband. It will be noted that this desirable phase characteristic has been achieved closely in the characteristics shown. If, in addition, the attenuation loss in the filter is adjusted so that the sum of the regular and vestigial sideband amplitudes corresponding to the low music frequencies is substantially constant and equal to the amplitude of the frequencies at midband, the desired flat transmission characteristic is assured.

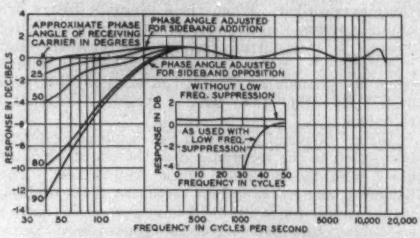


Fig. 7. Over-all transmission characteristics as a function of the phase relation of the receiving carrier

As was noted previously, this action can be carried out only if the phase angle of the receiving carrier is properly related to thht of the sideband frequencies and, in turn, to the carrier applied to the modulator at the transmitting terminal. The curves shown in Fig. 7 illustrate the influence that the phase adjustment of the carrier frequency has on the transmission of the lower frequencies in a system of this kind.

The upper curve shows the transmission frequency characteristic of one of the carrier channels measured from terminal to terminal between distortionless lines, when the phase angle of the receiving carrier is adjusted for its optimum value. Under these conditions the vestigial sideband and normal sideband supplement each other in their effects to produce substantially flat transmission. (The insert indicates the sustained transmission toward zero frequency when the 40-cycle highpass filter is omitted from the circuit.) It may be noted also that with this proper phase adjustment the full band transmission characteristic provided is sub-

This paper continued on p. 214. The sixth and final paper in this symposium entitled "Auditory Perspective—System Adaptation" follows the remainder of this paper, beginning on p. 216.

Lightning Measured on 4-Kv Overhead Circuits

For the past 4 years actual lightning potentials on the 4-kv overhead distribution system of the Commonwealth Edison Company, Chicago, have been measured by means of surge voltage recorders. The methods used and conclusions drawn from the results obtained are given here.

By
HERMAN HALPERIN
MEMBER A.I.E.E.
Commonwealth Edison Company, Chicago, Ill.

K. B. McEACHRON
MEMBER A.I.E.E.
General Electric Company, Pittsfield, Mass.

THIS work seems unique in that direct measurements of the potentials of natural lightning surges impressed on the distribution system have been made. Heretofore A.I.E.E. papers on the magnitude of natural lightning potentials on overhead systems have been confined to the results of measurements on high voltage lines. The direct application of this high voltage data to the design of overhead distribution systems is neither simple nor accurate; consideration must be given, for example, to the different types of construction involved, to the effect of tap lines and of spacing of equipment, to length of circuits, and to relatively low impulse strength of distribution equipment. Furthermore, on the high voltage lines it usually is possible to have a full development of lightning surges into traveling waves, whereas on distribution circuits the waves develop to little or no extent.

It seemed therefore that an investigation of the lightning potentials occurring on an overhead distribution system should be of considerable value in the design of transformers and other overhead plant equipment, and in the design and application of lightning protective equipment. The present study supplements Roper's[1] statistical investigations of lightning protection on the Chicago system.

The principal conclusions to be drawn from the results of this investigation are:

1. Lightning voltages at transformers are reduced materially by the use of arresters.

2. Usually arresters on urban circuits must be capable of discharging successfully surge currents less than 300 amperes.

3. With the arrester ground and secondary neutral main interconnected, only the arrester potential appears between the primary coil and the secondary neutral main.

4. Known direct strokes had negative polarity and the maximum voltage was 488 kv.

5. Where there was no evidence of flashover, the voltages recorded on these distribution lines in open territory with little equipment were about 300 kv or less.

6. Voltages below the flashover value of the line insulation probably were induced surges, and for the higher voltages there was a preponderance of negative surges.

7. The probability that high lightning voltages may occur at transformer locations on "long" circuits is 10 or 20 times as great as that for urban circuits. The probability of direct strokes is remote.

8. For the long circuits, lightning voltages caused by a single cloud discharge seem to cover 1,000 to 3,000 ft of the line. Generally on urban circuits the voltages are restricted considerably more by the closely spaced arresters.

9. Usually in urban territory the maximum lightning voltages impressed are considerably less than 200 kv.

10. For lightning voltages of the same magnitude, the insulation of transformers having the interconnection is stressed considerably less than insulation of transformers having normal arrester protection.

Distribution System

The distribution plant[1] is a 4-wire, 3-phase, 2,300/4,000-volt system with the neutral grounded at the substation. All the circuits leave the substations via underground cables, and all the line transformers are single-phase. Arresters are installed on the primary wires only. One 3,000-volt and one 300-volt arrester are installed on the same pole with each lighting transformer, while on 3-transformer installations 3 3,000-volt arresters and 1 300-volt arrester are installed with the further limitation that the maximum number on transformers in 1 block is 3 3,000-volt and 1 300-volt arrester. Arresters are installed at cable poles on each primary wire extending from the pole; the distance between arresters on each phase wire generally is less than 1,000 ft. The resistance of over 97 per cent of the arrester grounds is 25 ohms or less; and of 0.3 per cent the resistance is above 50 ohms.

The terrain of Chicago is quite flat. The primary wires are about 28 ft above ground; the secondary mains usually are installed on a separate arm 2 ft below the primaries. The wire spacings and insulators used are standard for such circuits. The secondary neutral main is grounded to driven pipes and generally to several water pipes in customers' premises in each block. In about 85 per cent of the cases the secondary neutral mains of adjacent blocks are interconnected. The combined secondary grounds have a resistance of less than one ohm.

Method of Investigation

The surge voltage recorders used were of the stationary film type[2] and were developed by the General Electric Company for this investigation. The device consists essentially of a porcelain housing and removable container with 2 films that record direct and reversed polarity measurements of each surge. The instrument has a range of 2.5 to about

Full text of a paper recommended for publication by the A.I.E.E. committee on protective devices, and scheduled for discussion at the A.I.E.E. winter convention Jan. 29-26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 13, 1933. *Not published in pamphlet form.*

1. For references see end of paper.

30 kv, and has a possible error of about 20 per cent. To record voltages above 30 kv, a capacitance voltage divider consisting of 1, 2, or 3 standard suspension insulator units was mounted rigidly on the top of the recorder, giving maximum voltages within

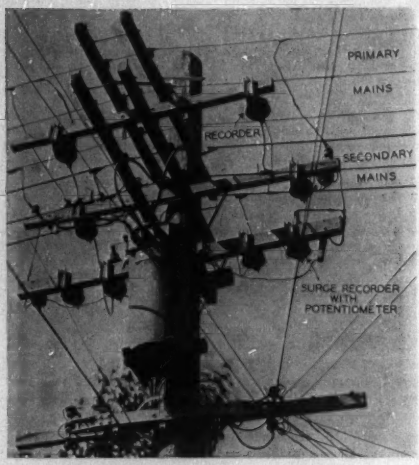


Fig. 1. Installation of 8 surge recorders on transformer pole. Voltages at transformer shown in Fig. 7 were obtained at a similar installation.

the calibration range of the recorder of 150, 230, and 390 kv, respectively. Voltages somewhat higher could be estimated.

About 100 recorders were installed in various types of locations scattered over the city. Recorders were installed on ordinary line poles and on poles carrying transformers or cable terminals with various types of arresters. Eight recorders were installed on each of 8 transformer poles (Fig. 1) to obtain information on the magnitude of the impressed lightning surge and on its division among the various portions of the apparatus (Fig. 7).

To determine the magnitude of surge currents passing through distribution arresters, a special thyrite arrester with leads brought out from the terminals of the thyrite disk itself was installed on the first pole adjacent to each of these transformer poles, and a recorder was connected in parallel with the disk. The arrester was connected to a different primary phase wire than was the transformer.

Two recorders were installed on each of 8 cable poles. Two of these installations were made in the same blocks as those in which 8 recorders were installed on the transformer poles. In these 2 blocks a recorder also was connected between the open end of the primary mains and ground.

In order to obtain information on long primary lines to which little apparatus is connected—a condition that applies to a small portion of Chicago—recorders were connected every 400 ft of 1,600 ft of primary line at 2 different locations in open country (see Fig. 2).

Early in 1932 the Commonwealth Edison Company began to make interconnections of the ground side of lightning arresters with the secondary neutral

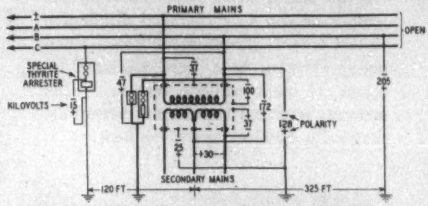


Fig. 2. Installation of surge voltage recorders on 2 "long" circuits. Spacings between recorders are averages for the 2 locations studied

mains. The data heretofore reported[3,4] on the benefit of interconnection have been obtained with artificial surges. In order to check these studies in the field, 2 recorders were installed at each of 12 locations having interconnections. These recorders are illustrated in Fig. 3.

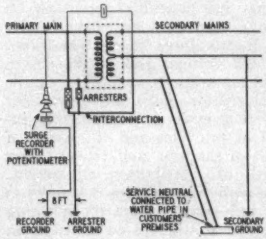


Fig. 3. Surge voltage recorders at transformer with interconnection

In general, precautions were taken to obtain clearances in order that the effects of mutual coupling of adjacent connections might be kept to a minimum. The separate grounds for the recorders were all driven 8 ft or more from the arrester ground, and the 2 ground wires were installed on opposite sides of the pole to minimize their mutual effects. The ground resistances at the test locations were about 15 ohms.

Replacements of films were made after each storm which seemed sufficiently severe to make probable the obtaining of records. It was possible that several surges could be impressed upon the recorders during any one storm, but there were few cases of superposition of Lichtenberg figures on the films. After development of the films, the voltages indicated by the positive figures were estimated from a calibration curve, since the negative figure cannot

accurately be calibrated. Information of trouble on the system due to lightning was correlated with the data furnished by the recorders.

Surge Voltages Recorded

During the investigation, 1,883 pairs of films were developed, or an average of about 5 pairs of films per recorder per year; 311 voltages were recorded. (Tables I and II.)

Analysis shows (Fig. 4) for both urban and "long" circuits a preponderance of negative surges of high magnitudes. Some high negative voltages not associated with damage to poles or crossarms were measured. These may have been induced by the discharge of a positive cloud or, in some cases, may have resulted from streamers from negative direct strokes. This is in agreement with measurements on transmission lines where the highest voltages were predominantly negative.

Table I—General Statistical Data on Lightning on 4,000-Volt Circuits

Year	No. of Thunderstorms	Transformer Troubles Due to Lightning: No. of Fuse Blowings	Transformer Troubles Due to Lightning: No. of Burnouts	No. of Pairs of Surge Recorder Films Installed	No. of Records Obtained	Per Cent of Films Showing Records
1930	37	229	103	392	33	8.4
1931	46	234	92	464	86	18.5
1932	40	287	101	511	91	17.8
1933*	37	267	106	516	101	19.6
Total	160	1,017	402	1,883	311	16.5

* To November 1, 1933.
Note: Average number of transformers on overhead system in 1930 to 1933, inclusive, was 32,926.

Figure 5 shows that the probability of high lightning voltages on long exposed circuits with low arrester densities is 10 or 20 times that on urban circuits. Under Chicago conditions, for example, the probabilities of a transformer installation being subjected to a surge voltage of 50 kv during a thunderstorm are about 1.9 per cent for long circuits and about 0.15 per cent for urban circuits. Very high voltages are rare; Chicago data[1] indicating 1 transformer failure due to a direct stroke per 200,000 transformers per storm. Cases in which there was damage such as shattering of the pole or cross-arm or injury to near-by trees were considered as direct strokes.

"Long" Circuits. The highest voltage recorded was 488 kv, and this was obtained on a long circuit. There was evidence that a direct stroke or side flash had occurred on the pole on which the record was obtained. The adjacent recorders on each side indicated voltages of the order of 290 kv and 95 kv. An arrester was installed at the latter location. At the other long circuit location, 475 kv was recorded in another storm; again there was evidence of a direct stroke on the pole on which the record was obtained. A record of 277 kv was obtained in a case where there was evidence of flashover on several poles. It was unusual that 3 direct strokes or side flashes occurred at these locations in only 4 years. Voltages of slightly lesser magnitude have been recorded where no evidence of flashover has been found. Probably the maximum voltage which can exist on these circuits without flashover of the line insulation is of the order of 300 kv.

Also, these installations have furnished some interesting data on the spread of voltages over the line, and have given evidence that fully developed traveling waves do not exist on distribution circuits (Fig. 6). An impulse voltage caused by a single cloud discharge seems to cover approximately 1,000

Table II—Summary of Surge Voltages Recorded From 1930 to 1933, Inclusive

Surge Voltage Recorder Connection	Number of Installations	Number of Surges Recorded in Voltage Range (Kv) Shown: 3–10	11–25	26–50	51–100	101–150	151–200	201–250	251–300	301–350	Over 350	Total
Transformer Poles	8											
Primary phase to transformer case			8	1	2(100)							11
Primary phase to separate ground			3	5		1(128)						9
Primary phase to arrester ground		25	18	2(47)								45
Primary neutral to transformer case		49	4	2(45)								55
Primary phase to secondary neutral			11	2	1		1(172)					15
Secondary phase to transformer case		2	1	1	1(78)							5
Secondary phase to secondary neutral		1	1	2(37)								4
Transformer case to separate ground			2(25)									2
Special Thyrite Arrester	8											
In parallel with thyrite unit		31	1(15)									32
Cable Poles	8											
Primary phase to lead sheath of cable			3	2(33)								5
Primary phase to separate ground				1	1(78)							2
Long Circuits	2											
Primary phase to separate ground			4	16	14	10	8	7	6	8	3(488)	76
Open Primaries	2											
Primary phase to separate ground			3	1				1(205)				5
Interconnections (1932 and 1933 only)	12											
Across transformer		21	15(23)									36
Primary phase to separate ground			3		2		1(158)					6
Totals		130	76	35	21	11	10	8	6	8	3	308*

Figures in parentheses are highest voltages in kilovolts recorded.
* Does not include 3 records containing negative figures only, from which voltages could not be determined.

to 3,000 ft of line and the profiles of the voltages possibly resemble the distribution of bound charges.

It is to be noted that the lightning voltages at the poles with arresters did not exceed 148 kv, and were considerably below the voltages measured at the adjacent recorder poles. In general, however, the voltages at these arresters were considerably above those recorded at the other locations, which were in normal city territory.

Cable Poles. At cable poles the maximum voltages recorded were 78 kv between phase wire and ground, and 33 kv between phase wire and lead sheath. There were no indications of direct strokes. The indicated voltage of about 45 kv between lead sheath and ground may lead one to expect severe damage to the lead sheath caused by arcing from the sheath to the iron pipe risers at the cable poles. No such damage has been found on the Chicago system. The existence of voltage between the

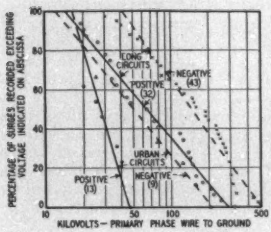


Fig. 4. Surge voltages due to lightning recorded on urban and "long" distribution circuits. Figures in parentheses are numbers of records obtained from primary phase to separate ground

sheath and ground near the pothead may be due to the fact that the sheath is not grounded throughly until it is bonded to the rest of the cable system some distance from the pothead. When the sheath potential rises, the potential of the iron pipe lateral, which has resistance to earth, rises also with the probable result that there is insufficient potential

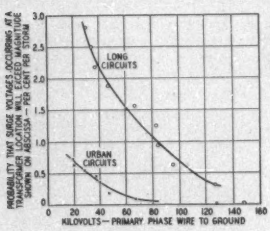


Fig. 5. Probability of voltages appearing at transformer locations during thunderstorms

built up between the sheath and this lateral to cause arcing.

Open Ends. The highest voltage recorded at the open ends of the primary mains was 205 kv to ground. In line with what would be expected on circuits of short length, the voltages at other recorders a few spans away (Fig. 7) were of the same general order. The statistical studies[1] had shown that transformers installed within 100 ft of the open end of primary lines had a rate of failure due to lightning about 20 per cent below the rate for other transformers.

Current Measurements. Voltages of 2.6 to 8.9 kv were recorded across the special thyrite disks in 31 of the 32 records, indicating discharge currents of about 300 amperes or less. In the remaining case the voltage was 15 kv corresponding to a discharge current of about 1,500 amperes. With such a current the lightning voltage would have to be several hundred kilovolts, which would have caused severe damage to the line. Since no damage

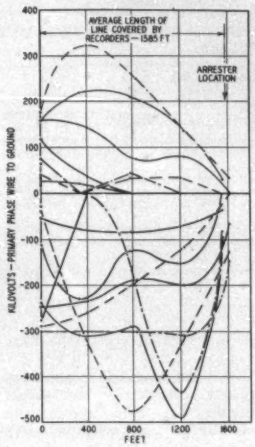


Fig. 6. Lightning voltages recorded on 2 "long" circuits. Each curve represents voltages obtained during 1 storm. Voltages shown as zero may have been as high as 20 or 25 kv

was found, possibly this case is one where an error approaching 20 per cent applies.

Transformers With Normal Arrester Protection. At one location, voltages were indicated on all 8 recorders at a transformer (Fig. 7). A voltage of 128 kv was recorded between the primary main and separate ground at the transformer, which is approximately the sum of the voltages recorded between primary phase and transformer case and between transformer case and separate ground. A voltage of 172 kv was recorded between the primary phase main and lighting secondary neutral main. This was the highest voltage recorded at transformer locations. (In some cases the voltage from primary phase wire to ground was more than from phase wire to secondary neutral.) The transformer fuse was not blown, largely eliminating the probability of a flashover at the bushings or an internal puncture that was later sealed up with oil.[5] The transformer on the pole was examined inside and outside and no arcing scars were found. Neither were there indications of flashover on the pole or recorders. Voltages recorded at transformers with normal arrester protection generally have been less than 100 kv.

Voltages of 30 and 37 kv have been indicated by recorders connected between the secondary phase main and the secondary neutral main at transformers. These are higher than would be expected, since the results of laboratory tests[6] have shown that only

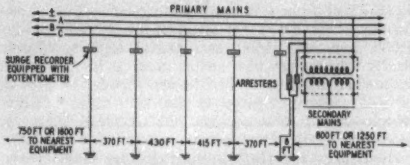


Fig. 7. Lightning voltages recorded at 1 location during 1 thunderstorm. In general, the voltages shown were among the highest obtained at such locations

a few kilovolts can be built up across the secondary coils. In line with previous Chicago experience no trouble occurred at customers' premises as a result of these voltages at the transformers.

Since recorders connected between the transformer case and separate ground were equipped with a potentiometer, the lowest voltage which could be recorded was about 18 kv. Only two records (18 and 25 kv) were obtained in these recorders, which gives some confirmation of staged tests[3] that the potential of the transformer case does not rise appreciably with the normal installation of arresters.

In all instances the potentials between the primary phase and transformer case were greater by about 2 to 1 than those recorded at the same locations between the primary neutral and case. These results are attributed largely to the difference in the arrester protection for the phase and neutral wires. In 7 of the 9 cases the difference did not exceed the difference in the breakdown values of the arresters.

Voltages as high as 82 and 100 kv were recorded between the primary phase and case, and at the same locations voltages of 62 and 172 kv were recorded between the primary phase and secondary neutral main. The maximum voltages recorded between primary phase and separate ground at *all* transformer locations were 158, 148, 128, 127, 95, 84, 83 kv, and 2 of 78 kv. No definite information on the time characteristics of these voltages is obtainable from the data. Because of the close spacing of arresters and transformers which is characteristic of most urban circuits and particularly of the major part of the Chicago system, it seems likely that the duration of these high voltages does not exceed a few microseconds.

Transformers With Interconnections. The outstanding data obtained at locations with interconnection (Fig. 3) were 13 kv across the transformer and 158 kv between the primary phase wire and separate ground. The interconnection definitely limited the voltage from the ends of the primary coils to the secondary neutral to the arrester voltage. The separate ground for the recorder connected between primary phase and ground had a resistance of 6 ohms. There was no evidence of a direct stroke on the pole.

Two other interesting records were obtained, 1 in which 15 kv was measured across the transformer and 78 kv was recorded between primary phase and ground, and 1 in which 13 kv was recorded across the transformer and 78 kv was recorded between primary phase and ground. In the first case the transformer fuse was blown. The transformer was examined on the pole and only 1 flashover was indicated by scars on the secondary neutral lead and case inside the transformer. The lead insulation may have been damaged by a previous surge. There was no scar to indicate from which lead the impulse had flashed to the case. The transformer was 22 years old.

Table III—Comparison of Lightning Voltages at Interconnected and at Normal Locations

Data Based on 5 Cases for Each Type of Arrester Installation

Type of Arrester Protection	Voltages—Kv		
	Normal A	Interconnection B	Ratio B/A
Primary phase to separate ground	60	72	1.2
Primary phase to secondary neutral	57	15	0.26

Where voltages were recorded simultaneously between primary phase and ground and between primary phase and secondary neutral at interconnected and at normal locations (Table III), the benefit of the interconnection definitely is indicated. The voltage stress on the transformer insulation, that is, between primary winding and secondary neutral, was about 75 per cent less than for installations with normal arrester protection. The 2 years' operating experience of the Commonwealth Edison Company with the interconnection has indicated that troubles at transformers due to lightning, that is, transformers burned out and fuses blown, are reduced by about 65 per cent and the interconnection causes no adverse incidents in the customers' premises.

References

1. Studies in Lightning Protection on 4,000-Volt Circuits—III, D. W. Roper. A.I.E.E. Trans., v. 51, March 1932, p. 252.

2. Instruments for Lightning Measurements, C. M. Foust. *General Electric Review*, v. 34, April 1931, p. 235.

3. Lightning Protection for Distribution Transformers, K. B. McEachron and L. Saxon. A.I.E.E. Trans., v. 51, March 1932, p. 239.

4. Interconnection of Primary Lightning Arrester Ground and the Grounded Neutral of the Secondary Main, C. F. Harding and C. S. Sprague. A.I.E.E. Trans., v. 51, March 1932, p. 234.

5. Impulse Voltage Testing, C. F. Harding and C. S. Sprague. A.I.E.E. Trans., v. 52, June 1933, p. 428.

6. Lightning Protection for Distribution Transformers, A. M. Opsahl, A. S. Brookes, and R. N. Southgate. A.I.E.E. Trans., v. 51, March 1932, p. 245.

Radial Versus Primary Network Distribution

In this paper is set forth the comparative investment in distribution plant necessary over a 10-year period to provide for load increase in a typical section of Chicago, either by means of the existing radial feeder system or a primary network system. The results show that, in terms of both total new investment and accumulated annual costs, the use of the radial feeder system is the more economical in this case.

By
H. E. WULFING
MEMBER A.I.E.E.

Commonwealth Edison Co., Chicago, Ill.

THE purpose of this study is to analyze the total investment required to serve a given area and to obtain comparative costs of providing for load increase in this area by means of 2 systems of distribution, (1) a 4-kv radial system, the standard type of distribution now used in Chicago, and (2) a 4-kv network system using unit type automatic substations as offered by the manufacturers. As shown in this paper, it is indicated that the extension of the radial system is more economical than the primary network system under the particular conditions existing in this Chicago area. Although the primary network may provide slightly better service continuity, the additional investment involved does not seem warranted.

Basis of the Study

The area selected for study consists of about 6 sq. miles in which the load is predominantly residential. The total investment values are based upon the plant in this area in 1929. At that time the distribution was by radial feeders from 4-kv substations located outside the area. It was apparent that substantial reinforcement of the distribution system within the area would be necessary in 1930. Two methods were possible: a new radial feeder substation; or a primary network installation. The comparison in this study is based upon the cost of installing these 2 systems to provide for load growth in the territory over a 10-year period from 1930. Only the incremental costs of those items which differ for the 2 systems are considered; that is, costs which are common to both systems are not included in the figures submitted.

Description of Systems of Distribution

The radial system of supply consists of a new remote-controlled 4-kv substation supplied from the 12,000-volt 3-phase transmission system. The transformer units are 5,000 kva, supplying 4,000-volt, 1,000 kva and 2,500 kva radial feeders. Each feeder phase has one switch and a 10 per cent induction regulator. The feeders consist of No. 0 or 375,000-cir-mil cable to the load centers, from which extend underground and overhead primary mains. Overhead equipment is carried on jointly owned poles and there is generally one transformer per block, with the secondary mains not extending beyond the block in which the transformer is placed.

For the primary network, it was assumed that 4-circuit units would be used, supplied from the 12,000-volt transmission system. These units are of 1,500-kw transformer capacity, capable of carrying 2,000 kw with auxiliary air blast. They are to be installed on property purchased by the company. Bus regulation is to be provided. Tie mains between units are assumed to be overhead where possible, elsewhere 4-conductor No. 0 underground cable.

Description of Area

The area selected is of relatively recent development, consisting of 6.25 sq miles in the northwest part of the City of Chicago. It is mostly residential, with bungalows and houses, and some apartment buildings. There are the usual number of commercial customers, with a small amount of manufacturing in the southern portion of the area, but no customers large enough to require primary supply. Details are shown in Table I.

Assumptions

In order to arrive at the probable load for the 10-year period considered, the load for the period

Table I—General Data, 1929

Area	Gross, 6.65 sq miles; net, 6.25 sq miles
Population density	10,000 per sq mile
Type of residence	medium bungalows and some apartments
Total underground circuit miles, primary	
In area	14 miles
To area	13 miles
Total overhead circuit miles, primary	
In area	86.4 miles
Number of distribution circuits	7–8
Average distance to load center	2.43 miles
Total kva load	6,250 kva, circuit maximum noncoincident
Customers supplied at primary voltage	none
Number of customers	18,200
Proportion of polyphase customers	2%
Kwhr sold, year	18,000,000
Proportion of kwhr sold to polyphase customers	25%
Demand at transformer secondaries	8,500 kva
Proportion of polyphase demand	20%
Load density, circuit demands	1,000 kva per square mile

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 20, 1933. *Not published in pamphlet form.*

between 1929 and 1932 was taken as base, and projected to 1939. (See Fig. 1.) The limit of voltage regulation allowed at radial feeder ends was taken as approximately one per cent. The average normal secondary pressure during load periods at the distribution transformer was taken to be 116 volts. The primary drop was assumed to be limited to 2 per cent. The area selected for study is shown in Fig. 2.

Method of Making Calculations

Capital Investment. The original investment in plant in the area was obtained by a check of the property records as of the year 1929, and the application of unit costs. Investments in 4-kv substations and in the 12-kv transmission system, including switching at the generating stations, are allocated to the area in question by load proportions, since these items are not devoted to supplying this area exclusively. The results of this analysis are shown in Table II.

Incremental Investment. For both the radial and the network schemes of supply, an estimate was made of the investment necessary for added equipment to take care of the annual increase in load. The estimate covers distribution and transmission conduit and cable, substations, and such overhead ties as are necessary in connection with the network system. In figuring increment investment, it was not thought necessary to consider other items, such as distribution transformers, services, and branch mains, which are common to both systems. In the case of conduit, the cost of all of the conduit is charged as installed, rather than on a conduit-foot basis. Incremental investment for the 2 systems is shown in Tables III and VI.

Credits. Credits are based upon the actual original cost of equipment released. Credit is not taken for conduit vacated, substation space vacated, or substation transformers unloaded.

Retirement Reserve Charges. No charge has been included for equipment that is taken out of service

Table II—Summary of Plant Investment, 1929

Item	Investment Dollars	Investment Per Cent
Transmission	$ 69,500	4.70
Substation	112,000	7.55
Underground primary conductors	132,700	8.95
Overhead primary conductors	88,900	6.00
Distribution transformers	86,440	5.75
Secondary conductors (overhead)	72,250	4.87
Services (overhead)	112,500	7.58
Conduits and manholes	552,400	37.20
Poles and fixtures	256,830	17.30
Total	$1,482,520	100.00

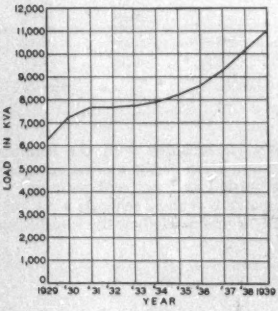


Fig. 1. Assumed noncoincident 4-kv circuit load in area. Loads for 1933 to 1939 were projected from the known 1929 to 1932 loads

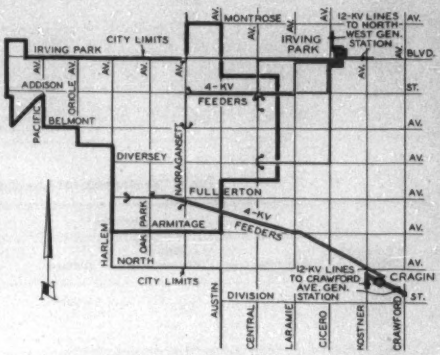


Fig. 2. Area selected for study as it was supplied from 4-kv radial system in 1929

Adjacent streets shown are approximately 1/2 mile apart

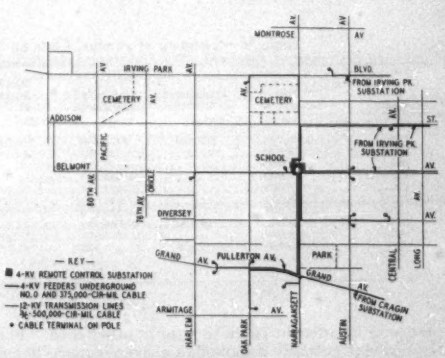


Fig. 3. First year (1930) of development of 4-kv radial plan of supply to area showing new substation and 4-kv feeders

Table III—New Investment, 4-Kv Radial System

	Distribution		Substation			Transmission			
Year	Cable	Conduit	Land	Building	Equipment	Cable	Conduit	H. V. Switching	Total
1930	$ 46,620	$155,000	$9,000	$36,000	$112,100	$ 72,000	$65,000		$495,720
1931	4,280	5,000			7,700				16,980
1932	2,000	5,000							7,000
1933	2,000	5,000							7,000
1934	2,000	5,000			21,000				28,000
1935	2,000	5 000							7,000
1936	12,800	65,000			10,500				88,300
1937	13,500	5,000							18,500
1938	12,800	12,000			14,200	55,000	33,000	$6,000	133,000
1939	10,350	30,000							40,350
Total	$108,350	$292,000	$9,000	$36,000	$165,500	$127,000	$98,000	$6,000	$841,850

Table IV—Investment Credit and Retirement, 4-Kv Radial System

	Substation				Distribution			
Year	Est. Orig. Cost	Cost of Removal	Salvage	Retirement Reserve	Est. Orig. Cost	Cost of Removal	Salvage	Retirement Reserve
1930	$29,200		$29,200		$50,630	$2,710	$34,550	$18,790
1931								
1932								
1933								
1934								
1935								
1936								
1937	7,300		7,300		16,420	230	15,050	1,600
1938								
1939					7,600	840	3,100	5,340
	$36,500		$36,500		$74,650	$3,780	$52,700	$25,730

Table V—Summary of Annual Costs on Net Additional Investment, 4-Kv Radial System

Year	New Investment	Investment Credit	Net Addn'l Investment	Fixed Charges 11.2%	Maintenance	Energy Loss	Retirement Reserve	Total Annual Cost	Present Value at 7%
1930	$495,720	$79,830	$415,890	$46,300	$3,000	$3,860	$18,790	$71,950	$71,900
1931	16,980		432,870	48,400	3,100	3,990		55,490	51,900
1932	7,000		439,870	49,200	3,200	4,050		56,450	49,200
1933	7,000		446,870	50,000	3,300	4,155		57,455	46,900
1934	28,000		474,870	53,200	3,400	4,715		61,315	46,200
1935	7,000		481,870	53,900	3,500	4,930		62,330	43,900
1936	88,300		570,170	63,800	4,100	5,090		72,990	48,700
1937	18,500	23,720	564,950	63,300	4,100	5,050	1,600	74,050	46,200
1938	133,000		697,950	78,100	5,000	5,540		88,640	51,500
1939	40,350	7,600	730,700	81,800	5,200	6,270	5,340	98,610	53,500
							Present value of 10 years' annual costs		$509,900

and can be used in place to supply other load. For equipment actually removed, a charge is made based upon estimated original cost, plus the cost of removal, less a credit allowance. Credit and retirement items are shown in Tables IV and VII.

Annual Costs. In figuring the annual costs, the fixed charges were based upon a weighted average percentage on all added investment. The rate was taken at 11.2 per cent, and includes interest, taxes, depreciation, and insurance. Yearly energy losses were estimated to include losses on feeders, regulators, and substation transformers supplying the area, at a rate of $^1/_2$ cent per kilowatthour. Maintenance was estimated on a unit cost basis for the net added investment. In connection with the cut-overs from the radial system to the network, the cost of the cut-overs is included with the maintenance cost. The summation of the annual costs for the 2 systems, discounted at 7 per cent per year, is the basis for a comparison of the 2 schemes of supply for this area. Tables V and VIII show the summaries of annual costs.

Provision of Capacity

Radial System. When the new substation was built, in the first year of the program, 6 1,000 kva feeders and one 2,500 kva feeder were installed. (See Fig. 3.) Due to the extensive rearrangement made necessary by the construction of the new substation, it was regarded as desirable to provide enough feeder capacity to care for the load growth

Table VI—New Investment, 4-Kv Network System

Year	Distribution			Substation			Transmission			
	Cable	Conduit	Ovhd. Ties	Land	Installation	Equipment	Cable	Conduit	H. V. Switching	Total
1930	$ 8,780	$118,000		$ 9,000	$ 9,400	$ 67,800	$ 80,000	$65,000		$ 357,980
1931	8,100	20,000	4,530	9,000	9,400	56,800	15,000			122,830
1932		5,000								5,000
1933		5,000								5,000
1934	2,730	15,000	7,410	9,000	9,400	56,800	11,000			111,340
1935	2,900	13,000	3,120	4,500	4,700	28,400	7,000			63,620
1936	9,520	68,000	4,437	4,500	4,700	28,400	4,000			123,560
1937	4,650	31,000	2,900	4,500	4,700	28,400	1,000			77,150
1938	4,050	33,000		4,500	4,700	28,400	71,000	33,000	$6,000	184,650
1939	6,000									6,000
Total	$46,730	$308,000	$22,400	$45,000	$47,000	$295,000	$189,000	$98,000	$6,000	$1,057,130

Table VII—Investment Credit and Retirement, 4-Kv Network System

Year	Substation				Distribution			
	Est. Orig. Cost	Cost of Removal	Salvage	Retirement Reserve	Est. Orig. Cost	Cost of Removal	Salvage	Retirement Reserve
1930					$10,230	$ 420	$ 8,680	$ 1,970
1931	$14,600		$14,600		24,490	1,030	18,380	7,140
1932								
1933								
1934	14,600		14,600		33,340	780	28,490	5,630
1935								
1936					520		520	
1937	7,300		7,300		6,720	490	3,750	3,460
1938								
1939								
Total	$36,500		$36,500		$75,300	$2,720	$59,820	$18,200

Table VIII—Summary of Annual Costs on Net Additional Investment, 4-Kv Network System

Year	New Investment	Investment Credit	Net Addn'l Investment	Fixed Charges 11.2%	Maintenance and Cutover	Energy Loss	Retirement Reserve	Total Annual Cost	Present Value at 7%
1930	$357,980	$10,230	$347,750	$ 38,900	$3,500	$3,240	$1,970	$ 47,610	$ 47,600
1931	122,830	39,090	431,490	48,300	4,100	3,095	7,140	62,635	58,500
1932	5,000		436,490	48,900	3,100	3,100		55,100	48,100
1933	5,000		441,490	49,400	3,200	3,100		55,700	45,400
1934	111,340	47,940	504,890	56,500	4,600	2,760	5,630	69,490	52,300
1935	63,620		568,510	63,600	4,600	3,035		71,235	50,300
1936	123,560	520	691,550	77,400	5,500	3,320		86,220	57,600
1937	77,150	14,020	754,680	84,500	5,900	3,320	3,460	97,180	60,600
1938	184,650		939,330	105,100	7,200	3,290		115,590	67,200
1939	6,000		945,330	105,800	7,300	3,065		116,165	63,000
							Present value of 10 years' annual costs		$550,600

Table IX—Comparative Load-Capacity Table

Year	Load Kva	Radial Plan			Network Plan		
		Radial Feeder Capacity From Outside of Area Kva	Radial Feeder Capacity From New Substation Kva	Total 4-Kv Feeder Capacity Kva	Radial Feeder Capacity From Outside of Area Kva	Network-Unit Capacity @ 1500 Kva Per Unit Kva	Total Capacity Network-Unit Plus Radial Feeders Kva
1930	7,225	3,000	8,500	11,500	7,000	3,000	10,000
1931	7,680	2,500	9,500	12,000	5,000	6,000	11,000
1932	7,645	2,500	9,500	12,000	5,000	6,000	11,000
1933	7,725	2,500	9,500	12,000	5,000	6,000	11,000
1934	7,900	2,500	9,500	12,000	3,000	9,000	12,000
1935	8,200	2,500	12,000	14,500	3,000	10,500	13,500
1936	8,600	2,500	12,000	14,500	2,500	12,000	14,500
1937	9,300	1,500	12,000	13,500	1,500	13,500	15,000
1938	10,200	1,500	14,500	16,000	1,500	15,000	16,500
1939	11,000	1,500	14,500	16,000	1,500	15,000	16,500

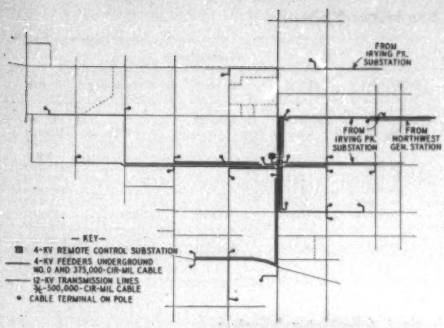


Fig. 4. The 4-kv radial plan of supply to area as developed at end of tenth year (1939)

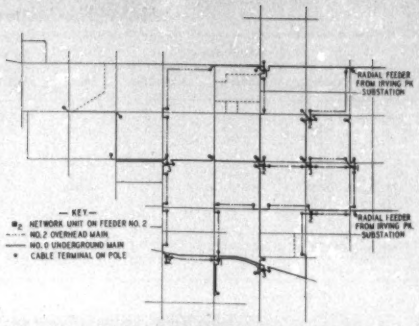


Fig. 6. The 4-kv mains for primary network plan of supply to area as developed at end of tanth year (1939)

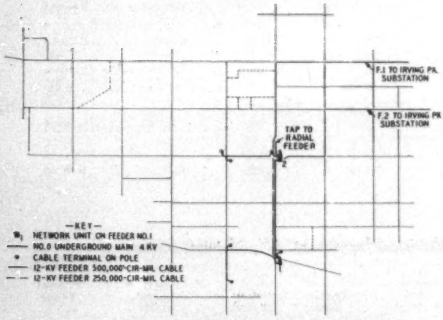


Fig. 5. First year (1930) of development of primary network plan of supply to area showing new network units and feeders superimposed on radial system shown in Fig. 2

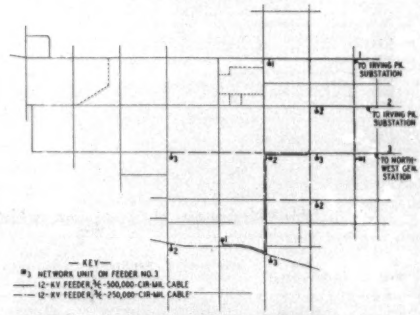


Fig. 7. The 12-kv feeders for primary network plan of supply to area as developed at end of tenth year (1939)

in the area for a somewhat longer period than would be customary otherwise. However, unexpected local development required the installation of another 1,000 kva feeder in the second year. No further reinforcement was found to be necessary until the sixth and ninth years, in each of which a 2,500 kva feeder is installed. Of the 7 feeders originally supplying the area, 4 were removed in the first year and one in the seventh year. In addition, about one-half the capacity of one feeder was released for use outside the area in the second year. The new substations and 4-kv feeders in service at the end of the tenth year are shown in Fig. 4. The net amount of feeder capacity in service in any year is shown in Table IX.

The original transformer installation in the new substation consisted of 2 5,000-kva, 3-phase units, the supply to which was from 2 12-kv transmission lines. In the fifth year of the program a third 5,000 kva unit was added, and in the eighth year an additional 12-kv transmission line to the station was necessary.

Network System. The plan followed with this system was to provide capacity in the form of network units as required, utilizing the original radial feeder capacity in the area to as great an extent and as long as possible. Consequently, only 2 units and 2 12-kv transmission lines were installed the first year of the program. (See Fig. 5.) Following this, 2 units were installed in the second year, 2 in the fifth year, and 1 each in the sixth, seventh, eighth and ninth years. A third transmission line was required in the eighth year. In carrying out this development 2 radial feeders were removed in the second year, 2 in the fifth year, and 1 in the eighth year. In addition, about one-half the capacity of 1 feeder was released for use outside the area in the seventh year. The units and principal mains in service in the tenth year are shown in Fig. 6, and the 12-kv feeders are shown in Fig. 7. The combined

network and radial feeder capacity in service in any year is shown in Table IX.

Discussion of Results

Although the total normal capacity in service on the 2 systems is different in various years, generally speaking the firm capacity of the 2 is the same. This apparent discrepancy is due partly to the inherently different availability of reserve on the 2 systems.

Comparison of the various investment items in the 2 plans shows that the investment in distribution cable for the network is much less than for the radial system. The difference in the 2 is about balanced, however, by the additional cost for transmission cable on the network system, which represents the primary laterals for the purpose of supplying the scattered network units. These primary laterals perhaps could be regarded as distribution cable with some justification, but here are classed as transmission. The fact that the distribution conduit in the 2 schemes is about the same while the distribution cable is much less in the case of the network is due to the fact that on the network plan no attempt was made to distinguish between conduit occupied within the area by network mains and that occupied by primary laterals, all such conduit being classified under distribution.

Conclusions

The analysis shows that, for the conditions upon which this study was based, the net new investment and accumulated fixed charges for the extension of the radial system are less than they would be for the provision of the necessary reinforcement by means of a primary network.

Although there is some reason to believe that the primary network provides slightly better service continuity when fully developed than does the radial system, the improvement does not seem to warrant the additional investment involved. The other factors, such as the uncertain period of development and experimentation in service before its full advantages may be realized, and the multiplication of public relations problems due to occupying many substation sites, detract from the desirability of the network system. It is, of course, recognized that for certain load densities and rates of growth, or in comparison with some other existing systems, the primary network might have an economic advantage.

Electrical Equipment for Induction Furnaces

By
C. C. LEVY
ASSOCIATE A.I.E.E.

Westinghouse Elec. & Mfg. Company, E. Pittsburgh, Pa.

Although frequencies now are standardized in the melting field and soon will be in the heating field, most types of furnaces require special equipment. The electrical equipment discussed in this paper includes the frequency converters, the switching, and the capacitors. Typical installations are shown and the advantages and possibilities of water-cooled equipment are mentioned.

THE APPLICATION of the inductive method for heating or melting requires electrical equipment of somewhat special character. Normal frequency supply cannot be used economically except in a few instances. Furthermore, the induction furnace is essentially a single phase load. For these reasons a motor-generator set is necessary in most cases, although some "core" type furnaces and furnace of the spark gap oscillator type can be connected to the normal frequency supply lines. In spite of the drawback of special and consequently more expensive electrical equipment, the use of induction furnaces has spread rapidly. This type of furnace has many advantages, particularly in the field of special alloy steels. Its basic principles, its design and practical applications have been discussed fully in previous papers and current literature. (See bibliography at end of paper.)

Full text of a paper recommended for publication by the A.I.E.E. committee on electrochemistry and electrometallurgy, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 22–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 16, 1933. *Not published in pamphlet form.*

Classification of Furnaces

There are 2 commercial types of induction furnaces: (1) the "core" type and (2) the "coreless" type. The first type uses a core of transformer iron for the magnetic circuit, whereas the second type (Fig. 1) has no closed magnetic circuit of iron. The core type either uses normal frequency or subnormal low frequency and a strong magnetic field while the coreless type uses a weak magnetic field but high frequency. The coreless type may be supplied by rotating generating equipment or by static high frequency spark gap or vacuum tube oscillator equipment. The core type also needs rotating

generating equipment for low frequency although normal frequency furnaces have been designed. The chief objection to the use of normal frequency is the violent stirring of the charge due to the action of electromagnetic forces. Because of the expense involved in large capacity low frequency generators, and the necessity for preventing freezing of the charge in the furnace the core type of furnace now is confined chiefly to the non-ferrous field and most of the ferrous melting installations are of the coreless type.

The coreless induction furnace is subdivided further by the range of high frequency employed and the apparatus used for generating it. When capacity exceeds 50 kw for melting applications 960 cycles is the standard frequency, although 480 cycles was used in earlier installations. For the smaller melting and heating capacities the spark gap oscillator or the vacuum tube oscillator is best fitted to furnish frequencies of the order of 20 kilocycles and higher which then can be used economically. Theoretically frequencies of this order could be used to advantage in the large capacity units also but the expense of the special rotating equipment needed would not be justified.

In heating applications the range of desirable frequency will be greater because of variation in the dimensions of the charge, and the conditions under which the heat energy must be applied. The power absorbed by the charge is proportional to the frequency used and the square of the ampere turns of the inductor coil, while the minimum frequency for effective transfer of energy to the charge is a function of the diameter of the charge and its resistivity.

Fig. 1. Two 600-lb coreless furnaces powered by a 300-kw 960-cycle generator

For these reasons the frequency used in many cases will be a compromise between the economic and the theoretical best frequency. Obviously the use of many different frequencies would not be practical because of the additional expense required for each generator. For such heating applications where normal frequencies cannot be used it is likely that 360 or 480 cycles in the lower ranges and 4,800 or 5,000 cycles in the higher ranges will become standard.

Because no new principle is involved but only a difference in temperature range and operating methods, the equipment described includes heating as well as melting applications.

The electrical equipment includes:

1. Motor-generator frequency converters.
2. Control panels for both motor and generator.
3. Capacitors for correction of furnace power factor.
4. Control and switching of capacitor units.
5. Miscellaneous equipment, such as inductor tap switches.

Frequency Converters

The single phase generators of these converters usually are driven by standard induction motors or synchronous motors. If the drive is synchronous 2

Fig. 2. Rotor of 300-kw 960-cycle single-phase salient pole generator

Fig. 3. Stator of 300-kw. 960-cycle single-phase salient pole generator

exciters are required, one for the generator and the other for the motor.

From the designers' standpoint the generator is a special one because the large number of poles even at the highest speed allowable results in special construction, and affects the electrical characteristics of the design. The rotor of a 300-kw generator illustrated in Fig. 2, in appearance resembles the rotor of a wound rotor motor. The poles, however, are well defined salient poles. Special construction is needed because of the very small pole pitch. The cap screws are passed through each end of the coil as it projects from the rotor; at each end of the rotor these screws are threaded into a plate which is fastened securely to the rotor spider.

Since the number of slots per pole is so low, the stator reactance is comparatively large, which results in increased field current. It is for this reason that designing these machines (Fig. 3) for any power factor other than unity becomes uneconomical. Another special feature inherent to this type of design is a comparatively large ratio of core length

to pole pitch. This makes ventilation a more difficult problem. For this reason the ventilating system differs from that used for normal frequency generators. The ordinary arrangement is to have air coming from each end between the field poles and

Fig. 4. Two 60-kw 3,600-rpm 4,800-cycle single-phase inductor type water-cooled generators with induction motor drive

discharging through stator vents. On these machines, however, it is necessary to bring air through ducts in the rotor because the space between field poles is far too small for that purpose.

Machines usually are built open, depending upon the normal ventilation of the room in which the machine is located. In some cases where the substation is small or the air not clean special precautions must be taken to supply the machines with clean air under slight pressure or supply forced ventilation. In such cases a machine totally enclosed with built-in circulating system and provision for cooling the circulating air by water may prove more economical and satisfactory than systems of substation ventilation, particularly if the air has to be cleaned as well as cooled.

When higher frequencies such as 4,800 or 5,000 cycles are required, the inductor type of generator design, which involves no windings on the rotor, can be used. Due to the absence of pole windings space limitation which hampers the salient pole design is removed, and the requisite number of poles can be obtained for the high frequency needed, without exceeding allowable peripheral speeds. Two generators of this type are shown in Fig. 4. The machines are enclosed, and water cooling provided to remove the heat losses from both stator and rotor.

The fundamental construction of the generator is shown schematically in Fig. 5. The rotor is a solid cylindrical disk pressed on a supporting spider. The surface of the rotor is slotted so as to cause a nearly sinusoidal variation in the field flux, with the required frequency. The field is wound in a slot between the 2 inner frames, and is covered by the outer frame. The stator core is cooled directly by imbedded water pipes, while the heat from the rotor is extracted by the circulating air which in turn is cooled by 2 circular water cooling coils at each end.

Also, the enclosing end bells serve materially to reduce the noise usually associated with the open type high frequency generator. The efficiency of these high frequency generators is lower than 60-cycle units of corresponding capacity. This is due to higher iron and load losses. Comparative ef-

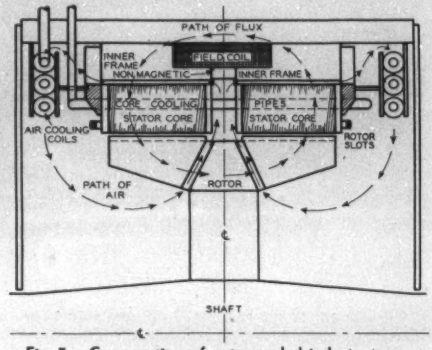


Fig. 5. Cross section of water cooled inductor type generator

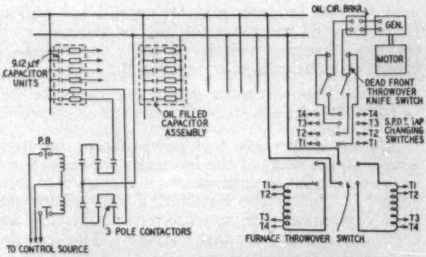


Fig. 6. Main connections for 2 induction furnaces operating from a single generator and capacitor bank

The triple series contactor shown simply represents the use of 3 550-volt units assembled for 1,250-volt service

ficiencies could be obtained only by a greater increase in the cost than is economically justifiable.

Control Panels

The control for these motor-generator sets is very simple. The metering equipment includes alternating current ammeter, wattmeter, voltmeter, and power factor meter designed and calibrated for the frequency used. A direct current field ammeter, automatic voltage regulator, field switch, generator oil circuit breaker, and overload relay complete the equipment generally used. When 4,800 cycles

is used the field switch is replaced by a field contactor to permit "killing" the field of the generator when the overload relay operates, since an oil circuit breaker for this frequency would have to be specially designed.

Fig. 7. A 900-volt 960-cycle 9.12-μf oil-filled capacitor unit

Adjustment of the generator voltage sometimes is needed to control the power input. This may be done readily by a voltage adjusting rheostat on the regulator. However, for any particular heat cycle, adjustment of power input can be made by changing the inductor taps. Hand operated switches are used for this purpose, and by special interlocking the voltage on the generator can be reduced while the tap changing switch is being operated. A typical installation is shown in Fig. 6.

Capacitors

Because of the very low power factor (approximately 10 per cent) of the induction furnace, power factor correction equipment is a necessary and most important part of the installation. Capacitors are more economical than synchronous condensers and invariably are used for this purpose. The equation

$$\text{Kva} = \frac{2\pi f\, CE^2}{10^9} \qquad (1)$$

indicates that the kilovoltampere rating of a capacitor increases directly with the frequency. That is to say, a 5-kva, 60-cycle unit will deliver 80 kva on 960 cycles at constant voltage. Over the range from 60 to 960 cycles the power factor and dielectric strength are substantially constant so that although the losses will increase in proportion to the increased rating, it is possible by special design and suitable cooling to remove them at a rate that will keep the temperature rise of the dielectric within a satisfactory limit of 25 deg C.

Above this range of frequency several important considerations limit the application of this equation to determine the rating.

1. The power factor increases, and therefore the losses no longer increase at a linear rate with the frequency.

2. The dielectric strength tends to decrease so that at 2,000 cycles it is about 70 per cent of its value at 60 cycles.

3. No matter how effective the heat transfer from the case of the unit may be, nor how careful a design is made the temperature gradient in the dielectric becomes too great and temperature rise exceeds a safe working value. It is desirable, therefore, for frequencies in excess of 1,000 cycles to derate the capacitor to allow for these conditions.

In actual practice, the standard oil-filled 9.12-μf, 900-volt unit is rated at 45 kva on 960 cycles. This unit is mounted with several others in an oil filled tank, with water cooling coils for removing the heat from the oil. The complete battery of capacitors consists of a number of these water-cooled tanks

Fig. 8. Typical induction furnace installation: (left) the motor-generator set, motor control panels, and water-cooled capacitor assembly; (below) furnace and control

mounted as close as possible to the furnace. Some of the important features of construction used in making this unit are:

1. The use of aluminum foil 0.00033 in. thick.

2. The foil is extended $^1/_2$ in. beyond the ends of the paper instead of buried in the paper as in the ordinary type of construction, the $^1/_2$ in. extension of the foil serving as a cooling fan.

3. The unit is built in 2 sections as shown in Fig. 7 separated in the middle to form a vertical oil passage, the 2 sections then are connected in series. This construction serves to distribute the heat conducting material through the dielectric.

4. Special precautions are taken to carry the heavy currents by riveting and soldering the terminal leads to the foil extensions.

The rest of the construction follows standard practice for power type capacitors, the sections being wound and heat treated in special vacuum dehydrating furnaces before impregnating in oil. Future possibilities are improvements in the construction and cooling methods and materials of impregnation, so that it is quite possible that further economies in application of these units may be effected.

The power factor of the furnace varies considerably during a heat cycle and provision must be made for increasing the number of capacitor units as the heat progresses. Table I illustrates the variation in voltage applied to the furnace by change in the inductor tap switches. It shows also the variation in the number of capacitor units connected in parallel with the furnace inductor and the kilovoltamperes per unit at different parts of the heat cycle.

Table I—Heat Cycle of a 1-Ton 300-Kw 960-Cycle Furnace

Time	Gen. Volts	Gen. Amp	Gen. Kw	Gen. % P. F.	Cap. Volts	No. Cap.	Cap. Unit Kva	Furn. Taps
1:10	800	420	315	96*	1250	36	84	2-3
1:17	805	300	230	100	1260	43	86	2-3
1:22	780	340	260	100	1090	43	64	2-4
1:27	800	340	260	98.5†	1120	43	68	2-4
1:32	795	345	260	98	1115	43	67	2-4
1:37	800	365	280	100	1120	43	68	2-6
1:42	800	390	300	98.5†	1020	45	56	1-3
1:45	800	390	300	98+	930	49	47	1-4
1:48	810	405	320	97.5†	945	50	48	1-4
1:53	795	410	310	100	930	55	47	1-4
1:58	800	420	320	98†	930	56	47	1-4
2:07	800	430	330	98†	930	56	47	1-4

* Leading power factor.
† Lagging power factor.

The general arrangement of an induction furnace installation is shown in Fig. 8. The small brick building houses the motor-generator set, while the control panel is shown inserted in one side of the front wall. There are 2 furnaces 1 on each side of the substation building.

Fig. 9. Installation of water-cooled conductors

The miscellaneous equipment such as furnace tap switches and bus connections are of special interest only in installations where large currents are involved. In one large installation the currents between the condenser bank and the furnace were more than 12,000 amperes. A normal type of construction was out of the question because of the inductive reactance of multiple conductors required for such currents. An extremely neat and clever solution of the difficulty was worked out by the use of water-cooled conductors (Fig. 9). The conductors consisted of water-cooled tubes and high current density so that only a few conductors were required.

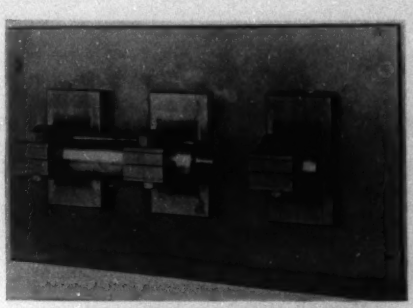


Fig. 10. Water-cooled switch unit

Figure 10 shows a water-cooled switch unit which could be used to great advantage in a layout such as that illustrated in Fig. 9 where the use of the ordinary type of knife switch made it necessary to spread the conductors. With a switch like the one illustrated a far more compact installation is possible and inductive drop can be greatly reduced. Judging from the past growth of this type of furnace, larger installations may be expected in the future, and designers will have to consider the problems of generating and transmitting large currents at high frequency. For transmitting, water-cooled conductors undoubtedly will answer the purpose; special methods of connection will have to be used in generation.

Parallel operation of generator units is perfectly feasible, so that there is no reason from the electrical equipment standpoint, why larger installations than those already existing cannot satisfactorily be supplied with energy at high frequency.

Bibliography

1. Power Problems in High Frequency Melting, E. F. Northrup. *Iron Age*, v. 127, No. 4, Jan. 1931.

2. Tonnage Melting by Coreless Inductor, E. F. Northrup. *Fuels and Furnaces*, v. 9, Nos. 4 to 9.

3. Typical Installations of Coreless Induction Furnaces, E. F. Northrup, *Iron Age*, v. 127, No. 5.

4. Electrical Apparatus for the Coreless Induction Furnace, N. R. Stansel. *Iron and Steel Engr.* v. 7, No. 11, Nov. 1930.

5. Electric Heating by Ironless Induction, E. F. Northrup. *General Electric Review*, Nov. 1922.

6. A High Frequency Induction Furnace Plant for Manufacture of Special Alloys, P. H. Brace. A.I.E.E. Trans., Sept. 1925, p. 849.

7. Induction Melting of Alloy Steels, H. H. MacKusick. *Electrical World*, July 30, 1932.

8. Producing Sheets and Alloys in Coreless Induction Furnaces, R. N. Blakeslee. *Steel*, v. 91, No. 4, July 25, 1932.

9. Ajax-Wyatt Vertical Ring Induction Furnace, W. Adam. *American Electrochem. Soc. Trans.*, v. 57, May 29–31, 1930.

10. Coreless Induction Furnace in Steel Industry, E. F. Northrup. *Iron and Steel Engr.*, v. 8, No. 5, May 1931.

Automatic Reclosing of Oil Circuit Breakers

Solutions for various problems encountered in connection with the automatic reclosing of oil circuit breakers are given in this paper. The results of studies made by several companies, and a brief description of devices for this type of service, also are given.

By
A. E. ANDERSON
ASSOCIATE A.I.E.E.

General Elec. Co.,
Philadelphia, Pa.

THE APPLICATION of automatic reclosing to oil circuit breakers covers a period of about 12 years. Although there are a few scattered applications antedating this period, and such applications have been duly recognized, nevertheless the broader and more general use of this type of switchgear may be said to have its inception around 1921.

It is estimated that the rated load handled by this type of equipment (in this country) is in excess of 10,000,000 kva, this figure representing over 50 per cent of the installed capacity of automatic switchgear. The advantages gained were at once apparent and the extent of the installed capacity is indicative of the industry's reception of this development. A majority of the applications fall in the 2,300–4,600 volt class, with a maximum of 154 kv. Practically all applications have been on stub or radial feeders, and as this type of feeder is typical, this paper is confined to stub feeder application.

Full text of a paper recommended for publication by the A.I.E.E. committee on protective devices, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 24, 1933. *Not published in pamphlet form.*

A greater part of the earlier installations was made on feeders on which lighting load predominated. A commonly accepted reclosing cycle was 15-30-75 sec, this cycle continuing in use up to the present time. The 15-sec interval was an arbitrary choice, and represented a marked improvement over previous manual reclosing, sufficing as a minimum value for several years. The remaining intervals also were arbitrarily chosen, with some consideration toward lessening the duty on the oil circuit breaker in case of successive operations.

Occasionally the question is raised concerning the possibility of automatically measuring the impedance of an a-c feeder, in order to determine whether or not the breaker should reclose. This method has been used for a number of years on d-c railway and industrial circuits. Such equipment for a-c circuits, has been built and tested but the results were not successful from an economic point of view due to a number of reasons. First, a large part of the load on the conventional a-c circuit consists of lamps, whose "cold" resistance may be only 10 per cent of the "hot" resistance. If a small load indicating or load measuring current is used, it is difficult to distinguish the difference between a short circuit and useful load. Another requirement is the detection of high resistance cable faults or defective insulators which may not break down until practically normal voltage is reached, subsequently developing into faults of low impedance. Although the measuring current and voltage may be increased, the few additional advantages do not warrant the increase in cost over the simple equipment which recloses the breaker, regardless of circuit conditions.

Operating experience over several years has indicated the practicability of reclosing the a-c feeder breaker without the use of load indicating equipment. Soon after a-c reclosing equipment began to be applied more generally, it was found that from 75 to 90 per cent of the breaker openings were caused by transient faults that disappeared after the first, second, or third opening.

Delayed Versus Immediate Initial Reclosure

During 1931 the Alabama Power Company, Georgia Power Company, Tennessee Electric Power Company, and the West Penn Power Company made a systematic study of the percentage of successful reclosures utilizing time delay. This study was made on overhead transmission feeders, from 2.3 to 110 kv, with reclosing cycles in the range of 15, 45 to 60, and 60 to 120 sec. During this period approximately 2,900 initiating operations were observed (initial breaker trip-out starting a reclosing cycle, which continues until successful reclosure or lockout) with the following percentage of successful reclosures and lockouts:

Reclosure	*Breaker Remained Closed*
First	86.9%
Second	3.4%
Third	0.9%
Lockout	8.8%

The time delay, before reclosure, for general application was governed largely by breaker derating

factors and only in a few isolated cases, such as allowing time for synchronous or other machinery to become disconnected, were load requirements given the consideration that would lead to better service.

During 1932 the first 3 of the companies mentioned conducted another general investigation, during which period there was recorded the results obtained from the operation of a large number of feeders, ranging from 2.3 to 66 kv, and equipped for immediate initial reclosure, that is, without any purposely added time delay. Over 1,600 initiating operations took place during this period with the following results:

Reclosure	*Breaker Remained Closed*
First	73.3%
Second	15.9%
Third	2.8%
Lockout	8.0%

The reclosing cycles used during this period were:

0– 15–120 sec
0– 60– 60 sec
0–120 sec (no third reclosure)

Although the percentage of successful first reclosures was less with immediate reclosure, actually it meant that 73.3 per cent of the faults did not develop interruptions to service from the consumer's point of view, and that 18.7 per cent were considered interruptions, in addition to 8 per cent lockouts, as contrasted with 91.2 per cent interruptions in addition to 8.8 per cent lockouts, where a time delay of 15 sec or more was used for the initial reclosure.

On the Georgia Power Company's system, practically all feeder and many tie line (44 kv and below) breakers have been equipped with the 0–15–120 sec reclosing cycle. The record of 1,010 initiating operations, during 1933, is given in the following:

Reclosure	*Breaker Remained Closed*
First	88.7%
Second	4.5%
Third	1.3%
Lockout	5.5%

The above data mark an improvement over the 1932 performance record and are attributed largely to more alert inspection and maintenance of lines and breakers, better tree trimming and improvement in automatic reclosing devices. The trend in improved operating service is evident readily upon consulting these tables.

The values in the foregoing tables show that the percentage of successful third reclosures forms, in general, an appreciable quantity in comparison with the percentage of lockouts. In other words, if the third reclosure had been omitted it would have increased the lockouts by approximately 25 per cent. Furthermore, the third reclosure can be obtained in the conventional design of a-c reclosing relay with practically no additional expense or complication.

Factors to Be Considered in Connection With Immediate Initial Reclosure

The improvement in service resulting from the use of immediate initial reclosure cannot be obtained without first taking into consideration some conditions which were of secondary importance when time delay initial reclosure was employed. These factors are given in the following paragraphs:

Cause of Outages. A greater portion of the faults on overhead a-c distribution systems are of a transitory nature. The usual types of faults are insulator flashovers, swinging faults, and short circuits. When flashovers occur, the fault may be cleared by removing the voltage long enough to extinguish the arc and to be certain that the arc path has recovered its dielectric properties. In the case of a swinging fault there also is a reasonable chance that the fault can be removed by opening and quickly reclosing the circuit breaker. (Some swinging faults may persist longer than the initial reclosing period, and therefore will require the second reclosure.) Short circuits of a permanent nature are the most probable cause of lockouts.

Primary distribution lines of 2,300 to 4,600 volts constitute a very substantial part of the total distribution system. It has been found that wind, sleet, trees, lightning, public interference, and foreign lines account for a high percentage of outages to the consumer, due to the comparatively high exposure of the lines to these conditions. Consequently it can be seen that proper sectionalizing plus automatic reclosing can improve the service now obtainable under multicircuit grouping.

Induction and Synchronous Motor Load. During the period that the fault exists on the feeder and the circuit breaker is in the open position, any motor connected to the feeder will, in all probability, be operating at reduced or zero voltage. This will retard the speed and may be ruinous to certain products. Even though the product is not affected, there may be cases where the motor cannot return to normal speed when the feeder voltage is restored. In many cases the products are not affected and intervals of 2 to 4 sec have been encountered without ill effect.

Generally speaking, induction motors will return to normal speed from any reduced value, inasmuch as their load usually is connected directly from standstill to normal operating speed. However, the longer the deënergized period the greater the decrease in speed, resulting in higher inrush current, which, at its poor power factor, gives a greater amount of line drop, and subsequent delay in returning to normal operating voltage.

Synchronous motors will not necessarily pull their load back to normal speed after a voltage interruption. Their ability to return to normal speed under this condition depends largely on pull-in torque and load characteristics. Those motors (50 to 60 per cent) that can resynchronize under load from any decrease in system voltage or from subnormal speed, will, in all probability, require automatic field removal and resynchronizing equipment. Such equipment is readily available. Those motors (40 to 50 per cent) that cannot resynchronize due to torque or load characteristics will require, in addition, suitable unloading features. Although in some cases synchronous motors have remained connected, after an interruption, without the use of the above equipment, such cases usually can be accounted for by certain load conditions or the presence of sufficient reactance in the system to absorb the out of

phase current. Synchronous motors (due to a small amount of stored energy) pull out of step rapidly, under conditions of reduced voltage, when carrying full load. Under this condition they can stand complete loss of voltage for only 2.5 to 5 cycles and still remain in synchronism. The restoration of normal operating voltage within this extremely short period is not available with present equipment. Furthermore, a period of 2.5 to 5 cycles, without voltage, may not be long enough to allow the dielectric in the path of the fault to recover its insulating properties to a degree that will permit successful reestablishment of normal operating voltage.

Synchronous motors (and condensers) tend to maintain arcs caused by the fault. Obviously the duration of these arcs will affect the choice of a suitable reclosing interval. Field tests and operating experience will be required before the effects of this characteristic on the general problem are fully known.

Lighting Load. Lighting load imposes no serious problem in connection with immediate reclosing. A reduction in the period of outage from a number of seconds to a second or less, will be of mutual advantage to the consumer and operating company.

Undervoltage Devices on Motor Controllers. Practically all motor controllers are equipped with some form of undervoltage protection; and, if service conditions are to be improved by quick reëstablishment of voltage, these devices must not disconnect the motor controller during the reclosing period. Instantaneous undervoltage devices, as a class, will not fulfill this requirement, since they will drop out within a few cycles after voltage has decreased below their drop-out value. Time delay undervoltage devices are required in order to take full advantage of the immediate initial reclosing cycle. The available timing interval of the undervoltage device for use with immediate reclosure should be long enough to overlap (1) the duration of the fault (which may decrease the voltage to something below the drop-out value of the device), (2) the time the breaker is open, and (3) the time it may require system voltage to return to at least the pick-up value of the device. In many cases normal voltage returns immediately with the closing of the circuit breaker, but there are cases where long lines coupled with heavy inrush current at a lagging power factor delay the return of the voltage to its normal value. A suitable drop-out value may reduce somewhat the required time delay but care must be taken to see that this value is not so low that other operating characteristics of the device are sacrificed.

A general consideration of this problem, together with a limited amount of operating data, has indicated that a device providing a time delay of 1 to 3 sec, after complete removal of voltage, will be suitable for a majority of these applications.

Oil Circuit Breakers and Mechanisms. Although oil circuit breakers are used in a very large portion of a-c reclosing equipments, nevertheless air circuit breakers have been used in this manner, principally on low voltage circuits. The general features mentioned in this paper in connection with oil circuit breakers apply equally as well to air circuit breakers.

Oil circuit breakers and mechanisms are available having minimum operating times (from energizing the trip coil to closing the breaker contacts) in the order of 30 to 80 cycles, on a 60-cycle basis, depending on the type and rating of the oil circuit breaker

Table I—Oil Circuit Breakers—Proposed Duty Cycles and Interrupting Ratings

No. of Groups	Total Number of Operating Cycles	Per Cent of Standard Ratings				
	Successive OCO Operations With 15-Sec Interval	0 to 5,000 Amp	5,001 to 10,000 Amp	10,001 to 20,000 Amp	20,001 to 40,000 Amp	40,001 and Above
	2	100	100	100	100	100
	4	95	95	90	85	80
	8	85	80	70	55	50
	16	75	65	50	35	
Groups of 2 OCO Operations 0 time between operations 2-min interval between groups						
1	2	90	85	75	65	60
2	4	80	75	60	45	
4	8	70	65	50	35	
8	16	60	55	40	25	
Groups of 4 OCO Operations with 0-15-60-sec time intervals. Two-min interval between groups						
1	4	85	80	65	50	
2	8	75	70	55	40	
4	16	65	60	45	30	

Fig. 1. Reclosing relay modified to permit immediate initial reclosure, showing contacts in the latched position

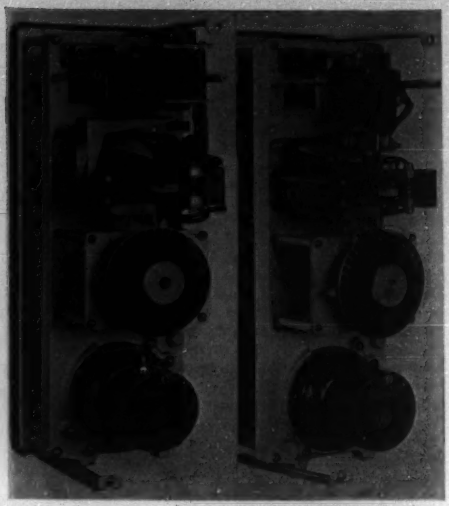


Fig. 2 (left). Reclosing relay available with provision for immediate initial reclosure showing front contact (for reclosing) and second contact (motor circuit) latched and ready for immediate operation

Fig. 3 (right). Reclosing relay without provision for immediate initial reclosure

and the form of mechanism. Generally speaking, the shorter times are obtained in connection with breakers of lower voltage ratings operating by solenoid mechanisms.

In Table I there is given a group of duty cycles and interrupting ratings, for use with oil circuit breakers, as proposed by a Joint Committee of the Edison Electric Institute, Association of Edison Illuminating Companies and the National Electric Manufacturers Association. This table includes a variety of reclosing cycles; it is evident that the trend is toward sanctioning higher interrupting duties for reclosing service. A comparison between this and similar data in use for the past 5 or 10 years will readily indicate this feature. It will be evident that suitable consideration has been given to the immediate initial reclosure, which has been incorporated in over 60 per cent of the duty cycles.

Those operating companies who have applied the immediate initial reclosure followed by 1 or 2 time delay reclosures report that the maintenance on the oil circuit breaker was not greater than that required where time delay reclosures were used throughout.

Due to the fact that trip free mechanisms utilize a latch that must reset before the closing force is applied to the breaker, it is necessary to make certain that the latch has reset before the closing effort is applied. Most available mechanisms of this type require a latch checking function. A time delay device can be used for this purpose, but such a device must have a setting long enough to take care of the various limiting conditions, such as those due to seasonal variations, and variations in operating voltage, thereby preventing the minimum time from being obtained under the more advantageous conditions. A switch in the reclosing circuit and actuated by the latching mechanism allows the shortest delay and is independent of temperature or operating voltage. This switch is adjusted to make its contact as late in the latch resetting motion as is consistent with dependable operation, and usually is connected (as shown in Fig. 4) so that its time of operation parallels that of the reclosing device. In this way the times are not additive, but are determined by the longer of the two, which usually is that of the latching mechanism. Trip free mechanisms incorporating latches with suitable resetting speeds, do not require the latch checking function.

Protective Relay Considerations. In the application of immediate initial reclosure, consideration must be given to the protective relay system. First, circuit closing protective relays must open their tripping contacts, with some safety factor, during the de-energized period. Most overcurrent relays of recent manufacture readily will meet this requirement. Some of the older types which require a comparatively long time to reset, can be modified readily to give the desired quick-resetting feature.

The selectivity of the relay system must not be upset in the case of immediate reclosure on a persisting fault. In the circuits under consideration, selectivity is obtained mostly by time differentials. The time interval between cascaded relays must be long enough to permit 2 operations, in rapid succession, of the breaker feeding directly into the fault, without the unnecessary tripping of other breakers. In many cases the protective relay has to be selective with respect to high tension transformer fuses. Applications of this type require careful coördination between the relay and transformer fuse characteristics.

As a conservative guide the spacing between successive relay times should be at least twice the time required for the breaker to clear after the trip coil is energized. The actual interval used may be reduced, depending on the length of time the circuit is open and the speed with which the relays reset. A tabulation of existing practice would be a valuable guide to operators intending to install equipment incorporating immediate initial reclosure.

Reclosing Devices Available

There are several solutions of the various problems that enter into the design and application of a-c reclosing devices. Some of the available devices have common characteristics, while others differ quite radically. In the following paragraphs there is included a brief description of a group of devices that are available for this class of service. Each of these devices has certain limits of application, as indicated in the text, and the group as a whole should be considered as being typical or representative of their class of control devices.

The electrically operated devices available for producing the required reclosing impulses, while naturally differing in detail, consist of the following elements: release mechanism; timing mechanims; contacting mechanism; antipump means; and lock-out means.

When conditions on the feeder circuit are normal and no operation of the device is required, the recloser

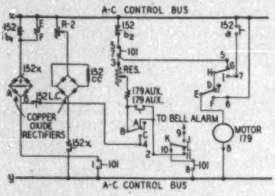


Fig. 4. Circuit for immediate initial reclosure (a-c control). Devices shown in position following opening of oil circuit breaker but prior to immediate reclosure

When breaker trips 152 b-2 closes, energizing 179 auxiliary ("anti-pump" or "set-up" relay) releasing *BA* and *ED* and closing *BC* and *EF;* 179 auxiliary closes and seals itself in. *BC* in closing completes circuit to 152-*X* and its rectifier, through latch—checking switch. Then 152-*X* picks up, energizing 152 closing coil through its rectifier. *EF* in closing seals motor circuit to *X*

is held in its so-called normal position (ready to operate) either by a mechanical stop or by an open contact in its operating circuit. The closing of a "b" auxiliary switch on the circuit breaker, energizes the release mechanism, thereby placing the recloser in operation.

The timing mechanism ordinarily consists of a motor driving a contacting mechanism through a suitable gear train. The contacting mechanism usually consists of 2 sequentially operated contacts—the first closing the circuit to the "set-up" or "anti-pump" relay which seals itself in through the "*b*" switch—the second contact completes the closing circuit of the breaker through the set-up relay contacts. Provision is made for a maximum of 3 reclosures with the time between operations individually adjustable.

The closing of the oil circuit breaker, following the operation described for the timing mechanism, releases the set-up relay. In this way "pumping" of the breaker is prevented as the sequential operation of the contacts must be repeated before another closing impulse can be given.

The lock-out means stops the recloser after the third successive operation if the breaker fails to remain closed. The recloser may be arranged to be reset to normal by hand or it may be arranged to reset itself automatically by the subsequent reclosure of the breaker.

In general, with the reclosing equipments, the control switch associated with the circuit breaker should have extra contacts for preventing operation of the recloser when the circuit is being controlled manually.

(*1*) *Modifications in Existing Reclosers Giving Immediate Initial and Subsequent Time Delay Reclosures.* Most of the reclosers furnished until recently could be adjusted for a minimum delay of 1 to 3 sec for the initial operation; usually this is not fast enough where immediate reclosure is desired. Some early reclosers can be modified so as to be suitable for immediate reclosing duty. In one case, the first of the sequentially operated contacts is latched closed at the normal position. With this arrangement the opening of the breaker through its "b" switch immediately energizes both the release and the antipump relay. The release magnet starts the timer and simultaneously the contact latch is released, permitting the closing circuit to be made. The arrangement is such that immediate initial reclosure may be used or not, as desired. Details of the construction are shown in Fig. 1.

(*2*) *Modern Reclosers With or Without Immediate Initial Reclosure and Subsequent Time Delay Reclosures.* A more modern recloser available to give immediate reclosing or not, as desired, is shown in Fig. 2. A modification which only permits reclosing after approximately 1 sec is shown in Fig. 3. In both of these motor-driven devices, normal and lock-out positions are determined by cam-operated con-

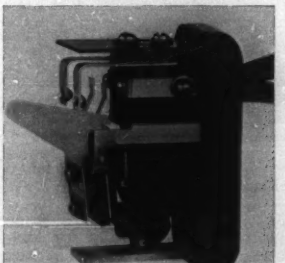


Fig. 5. Relay for 1 immediate reclosure (for attended stations) shown in normal latched position

tacts, which transfer the motor circuit to auxiliary switches on the breaker, at proper points in the reclosing cycle.

In the normal position, the recloser motor circuit is complete except at the breaker "b" switch. As soon as the breaker opens, the "b" switch closes (see Fig. 4) and starts the device, transferring this circuit direct to the supply. Near the lock-out point the motor circuit is transferred from direct supply to a connection through an "a" switch. If the breaker is in the closed position, the recloser continues to the normal position at which point the motor circuit is transferred up to the "b" switch and stops in the normal position, ready for another reclosing cycle. When the breaker remains open, the recloser stops in the lock-out position and remains there until the breaker is reclosed.

In the immediate reclosing form, the motor control contacts are latched closed on *DE* and the reclosing contacts on *AB*, as shown in Fig. 4. When the release coil (179 auxiliary) is energized, the latch is broken and contacts *EF* close connecting the motor directly to the line. Simultaneously, contacts *BC* close, energizing the breaker control relay. The

mechanism is so arranged that the immediate reclosure may be changed to time delay simply by the adjustment of the contact arms.

(3) *One Shot (Immediate) Recloser for Attended Stations.* In stations where operators are available, a great improvement in service is possible by applying a recloser for 1 operation and leaving resetting and subsequent reclosing to the operator.

A simple and inexpensive relay giving 1 immediate reclosing impulse is shown in Fig. 5, which also shows the relay held by its latch in its normal position, with both contacts open. The closing of the breaker "b" switch energizes the reclosing relay coil and the armature picks up to close the contacts, which in turn close the breaker. At the same time the relay latch is released. When the breaker closes, its "b" switch opens and the reclosing relay armature falls to the fully open position. From this point it cannot be picked up electrically, but must be returned by hand to its normal position, thus providing the required anti-pump feature. In the fully open position a second set of contacts is closed, which may be used to energize a signal calling the operator's attention to the fact that further operation is in his hands.

(4) *Mercury Reclosing Device.* A reclosing device actuated directly by the circuit breaker mechanism, giving 1, 2, or 3 reclosures at fixed time intervals, is shown in Fig. 6. The contacts and timing element are embodied in a hermetically sealed tube containing mercury. The flow of the mercury through fixed orifices, in the various chambers, provides the desired intervals between reclosures, as well as the time required for resetting. These intervals are independent of each other.

Fig. 6. Mercury reclosing device for direct operation from breaker mechanism shown in position corresponding to closed breaker

When the breaker opens, the tube is rotated to a vertical position, where contact is made, after sufficient mercury flows into the contact chamber from the initial chamber (lower end Fig. 6) thus reclosing the breaker. When the breaker recloses, the tube is returned to its original position and the mercury in the contact chamber is emptied quickly into the lock-out chamber (outer and upper chamber Fig. 6). After a predetermined number of successive operations, within a prescribed time, the mercury is all accumulated in the lock-out chamber, leaving none with which to make contact, and the breaker is locked out. If the breaker remains in the closed position for a sufficient length of time, the mercury is returned through the resetting orifice, to the initial chamber.

The "timing" orifice can be enlarged so as to give 1 reclosing operation within 30 to 60 cycles. A number of tubes can be grouped together so as to give different timing intervals between reclosures.

Table II

Type of Device Numbers in Parenthesis Refer to Corresponding Paragraphs	Fig. No.	Minimum Time From Energizing Recloser to Closing of Breaker Control Circuit, in Cycles, on a 60-Cycle Basis	Breaker Operating Cycle: OCO 15 sec OCO (2 or 4 operating cycles)	Breaker Operating Cycle: OCO 0 sec OCO	Breaker Operating Cycle: OCO 0 sec OCO 15 sec OCO 60 sec OCO	Remarks
Motor-driven (1)	1	6	x	x	x	Existing reclosers of this general design may be modified for immediate initial reclosure.
Motor-driven (2)	2	6	x	x	x	Can be adjusted for immediate initial or for time delay reclosures throughout.
Motor-driven (2)	3	40–60	x	x	x	Minimum reclosing interval 40–60 cycles.
One-shot recloser (3)	5	4	*	x	*	Simple and compact electrically operated device for obtaining 1 immediate reclosure, for attended stations. Manually reset.
Mercury reclosing device (4)	6	30–60	x	x	†	Simple and compact mechanically operated device giving a number of equally timed reclosures or 1 reclosure of 30–60 cycle interval

x available
* not available
† requires 3 elements

In Table II there is given a brief résumé of the essential characteristics of the group of reclosers, described in this paper, particularly in relation to a few of the proposed duty cycles (given in Table IV) that are typical of the automatic reclosing sequences.

The author desires to acknowledge the assistance given by L. F. Kennedy of the General Electric Company, Philadelphia works, in the preparation of this paper, particularly that section devoted to protecting and reclosing relays; and also the use of certain valuable data contained in 3 N.E.L.A. electrical apparatus committee reports (issued in 1931 and 1932), together with subsequent data relating to operating experience with a-c reclosing equipment prepared by J. T. Logan of the Georgia Power Company.

Effects of Rectifiers on System Wave Shape

Operation of mercury arc rectifiers generally results in increased harmonic currents in the rectifier supply circuits and may result in increased harmonic voltages. While these harmonics usually are not serious from the standpoint of the power system, they may result in interference to communication circuits exposed to the power circuits. This paper presents a method of computing these harmonic voltages and currents, and discusses methods of coördinating telephone systems and a-c power systems supplying rectifiers.

By
P. W. BLYE
MEMBER A.I.E.E.
Am. Tel. & Tel. Co., New York, N. Y.

H. E. KENT
MEMBER A.I.E.E.
Edison Elec. Inst., New York, N. Y.

AN INHERENT characteristic of the mercury arc rectifier is that the wave form of the current it draws when connected to an a-c source is distorted in character even though the wave form of the supply voltage is sinusoidal. The degree to which this distorted current may react upon the voltage wave shape of the supply system depends upon the size of the rectifier and the impedance at harmonic frequencies of the supply system. Where the distortion of the system voltage wave form by the rectifier is important, harmonic voltages and currents may appear on power circuits in addition to that supplying the rectifier, and, under certain conditions, the resulting wave shape disturbance may be widespread in character.

The harmonic voltages and currents introduced by a rectifier are usually not serious from the standpoint of the operation of the power system. In several cases that have arisen during the past few years, however, these components have resulted in noise interference arising by induction in telephone circuits involved in exposures with the power system. The increasing use of the rectifier as a source of supply for d-c traction systems and its further application in connection with high powered radio transmitting equipment have made the problem of inductive coördination between telephone circuits and power systems supplying rectifiers one of increasing importance. Project Committee 1C on Wave Shape of the Joint Subcommittee on Development and Research* of the National Electric Light Association and Bell Telephone System has conducted an investigation of the effects of rectifiers on supply system wave shape. The present paper is based to a considerable extent upon the results of that investigation.

This paper presents a method, employing equivalent circuits and empirical formulas, that has been developed for computing the harmonic voltages and currents to be expected from a rectifier installation, discusses the various factors influencing the problem, and considers methods of coördinating telephone systems and a-c power systems supplying rectifiers. The use of the empirical formulas for estimating the magnitudes of the harmonic components to be expected from a rectifier requires a knowledge of the impedance at harmonic frequencies of the supply system involved. This paper also describes a method of estimating this impedance from the physical dimensions of the lines and name plate data on the associated apparatus. The theoretical information presented is supported by considerable data representing the results of field studies arranged to check the accuracy of the empirical formulas in connection with operating rectifier installations.

In this paper only the usual type of polyphase rectifier operating without control grids is considered.

Summary of Conclusions

The following general conclusions have been drawn from the results of the field investigations conducted by Project Committee 1C and a supplementary theoretical study of the factors influencing this problem. Certain results of the study are discussed in somewhat greater detail in subsequent portions of the paper.

1. The operation of a rectifier generally results in an increase in the magnitudes of the *odd nontriple* harmonic currents present in the supply circuit, and may result in an increase in the corresponding harmonic voltages.

2. The magnitudes of these harmonic components depend upon several factors including:

Supply Circuit Voltage. If all other factors remain the same, the use of a higher voltage feeder for supplying the rectifier will tend to reduce the magnitudes of the harmonic voltages and currents on that feeder.

Power Supplied to Rectifier. In a given situation the inductive influence of the supply feeder increases with an increase in power supplied to the rectifier.

Supply System Impedance. Within certain limits the voltage wave-shape distortion increases with an increase in the power system impedance at harmonic frequencies, while the distortion of the current wave form tends to decrease. Under certain conditions this effect is reflected in less voltage wave shape distortion on under-

Full text of a paper recommended for publication by the A.I.E.E. committees on (1) electrical machinery, (2) communication, and (3) power transmission and distribution; and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 14, 1933; released for publication Nov. 22, 1933. *Not published in pamphlet form.*

* As discussed in a "Symposium on Coördination of Power and Telephone Plant" presented at the winter convention of the A.I.E.E. in 1931 (A.I.E.E. TRANS., v. 50, 1931, p. 437–74) the Joint Subcommittee on Development and Research was established by the N.E.L.A. and the Bell Telephone System in 1923 as an agency for carrying out technical work on mutual problems of inductive coördination. Participation of the electric light and power industry in the activities of this subcommittee now is being continued under the sponsorship of the Edison Electric Institute.

ground cable circuits than on overhead lines for a given rectifier load and supply system voltage.

Number of Rectifier Phases. The distortion of both the current and voltage wave shape is less for 12-phase rectifiers than for 6-phase rectifiers. In the cases investigated by the committee, 12-phase operation resulted in an average reduction in the current and voltage telephone interference factors (T.I.F.'s)[1] on the supply circuit of approximately 50 per cent, compared with 6-phase operation in the same location.

3. In certain cases, the operation of a rectifier may increase the inductive influence of considerable portions of the power system, in addition to the particular circuit supplying the rectifier.

4. An empirical method has been developed for estimating the approximate magnitudes of the harmonic voltages and currents in the supply circuit to a rectifier in terms of the fundamental frequency voltage and current, the order of the harmonic component in question, and the impedance at harmonic frequencies of the supply system. The results of the field measurements indicate that this method gives reasonably accurate results over a wide range of conditions.

5. In the present state of the art, there is no single, universally applicable method of coördinating telephone systems and a-c power systems supplying rectifiers. In a particular situation, a study of the conditions will indicate which of the various methods of coordination available for use in the power or telephone systems will meet best the service requirements of both these systems in the most convenient and economical manner. Two of the methods relating particularly to the control of the influence of rectifier supply circuits are described in some detail in this paper. Measures relating to other phases of the control of influence, coupling, and susceptiveness which should be considered in the solution of a given problem are treated in various publications of the joint subcommittee on development and research.

Method of Estimating Magnitudes of Harmonic Currents and Voltages

The wave shape of the current in the supply circuit to a rectifier under light-load conditions or for the ideal case of a source of supply without reactance has been analyzed by a number of authors.[2,3] Under load conditions, in the practical case in which supply system reactance is appreciable, this wave shape may be modified considerably and different methods have been proposed for estimating the wave shape under these conditions. One of these[4] involves the extension of the light-load formula along theoretical lines. The method worked out by Project Committee 1C makes use of empirical formulas developed from a theoretical study of the factors influencing the problem. The empirical constants employed were determined from the results of actual measurements of the harmonic currents and voltages in the supply circuits to a number of rectifiers.

1. For all numbered references, see list at end of paper.

Current Wave Shapes

Ideal Case, No Supply System Reactance. As a preliminary step in the development of the equivalent circuit and empirical formulas for the practical case, it is helpful to consider first the ideal case, not approached in practice, in which a rectifier is supplied from a system of negligible reactance through a transformer of negligible leakage reactance.

Figure 1 illustrates the theoretical or light-load wave shapes of the currents in the a-c supply circuits to 3 rectifier arrangements frequently used in practice. Cases 1 and 2, as indicated in the schematic diagrams, apply to common types of 6-phase rectifiers while case 3 illustrates a transformer arrangement often employed with 12-phase rectifiers. The manner in which these current wave shapes arise has been treated thoroughly in texts on the subject[2,3] and will not be analyzed here.

The so-called 3-phase full-wave rectifier is equivalent in its operation to a 6-phase rectifier and, therefore, the conclusions drawn in this paper for the latter hold equally well for the former.

The current wave illustrated in case 1 may be resolved readily into a Fourier series consisting of a fundamental component and harmonics of orders $6S \pm 1$ where S is any positive whole number—namely, harmonics of orders 5, 7, 11, 13, 17, 19, 23, 25, etc. In each case the magnitude of the nth harmonic component is equal to $1/n$ times the fundamental current. The current wave illustrated in case 2 may be resolved into a similar series, the harmonics differing from those in case 1 in phase only.

The current wave of the 12-phase rectifier may be resolved similarly into a Fourier series consisting of a fundamental component and harmonics of orders $12S \pm 1$ where S is any positive whole number—namely, harmonics of orders 11, 13, 23, 25, etc. As in the case of the 6-phase rectifier the mag-

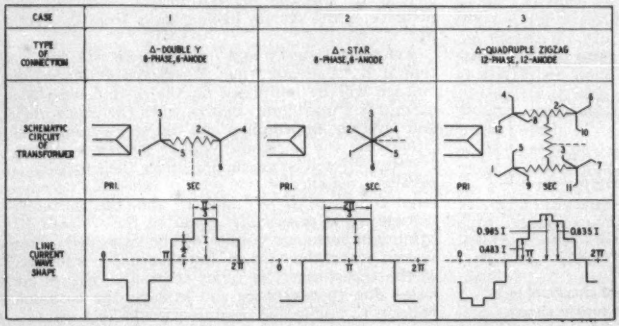


Fig. 1. Theoretical wave shape of input current to a rectifier operating on a supply circuit of negligible reactance

Overlapping effects and transformer magnetizing current neglected; rectifier output circuit assumed to be inductive. I = rectified direct current

nitude of the nth harmonic is equal to $1/n$ times the fundamental component. It may be noted that harmonics of orders 5, 7, 17, 19, etc., which were present in the case of the 6-phase rectifier are not, theoretically, present in the 12-phase arrangement.

Figure 2A illustrates an equivalent phase-to-neutral circuit that represents the ideal case of no supply system reactance. If n represents the order of any harmonic that may be present and I_{no} represents the harmonic current in the ideal case at that frequency, from the foregoing analysis

$$I_{no} = \frac{I_\phi}{n} \tag{1}$$

where I_ϕ represents the fundamental frequency line current.

In Fig. 2A, R_o, is a fictitious quantity representing the internal resistance of the rectifier and E_n represents the harmonic voltage that will produce a current I_n in a circuit of impedance R_o (since the external impedance, that of the supply circuit and transformer, has been assumed negligible in this case). Then E_n is considered as the "open-circuit" harmonic voltage generated by the rectifier and

$$E_n = I_{no}R_o \tag{2}$$

Measurements on a comparatively large number of rectifiers indicate that the magnitude of the so-called internal resistance is approximately

$$R_o = \frac{V_{\phi-N}}{3I_\phi} \tag{3}$$

where $V_{\phi-n}$ represents the fundamental frequency phase-to-neutral voltage.

Substituting eqs 1 and 3 in eq 2, the magnitude of the "generated voltage" E_n becomes

$$E_n = \frac{V_{\phi-N}}{3n} \tag{4}$$

Practical Case. An equivalent circuit for the practical case taking into account the modification of the current wave shape by the supply system reactance may be set up now by merely adding to the circuit for the ideal case elements representing the impedance of the supply system and the leakage impedance of the rectifier transformer. An equivalent circuit so modified is illustrated in Fig. 2B. In this revised circuit,

$$I_n = \frac{E_n}{\sqrt{R_o^2 + Z_n^2}} \tag{5}$$

where Z_n represents the vector sum of the transformer leakage impedance (Z_{tn}) and the system phase-to-neutral impedance (Z_{sn}) at the harmonic frequency, both referred to the fundamental frequency voltage $V_{\phi-N}$.

Substituting eq 4 in eq 5

$$I_n = \frac{V_{\phi-N}}{3n\sqrt{R_o^2 + Z_n^2}} \tag{6}$$

It may be noted from eq 6 that, in order to compute the magnitude of any harmonic current component, it is necessary to know: (1) fundamental frequency voltage $V_{\phi-N}$, (2) the fundamental frequency current (see eq 3), and (3) the combined impedance at the harmonic frequency of the rectifier transformer and the supply system.

An examination of eq 6 and the equivalent circuit (Fig. 2B) indicates that the maximum current at any harmonic frequency will obtain when a condition of resonance exists between the transformer leakage reactance and the system reactance. Under this condition the term Z_n becomes small compared to R_o and the harmonic current approaches that which would obtain in the ideal case of no supply circuit reactance. Under this condition, from eq 1

$$I_n = \frac{I_\phi}{n}$$

Conversely, the harmonic current is minimum at any frequency when there is a condition of parallel resonance in the system impedance. Under this condition the term Z_n becomes relatively large compared to R_o. If it were not for losses due to resistance and leakage in the system, the system impedance at parallel resonance would be infinite and the harmonic current at that frequency would be zero.

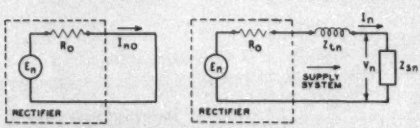
Voltage Wave Shape

Referring again to Fig. 2B, the phase-to-neutral harmonic voltage on the supply circuit at the line terminals of the rectifier transformer is

$$V_n = I_nZ_{sn} \tag{7}$$

The phase-to-neutral harmonic voltage at any other point on the system may be computed in a similar manner from the product of the harmonic current at that point and the phase-to-neutral harmonic impedance of the system looking away from the rectifier.

Reference to eqs 6 and 7 and Fig. 2B will indicate that if Z_{sn} is greater than R_o, maximum harmonic voltage will be impressed on the system when the current is a maximum, that is, when the transformer and system impedances are in series resonance. Otherwise, the harmonic voltage impressed on the system (V_n) will be maximum under the condition of parallel resonance of the system, when Z_{sn} becomes large compared to Z_{tn} and R_o and the harmonic voltage V_n is practically equal to the voltage E_n. Minimum harmonic voltage will be impressed on the system when the system impedance Z_{sn}, exclusive of the transformer, is series resonant. Except for losses due to resistance and leakage, the harmonic voltage V_n under this condition would be zero.



A. Rectifier supplied from circuit with negligible impedance (theoretical case; see eqs 1 to 4)

B. Rectifier supplied from circuit with external impedance (practical case; see eqs 5 to 7)

Fig. 2. Phase-to-neutral equivalent circuits of rectifiers for calculating harmonics in supply circuit

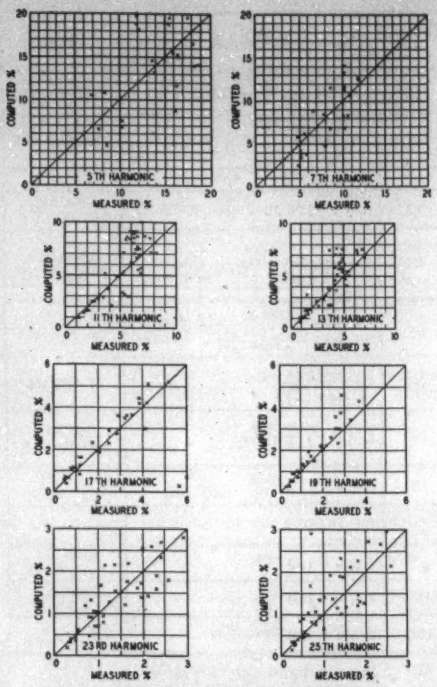


Fig. 3. Comparison of harmonic currents computed by empirical method with measured values

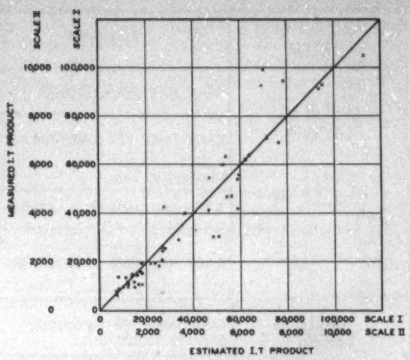


Fig. 4. Comparison of I.T products estimated by empirical method with those measured on circuits supplying rectifiers

o = scale I; x = scale II

Application of Formulas to 12-Phase Rectifiers

In the discussion of the ideal case of no supply circuit reactance it was brought out that, theoretically, harmonics of orders 5, 7, 17, 19, etc., are not present in the input circuit of a 12-phase rectifier. In practice, however, presumably due to unbalances between the 2 6-phase units that make up a 12-phase rectifier, these components are not reduced to zero. While their relative magnitudes have been found to vary with different rectifier installations, experience indicates that on an average these theoretically suppressed components appear in magnitudes approximately equal to $^1/_5$ those that would result from 6-phase rectifiers. The empirical formulas (eqs 6 and 7) therefore, may be modified for application to 12-phase rectifiers as follows:

$$I_n = \frac{KV_\phi - N}{3n\sqrt{R_s^2 + Z_n^2}} \tag{8}$$

$$V_n = I_n Z_{sn} \tag{9}$$

For 6-phase rectifiers, $K = 1$. For 12-phase rectifiers, $K = 1$ for $n = 11, 13, 23, 25$, etc.; $K = 0.2$ for $n = 5, 7, 17, 19$, etc.

Accuracy of Empirical Formulas

The accuracy of the foregoing formulas depends upon the accuracy of the assumption that E_n is a fixed and constant voltage and the degree to which the quantity R_s is represented correctly by eq 3. The accuracy of results obtained by the formula also depends upon the precision to which the system impedance is known. Project Committee 1C has carried out a rather extensive series of calculations and measurements to check the over-all accuracy of the method.

The correlation between calculated and measured values of the individual harmonic currents in the various cases tested is indicated in Fig. 3. In order to demonstrate the accuracy of the formula itself, the calculations are based upon measured, rather than calculated, system impedances. It may be noted that the greatest spread between measured and computed values was found in the case of the 5th harmonic. This can be explained in part by the presence of 5th harmonic components from sources on the system other than the rectifier which affected the measured values, but which were not considered in the computations. This effect is probably also present, but to a less marked degree, at the other harmonic frequencies. In general it appears that in a large majority of cases the individual harmonic components can be computed to within ±30 per cent. In view of the nature of the quantities being computed, which are often highly variable in character due to rectifier load fluctuations, the method is considered sufficiently accurate for all practical purposes.

In inductive coördination studies a weighted combination of the various harmonic components present added in accordance with the root-sum-square method and called the "telephone interference factor" or T.I.F.[1] is usually of greater interest than the magnitudes of the individual harmonics. The phase

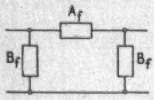
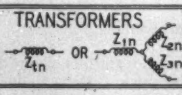
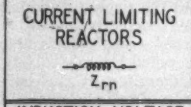
PORTION OF SYSTEM	QUANTITY	FORMULA NO.	FORMULA	UNITS
OVERHEAD CIRCUITS 	INDUCTANCE PER CONDUCTOR	(10)	$L = 0.741 \log_{10} \frac{D}{r} + 0.080$	MH. PER MILE
	CAPACITANCE PER CONDUCTOR	(11)	$C = \frac{0.0388}{\log_{10} \frac{D}{r}}$	µF. PER MILE
	HYPERBOLIC ANGLE	(12)	$\theta = 6.28\, \ell \sqrt{0.1\, LC}\ 10^{-4} f$	RADIANS
	SERIES IMPEDANCE OF π NETWORK	(13)	$A_f = +j\, 6.28\, \ell L \left[\frac{\sin\theta}{\theta}\right] 10^{-3} f$	OHMS AT FREQUENCY f
	SHUNT IMPEDANCE OF π NETWORK	(14)	$B_f = -j \frac{10^6}{3.14\, \ell C \left[\frac{\tan\theta/2}{\theta/2}\right] f}$	OHMS AT FREQUENCY f
CABLE CIRCUITS 	CAPACITANCE PER CONDUCTOR, 3-PHASE BELTED CABLE	(15)	$C = \frac{0.0776\, K}{\log_{10} \left[\frac{3a^2 (R^2 - a^2)^3}{r^2 (R^6 - a^6)}\right]}$ (SEE FIG. 8)	µF. PER MILE
	CAPACITANCE PER CONDUCTOR, 3-PHASE SHIELDED OR 1-PHASE CABLE	(16)	$C = \frac{0.0388\, K}{\log_{10} \left(\frac{R}{r}\right)}$ (SEE FIG. 8)	µF PER MILE
	EQUIVALENT SHUNT IMPEDANCE (FOR π NETWORK USE FORMULAS 13 & 14)	(17)	$Z_{cn} = -j \frac{10^6}{6.28\, f \ell C}$	OHMS AT FREQUENCY f
TRANSFORMERS 	EQUIVALENT SERIES IMPEDANCE TWO-WINDING TRANSFORMER	(18)	$Z_{tn} = +j(n) \frac{\% X}{100} \frac{V^2}{1000\,(KVA)}$	OHMS AT n^{TH} HARMONIC.
	EQUIVALENT CIRCUIT THREE WINDING TRANSFORMER	(19)-(28) INCL.	SEE FIGURE 9	
CURRENT LIMITING REACTORS	EQUIVALENT SERIES IMPEDANCE	(29)	$Z_{rn} = +j(n) \frac{V_r}{I}$	OHMS AT n^{TH} HARMONIC
	EQUIVALENT SERIES IMPEDANCE	(30)	$Z_{rn} = +j(n) \frac{\% X}{100} \frac{V}{\sqrt{3}\, I}$	OHMS AT n^{TH} HARMONIC
	EQUIVALENT SERIES IMPEDANCE	(31)	$Z_{rn} = +j(n) \frac{1000\ KVA}{I^2}$	OHMS AT n^{TH} HARMONIC
INDUCTION VOLTAGE REGULATORS	EQUIVALENT SERIES IMPEDANCE 3-PHASE REGULATOR	(32)	$Z_{REG\,n} = +j(n) \frac{\% X}{100} \frac{(1000)(KVA)}{3 I^2}$	OHMS AT n^{TH} HARMONIC
	EQUIVALENT SERIES IMPEDANCE SINGLE-PHASE REGULATOR	(33)	$Z_{REG\,n} = +j(n) \frac{\% X}{100} \frac{(1000)(KVA)_1}{I^2}$	OHMS AT n^{TH} HARMONIC
ROTATING MACHINERY	EQUIVALENT SHUNT IMPEDANCE	(34)	$Z_n = +j(n) \frac{\% X}{100} \frac{V^2}{1000\,(KVA)}$	OHMS AT n^{TH} HARMONIC

Fig. 5. Equivalent circuits of various portions of a power system, and formulas for calculating their phase-to-neutral impedances at harmonic frequencies

a = Cable dimension (inches) (see Fig. 8)
A_f = Series impedance of equivalent π network
B_f = Shunt impedance of equivalent π network
C = Capacitance to-neutral per conductor per mile (microfarads)
D = Mean spacing of conductors (inches) $D = \sqrt[3]{D_{12} D_{23} D_{31}}$
f = Frequency (cycles per second)
I = Rated full-load current per phase (amperes)
K = Specific inductive capacity of cable insulation (see Fig. 8)
KVA = 3-Phase rating (kilovoltamperes)
KVA_1 = Single-phase rating (kilovoltamperes)
L = Inductance per conductor per mile (milhenries)
= Length of line (miles)
n = Order of harmonic
$\% X$ = Reactance expressed in per cent
R = Cable dimension (inches) (see Fig. 8)
r = Radius of conductor (inches)
$\frac{\sin\theta}{\theta}$ = Correction factor (see Fig. 6)
$\frac{\tan\theta/2}{\theta/2}$ = Correction factor (see Fig. 7)
V = Rated phase-to-phase voltage (volts)
V_r = Reactive voltage drop across reactor (volts)
θ = Hyperbolic angle of circuit (radians)

current multiplied by its telephone interference factor (I.T) frequently is used as an index of the inductive influence of a power circuit from the standpoint of induction from balanced currents. The correlation between the measured and computed I.T products from the cases tested by the committee is indicated in Fig. 4. Except in a few cases the computed values were within about ±20 per cent of the measured values. The accuracy of these calculations is better than that for the individual harmonics because in making the summation certain errors in the individual components tend to average out.

The accuracy of the calculation of individual harmonic voltages and the voltage T.I.F. to which they contribute depends upon the accuracy with which the system impedance at harmonic frequencies is known.

Method of Computing System Impedances at Harmonic Frequencies

Measured values of the impedance of the supply system at harmonic frequencies required in the empirical formulas discussed are seldom available. In using the formulas, therefore, it is usually necessary to estimate this impedance, at the various frequencies desired, from the physical dimensions of the lines and cables involved and the name plate data on the associated apparatus.

In making calculations of system impedance it has been found convenient to build up a composite equivalent circuit made up of elements representing the impedances of the lines and of the various pieces of connected equipment. It has been found that overhead transmission lines or cables may be represented by networks of inductive and capacitive reactances, while apparatus such as transformers, reactors, regulators, and rotating machinery can be represented approximately by inductances. When all the elements of the equivalent circuit have been assembled in their proper physical relationships, they may be combined at any desired frequency to reduce the entire network to a single impedance (Z_{sn}) as required in the empirical formulas.

At harmonic frequencies the resistance and leakage of the various elements of the power system are ordinarily negligible compared to the inductive and capacitive reactance. However, at frequencies where series or parallel resonance occurs, the resultant impedance is determined largely by the resistance and leakage. From a practical standpoint, the error introduced in impedance calculations near points of resonance by other approximations involved is probably as important as that due to neglecting resistance or leakage. Moreover, as series or parallel resonant points in the system impedance are approached, the harmonic currents and voltages from a rectifier approach values fixed by other elements, and relatively large errors in the system impedance are not critical.

In general, the lowest impedance path to harmonics is that toward the main source of supply and the impedance of that source is, therefore, generally the controlling factor in the system impedance. Except in unusual cases the shunting effects of load equipment may be neglected. However, the shunting effects of cables or long overhead lines other than that feeding the rectifier, but supplied from the same source, may be important and must be considered.

In establishing the equivalent circuit for a system it is necessary, of course, to reduce the impedances of the various elements to a common voltage basis usually determined by the fundamental frequency voltage at the point where the harmonic components are to be calculated.

Formulas for the equivalent phase-to-neutral impedances at harmonic frequencies of various portions of a power system are summarized in Fig. 5.

Overhead Lines and Cables. It may be noted that in Fig. 5 the complete equivalent circuit for an overhead line or cable is shown in the form of a π-network. The method[5] of computing the elements of this network makes use of the hyperbolic angle θ of the line and the formulas involve the functions $\frac{\sin\theta}{\theta}$ and $\frac{\tan\theta/2}{\theta/2}$. For convenience these 2 quantities have been plotted against values of the angle θ (in radians) in Figs. 6 and 7, respectively.

Formulas for the capacitance-to-neutral (C) of a cable involve details of the cross-sectional dimensions of the cable as indicated in Fig. 8. For shorter lengths of cables (of the order of 5 miles or less) the series reactance may be neglected and the cable may be represented by a simple shunt capacitance as indicated in eq 17.

Transformers. The per cent reactances to be used in the transformer equations (18 to 28) should

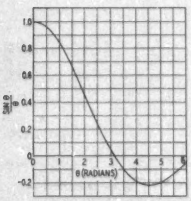


Fig. 6 (above). Curve of $\frac{\sin\theta}{\theta}$ in terms of angle θ

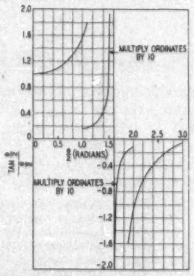
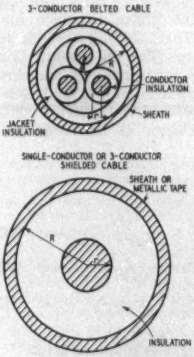


Fig. 7 (right). Curves of $\frac{\tan\theta/2}{\theta/2}$ in terms of $\frac{\theta}{2}$



$$C = \frac{0.0776\,K}{\text{Log}_{10}\left[\frac{3a^2\,(R^3-a^3)^3}{r^3\,(R^6-a^6)}\right]}\ \mu f \text{ per mile}$$

R = Distance from center of cable to sheath

a = Distance from center of cable to center of conductor

$$C = \frac{0.0388\,K}{\text{Log}_{10}\left(\frac{R}{r}\right)}\ \mu f \text{ per mile}$$

(For shielded cable, R is the distance from center of conductor to metallic tape around conductor insulation)

Fig. 8. Formulas for calculating phase-to-neutral capacitance of power cables

Approximate values of specific inductive capacity (K)

Impregnated paper (solid)	= 3.7
Impregnated paper (oil filled)	= 3.5
Rubber	= 6.0
Varnished cloth	= 4.5

Formulas from "Principles of Electric Power Transmission and Distribution," by Woodruff, John Wiley and Sons, 1925, P. 56–8)

be taken from the name plate of the transformer whenever possible. Where this value is not available, the following approximate percentages, based upon experience, have been found suitable for use in preliminary estimates:

Rectifier transformers	4%
Distribution transformers	3%
Power transformers for primary voltages up to 33 kv	6%
Power transformers for primary voltages above 33 kv	10%

Formulas for the equivalent circuit of a 3-winding transformer are given, together with a schematic circuit diagram, in Fig. 9. It may be noted that the reactances in Fig. 9 are at the fundamental frequency. The corresponding impedances at the frequency of the nth harmonic, therefore, would be obtained by multiplying these quantities by n. For example:

$$Z_{1n} = +jn(X_1) \tag{28}$$

Induction Voltage Regulators. The results of measurements at harmonic frequencies of the impedance and ratio characteristics of induction voltage regulators indicate that these devices may be considered equivalent to variable ratio autotransformers the leakage reactance of which varies with regulator setting. In view of this variation in impedance, it is generally necessary to use an average value in system impedance estimates. Measurements on a limited number of regulators indicate that this reactance averages about 18 per cent, based upon the regulator rating, for either 3-phase or single-phase regulators.

Rotating Machinery. Since very little information has been available heretofore on the reactance of rotating machinery to impressed harmonics, project committee 1C conducted measurements in the field on 49 machines, the results being as shown in Table I.

The results of the tests indicated a fairly consistent relationship between the impedance to impressed harmonics and the negative phase sequence impedance of the machine. Where the negative phase sequence impedance of a machine is known, this quantity multiplied by 0.9 for turbine generators and by 0.7 for hydroelectric generators and synchronous condensers may be used in eq 28 for computing the equivalent reactance at harmonic frequencies.

Illustrative Example of Equivalent Network

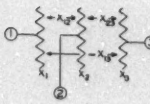
An example of the method of setting up a phase-to-neutral equivalent circuit for use in computing the impedance of a system supplying a rectifier is illustrated in Fig. 10. In the upper part of the figure is given a single-line diagram of the system; in the lower part is shown the equivalent circuit, each portion of which is numbered to correspond to the portion of the system it represents. The formula applying to each element of the circuit is indicated. It should be appreciated that this example purposely has been made complicated in order to illustrate a large number of equivalent circuits. In many cases the rectifier transformer and the circuit between the rectifier and the substation control the system impedance to harmonics.

Coördinative Measures

As previously discussed, experience indicates that the inductive influence of a power circuit when supplying rectifiers may be considerably greater than when supplying the more usual types of load. Therefore, coördination of exposed telephone circuits with power circuits supplying rectifiers may be expected to be more difficult than with circuits supplying other loads. In this problem, as in all inductive coördination work, the general principle[6] of coöperative advance planning of the power and telephone system is, of course, very helpful.

In the present state of the art, the following specific coördinative methods appear to be the most promising:

1. Advance planning of method of supplying rectifier from the standpoint of minimizing wave shape distortion.
2. Frequency selective devices.
3. Coördinated power circuit transpositions.
4. Reduction of power circuit unbalances, such as those caused by single-phase branches.
5. Coördinated telephone circuit transpositions.
6. Reduction of telephone circuit unbalances, such as those caused by the connection of ringer windings from one side of line to ground for selective ringing.
7. Shielding of telephone cable circuits by grounding the cable sheath.

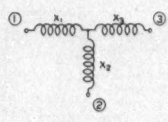


$$X_{12} = \frac{\%X_{12}}{100} \times \frac{V_1^2}{1{,}000(KVA)_{12}} \text{ (ohms)} \tag{19}$$

$$X_{23} = \frac{\%X_{23}}{100} \times \frac{V_1^2}{1{,}000(KVA)_{23}} \text{ (ohms)} \tag{20}$$

$$X_{13} = \frac{\%X_{13}}{100} \times \frac{V_1^2}{1{,}000(KVA)_{13}} \text{ (ohms)} \tag{21}$$

$\%X_{12}$ = Per cent reactance between windings 1 and 2
$\%X_{23}$ = Per cent reactance between windings 2 and 3
$\%X_{13}$ = Per cent reactance between windings 1 and 3
V_1 = Rated voltage of winding 1 (phase-to-neutral)
V_2 = Rated voltage of winding 2 (phase-to-neutral)
V_3 = Rated voltage of winding 3 (phase-to-neutral)
$(KVA)_{12}$ = KVA base (per phase) for reactance rating $\%X_{12}$
$(KVA)_{23}$ = KVA base (per phase) for reactance rating $\%X_{23}$
$(KVA)_{13}$ = KVA base (per phase) for reactance rating $\%X_{13}$



$$X_{12} = X_1 + X_2 \text{ (ohms)} \tag{22}$$

$$X_{23} = X_2 + X_3 \text{ (ohms)} \tag{23}$$

$$X_{13} = X_1 + X_3 \text{ (ohms)} \tag{24}$$

$$X_1 = \frac{X_{13} - X_{23} + X_{12}}{2} \text{ (ohms)} \tag{25}$$

$$X_2 = \frac{X_{12} - X_{13} + X_{23}}{2} \text{ (ohms)} \tag{26}$$

$$X_3 = \frac{X_{13} - X_{12} + X_{23}}{2} \text{ (ohms)} \tag{27}$$

X_1 = Leakage reactance associated with winding 1
X_2 = Leakage reactance associated with winding 2
X_3 = Leakage reactance associated with winding 3
X_{12} = Total leakage reactance between windings 1 and 2
X_{23} = Total leakage reactance between windings 2 and 3
X_{13} = Total leakage reactance between windings 1and 3

Fig. 9. Equivalent circuits of 3-winding transformers

Note. All reactances must be referred to the same phase-to-neutral voltage base (here V_1); the reactances may be referred to phase-to-neutral voltage base V by multiplying each reactance by $(V/V_1)^2$

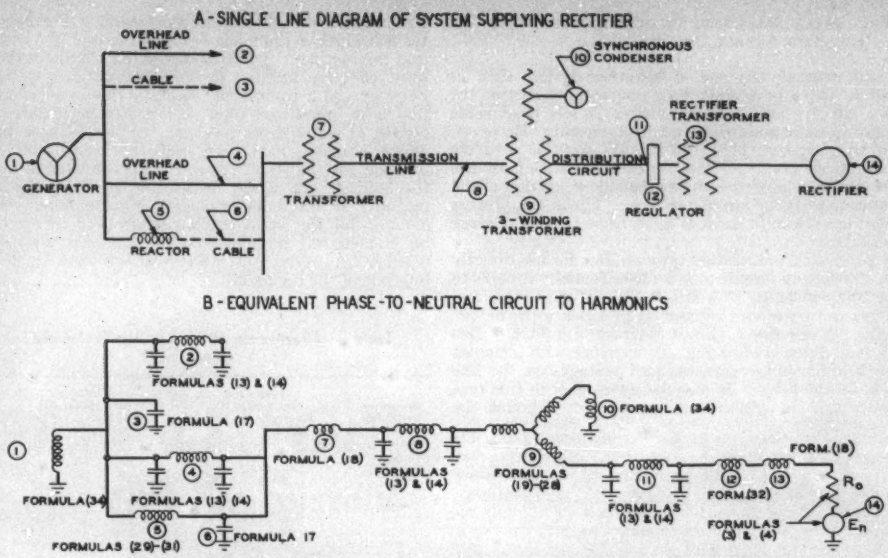


Fig. 10. Example of application of equivalent circuits and corresponding formulas

Of these methods, only the first 2 are discussed in this paper. Various engineering reports of the Joint Subcommittee on Development and Research contain information on the remaining items. These other factors, of course, should be given due consideration in any coördination study.

As shown by the diverse character of the items listed, no single method of coördination is universally applicable in all cases. A study of the various factors present in a particular situation will indicate what method, or methods, of coördination applied to the telephone system, the power system, or both will meet best the service requirements of both systems in the most convenient and economical manner.

Power System Factors Affecting Wave Shape

In many cases the distortion in supply system wave shape may be minimized by advance consideration from the coördination standpoint of the method of supplying a rectifier. Economies in the application of coördinative measures often may be realized when the following points are considered in selecting the method of supplying power to a rectifier:

1. The voltage wave shape distortion generally will be minimized when the rectifier is supplied from a power source of relatively large capacity over a short length of circuit. However, the current wave shape distortion may be important if telephone lines are exposed to this circuit.

2. Other conditions remaining the same, the higher the supply circuit voltage the less, in general, will be the distortion of both the current and voltage wave shape.

Table I—Measured Per Cent Reactance (Referred to 60 Cycles) to System Harmonics of 60-Cycle Rotating Machinery

	Turbine Generators	Hydroelectric Generators	Synchronous Condensers
Average	11 (24)	23 (14)	21 (11)
Minimum	4.7	12	14
Maximum	17	29	35

Note: Figures in parentheses indicate number of machines included in average.

3. The distortion of the supply circuit voltage wave shape generally will be less when the rectifier is supplied from a cable network than from overhead lines.

4. The distortion of voltage wave shape on distribution circuits applied from the same transmission system as a rectifier may be an important factor. This is especially true where the distribution circuits occupy poles jointly with telephone circuits. As an approximation, the voltage T.I F. on the distribution system may be assumed equal to the voltage T.I.F. of the transmission system at the point where the distribution system is supplied. The voltage T.I.F. at any point on the transmission system may be estimated by the empirical methods previously discussed.

5. Where various methods of supplying power to a rectifier are available, a preliminary investigation of the power system impedance at harmonic frequencies will indicate the method that will cause the least distortion of the system voltage wave shape. In the cases investigated, the most desirable arrangement has been found to be that in which a relatively low impedance is seen looking away from the rectifier at points from which other circuits involved in exposures with the telephone plant are supplied.

Frequency Selective Devices Applied to Rectifier Supply Circuit

In general, the use of selective devices such as filters for suppressing harmonic components in the a-c supply circuit to a rectifier is less practicable than in the case of the d-c output circuit. However, in some cases where the smaller sizes of rectifiers have been involved, the use of selective devices has been found to be the most economical solution of the inductive coördination problem. Up to the present time no selective devices have been applied to large rectifiers.

The most practicable type of filter for use directly in the supply circuit to a 6-phase rectifier appears to be one consisting of a bank of shunt capacitors and a group of reactors connected in series with the circuit. A schematic circuit diagram of a filter of this type is illustrated in Fig. 11, together with formulas for the harmonic currents and voltages on the line side of the filter. It may be noted that in this case the shunt capacitors are Δ-connected, although the same capacitor rating in kilovoltamperes would be required if they were Y-connected.

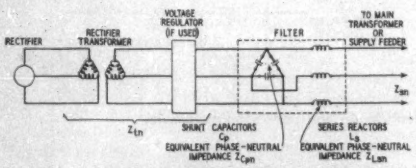


Fig. 11. Schematic diagram of a filter for improving wave shape of a-c supply to a rectifier

Harmonic current on line side of filter

$$I'_n = \frac{V_{\phi-n}}{3_n} \cdot \frac{Z_{Cpn}}{Z_{Cpn} + Z_{LSn} + Z_{Sn}} \cdot \frac{1}{\sqrt{R_s^2 + \left[Z_{tn} + \frac{Z_{Cpn}(Z_{LSn} + Z_{Sn})}{Z_{Cpn} + Z_{LSn} + Z_{Sn}}\right]^2}} \quad (35)$$

(Impedance to be added vectorially.) Harmonic phase-to-neutral voltage

$$V'_n = I'_n Z_{Sn} \quad (36)$$

Usually this type of filter is most effective if the shunt capacitors are connected on the line side of, and immediately adjacent to, the rectifier transformer. The most favorable location for the series reactors has been found to be on the line side of the capacitors. The values of shunt capacitance and series inductance chosen depend upon the size of the rectifier, the voltage of the circuit in which they are to be connected, the system impedance, the effectiveness desired, and the effect on fundamental frequency voltage regulation.

In one situation, a successful combination for use in the 2,300-volt supply circuit to a 200-kw rectifier associated with a 50-kw radio broadcasting station was found to be a Δ-connected bank of capacitors of 15 μf each and series reactors of 13 mh each. Frequently, in radio transmitting stations, 2 voltage transformations are made between the supply feeder and the rectifier. In situations of this character the most effective location for the filter appears to be between the 2 transformer banks. In special cases the most practicable filter design may be found to consist of shunt capacitors only, and in one case on which estimates have been made the most effective location for the shunt capacitors appeared to be on the rectifier side of the rectifier transformer. In a majority of the cases examined, however, the best location for the shunt capacitors has been found to be immediately adjacent (on the line side) to the rectifier transformer, or, if a regulator is used, on the line side of the regulator.

Table II—Effectiveness of Filter in Rectifier Supply Circuit

Frequency Cycles Per Second	Feed No. 1 Line Voltage (%) Filter Out	Feed No. 1 Line Voltage (%) Filter In	Feed No. 2 Line Voltage (%) Filter Out	Feed No. 2 Line Voltage (%) Filter In
300	4.0	2.55	6.62	3.40
420	3.51	0.80	5.35	1.42
660	2.07	0.30	2.70	0.35
780	1.55	0.15	2.01	0.21
1020	1.08	0.076	1.88	0.084
1140	1.10	0.047	1.84	0.066
1380	0.93	0.031	1.49	0.12
1500	0.85	0.034	1.44	0.047
T.I.F.	220.	29.5	380.	37.5

The effectiveness of the filter mentioned in the preceding paragraph, consisting of 15-μf capacitors Δ-connected and series reactors of 13 mh, is illustrated in Table II. In a filter of this type the series reactors must be designed to carry continuously the full fundamental frequency phase current required by the rectifier and to withstand safely momentary current surges resulting from short circuits in the rectifier station. The capacitors must be designed to withstand the peak voltage to which they may be subjected, including both the fundamental frequency voltage and the arithmetic sum of the harmonic voltages. The effect of the filter on voltage regulation must be taken into account.

In designing a filter of this type it is necessary to consider the possibility of various conditions of resonance between the filter and the system which might adversely affect the effectiveness of the filter.

In certain cases in which it is desired to reduce only a small number of harmonic components in the circuit supplying a rectifier, resonant shunts tuned to the frequencies of these components might be substituted for the shunt capacitors shown in Fig. 11. In computing the effectiveness of such an arrangement at a given frequency the effective resistance of the resonant shunt tuned to that frequency should be substituted for Z_{Cpn} in eq 35. Since this effective resistance, r_{pn}, would be small and at right angles to Z_{Lsn} and Z_{sn}, eq 35 in this case would reduce to approximately:

$$I'_n = \frac{V_{\phi-N}}{3n} \cdot \frac{r_{pn}}{Z_{Lsn} + Z_{sn}} \cdot \frac{1}{\sqrt{R_s^2 + Z_{tn}^2}} \quad (37)$$

In some cases the series reactors may be omitted and eq 37 may be reduced still further by eliminating Z_{Lsn}.

At frequencies other than those for which shunts are provided, the effectiveness can be computed from eq 35 by substituting for Z_{Cpn} the impedances of all the resonant shunts in parallel at the frequency in question. At these frequencies there is a possibility of adverse resonance conditions involving the resonant shunts and other portions of the system and in each case this possibility must be investigated.

In computing the effectiveness of a filter of this type it should be noted that all impedances are taken as phase-to-neutral impedances. Where equal shunt elements are Δ-connected, therefore, their impedances should be divided by 3 when used in the formulas.

References

1. Review of Work of Subcommittee on Wave Shape Standard of the Standards Committee, H. S. Osborne. A.I.E.E. Trans., v. 38, 1919, page 261–88.

2. Principles of Mercury Arc Rectifiers and Their Circuits (a book), Prince and Vogdes. McGraw-Hill Book Co., 1927.

3. Mercury Arc Power Rectifiers, Theory and Practice (a book), Marti and Winograd. McGraw-Hill Book Co., 1930.

4. Current and Voltage Wave Shapes of Mercury Arc Rectifiers, H. D. Brown and J. J. Smith. A.I.E.E. Trans., v. 52, 1933, p. 973–84.

5. Electric Lines and Nets (a book), A. E. Kennelly. McGraw-Hill Book Co., 1928.

6. Principles and Practices for the Inductive Coördination of Supply and Signal Systems, Reports of the joint general committee of National Electric Light Association and Bell Telephone System on physical relations between electrical supply and signal systems. Edition of Dec. 9, 1922.

Petersen Coil Tests on 140-Kv System

Petersen coils installed on part of a 140-kv transmission system operating with the neutral ungrounded have successfully eliminated a large percentage of interruptions due to line-to-ground faults which occurred on that section. Detailed tests, presented in this paper, also have been made, and indicate many characteristics of the Petersen coil system.

By

J. R. NORTH
MEMBER A.I.E.E.
The Commonwealth & Southern Corp., Jackson, Mich.

J. R. EATON
ASSOCIATE A.I.E.E.
Consumers Power Company, Jackson, Mich.

THE 140-kv transmission system of the Consumers Power Company in the state of Michigan has a total connected length of approximately 1,000 miles and is operated with the neutral ungrounded; protection is provided by means of directional phase and directional ground relays, the latter operating on residual charging current and residual voltage to ground.[1] A study indicated that the installation of ground fault compensating coils offered possibilities of improving system operation by permitting line-to-ground faults to be cleared without circuit interruptions.

In order to determine the efficacy of such coils on the 140-kv transmission system, initial installations of Petersen coils were made in 1931 on a portion of this system which was isolated from the remainder by delta-delta connected transformers. These Petersen coils, each rated at 10,773 kva, were installed at the Saginaw River plant and at the Alcona hydroelectric plant. During August 1931, the Consumers Power Company with the assistance of the Joint Subcommittee on Development and Research of the Edison Electric Institute and the Bell Telephone System, and the General Electric Company, conducted extensive field tests to study the operation of the coils under a wide range of conditions. These included various fault conditions with the Petersen coils in service, with the neutral isolated, and with the neutral grounded by means of a grounding bank.

The following conclusions may be drawn from the results of these tests and subsequent operating experience:

1. The shock to the system during line-to-ground faults is very small with the Petersen coils in service and the ground fault current is of a low value.

2. The tuning of the Petersen coils may be determined either by calculations, by ammeter tuning, or by fault tuning. The operation of the coils when in tune is not affected by the location of the fault or by the particular conductor faulted.

3. Successful operation of the coils as regards arc extinction requires that the uncompensated fault current be kept to a low value. In this connection it is very important that the line conductor sizes and the transmission voltage be properly correlated so that the corona current will not be excessive during fault conditions.

4. The maximum overvoltages recorded during the tests were approximately 3 times normal and in no case were there any excessive voltages attributable to arcing grounds, Petersen coil resonance, or to any other causes.

Operating experience on the Petersen coil section of the system during the past $2^1/_2$ years has demon-

Full text of a paper recommended for publication by the A.I.E.E. committee on protective devices, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 29–26, 1934. Manuscript submitted Oct. 30, 1933; released for publication Nov. 13, 1933. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

strated that the coils successfully eliminate a large percentage of interruptions due to line-to-ground faults. The use of the coils does not interfere with the normal routine operation of the system.

Theory of Petersen Coil Operation

A ground fault compensating coil is an inductance suitable for connection in a transmission system in such a manner that, in case of an arc from one conductor to ground, the fault current will be of such low value that the arc will be self-extinguishing under conditions usually encountered. The original form of this device, developed by Dr. Petersen in Germany and therefore termed a Petersen coil, consists of an inductance connected between ground and the neutral point of a wye-delta connected transformer bank operating on a transmission system which is otherwise ungrounded.

A simplified diagram of connections is shown in Fig. 1(*a*), in which the capacitance between ground and each of the 3-line conductors is represented by C_1, C_2, and C_3. Consider this first as an isolated neutral system (neutral switch S open) and neglect leakage resistances and circuit losses. With a fault to ground on conductor 1, the voltage across C_1 falls to zero, while the voltages across C_2 and C_3 become line-to-line voltage, E_{2G} and E_{3G}, respectively, as shown by the vector diagram of Fig. 1(*b*). The current in the fault $(I_{2G} + I_{3G})$ will then be the sum of the currents through the capacitances to ground. This current will lead the residual voltage E_R by approximately 90 deg, as shown in Fig. 1(*b*). Consider now that the Petersen coil, a variable inductance, is connected between neutral and ground (switch S closed). The voltage between neutral and ground E_{GN} $(E_R/3)$ impressed across this inductance will cause a current I_{NG} $(-I_P)$ to flow which will lag

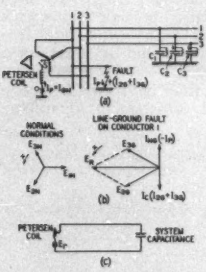


Fig. 1. Petersen coil system, showing (a) system connections, (b) simplified vector diagram, and (c) equivalent single phase circuit

E_{1G}, E_{2G}, E_{3G} = line-to-ground voltages
E_R = residual voltage to ground $= E_{1G} + E_{2G} + E_{3G}$
I_C = charging current to ground from sound phases
I_P = Petersen coil current, ground to neutral

this voltage by approximately 90 deg. As the path of this lagging current is also through the fault, the fault current will now become the vectorial sum of $-I_P$ and $+I_C$. If the Petersen coil is tuned so that its inductance is of the correct value, I_P will be equal and opposite to I_C and, neglecting losses, the fault current will theoretically be zero. Actually, losses due to conductor resistance, corona, etc., cause a small amount of in-phase current (not shown in this vector diagram) which is not balanced out by the Petersen coil. This unbalanced current in the fault is expected to be of such a small value that arcs over insulator strings, or across gaps of the same lengths, will be unstable and will be broken by air currents within a few cycles.

Since under normal operating conditions voltage between neutral and ground is of very low value, the Petersen coil can be left in the circuit at all times and hence is at once effective in case of a fault to ground. Provision is sometimes made for taking the coil out of service in case a permanent fault develops (such as, a conductor on the ground, a punctured insulator, etc.). Obviously, the Petersen coil can be effective in clearing trouble only when the fault is an arc from one conductor only to ground inasmuch as trouble involving more than one conductor constitutes a line-to-line short circuit.

Previous Operating Experience

Although the installation of Petersen coils on the Consumers Power Company system is the first application to systems above 100 kv in this country, it is not to be inferred that they are a new development in the art. The first coils were built and installed in Germany in 1917, and since then the installation of ground-fault compensating coils has come to be considered standard practice in Germany (the law there prohibits solidly grounding the neutral), with the result that today practically all high voltage systems there are so equipped. Lines protected by these coils total 100,000 miles in length with operating voltages as high as 220 kv.

In 1921 the first Petersen coil in the United States was put in service on a 93-mile 44-kv system in Alabama.[2,3] The coil used in this installation was later found to have certain electrical characteristics which permitted resonant conditions and consequent overvoltages. (To eliminate this behavior, coils are now designed to saturate at abnormal voltages and so destroy the condition of resonance with rise of voltage.) Its service record, however, was satisfactory as it neutralized approximately 55 per cent of the faults which occurred on the system. The coil was taken out of service when extensive changes were made on the 44-kv system, which resulted in a considerable increase in the connected circuit mileage. The coil was moved to a location on the Georgia Power Company's system where it has been in successful operation on a small 44-kv section of line up to the present time.

Description of Installations

The 140-kv lines of the Consumers Power Company having a total connected length of approximately 1,000 miles are arranged in the shape of a large "U" extending along the eastern and western sides and through the southern portion of the state of Michigan. Power is generated by hydroelectric generating stations and by steam generating stations located at various advantageous points close to the load centers. The system is interconnected with the Detroit Edison Company through a 132-kv

transmission line and a 30,000-kva transformer bank.

The 2 Petersen coils installed on the system of the Consumers Power Company in 1931, one at Saginaw and one at Alcona, were manufactured by the General Electric Company and have identical characteristics. They are each rated: 10,773 kva, 133 amp, 60 cycles, 81 kv, and are protected by a thyrite resistor installed inside the tank under oil and connected across the terminals. Tap changing under load equipment is provided which permits the use of any of the taps indicated in Table I.

Table I—Petersen Coil Characteristics

Tap	Impedance	10-Min Rating
1	4.46 + j1482 ohms, 100.0%	56.6 amp
2	3.95 + j1206 ohms, 81.4%	86.4 amp
3	3.55 + j1020 ohms, 68.8%	75.7 amp
4	3.17 + j870 ohms, 58.8%	86.2 amp
5	2.97 + j770 ohms, 52.0%	95.2 amp
6	2.76 + j676 ohms, 45.7%	105.0 amp
7	2.60 + j611 ohms, 41.3%	115.0 amp
8	2.46 + j556 ohms, 37.5%	125.0 amp
9	2.38 + j515 ohms, 34.8%	133.0 amp

At Saginaw the coil is connected in the neutral of a 9,000-kva wye-delta connected transformer bank having a zero sequence impedance of 76 + j638 ohms. At Alcona the main 9,000-kva station transformer bank is connected wye-delta with the Petersen coil in the neutral circuit. The zero sequence impedance of this transformer bank is 17 + j202 ohms. Each coil was specified to cover a range of 75 to 175 miles and to have taps which would be suitable for tuning equal increments of line, which required that the percentage change in impedance between the Petersen coil taps be smaller at the higher taps.

The installations are arranged so that if a line-to-ground fault persists, the Saginaw coil will be short-circuited by an oil circuit breaker connected by a definite time overcurrent relay and the neutral circuit at the Alcona plant will be opened by a circuit breaker after a similar time delay. The neutral of the system then will be grounded directly by the Saginaw bank permitting ordinary directional residual ground relays to clear the section of line in trouble.

Purpose of Tests

The purpose of the tests was to determine experimentally the proper tuning for the coils as compared with calculated tuning points and to check the operation of the coils under various fault conditions similar to those which might be expected in practice. Tests were made to determine the tuning point as indicated by observation of the neutral current under normal conditions, and compare it with the tuning point determined by measurements of fault current under fault conditions. Observations were made regarding the effect on coil tuning of the location of the fault, the conductor faulted, and the operation of the system at voltages ranging from 70 to 140 kv. A study was made of the performance of the system with Petersen coils as compared with its behavior as an isolated neutral or grounded neutral system.

The tests may be divided into the following classifications:

1. Tuning of Petersen coils with power system
   a. Method using neutral ammeter under normal conditions
   b. Method involving line-to-ground faults
2. Line-to-ground fault tests with neutrals of wye-delta transformer banks at Saginaw and Alcona connected:
   a. Isolated
   b. To ground through Petersen coils
   c. Directly to ground (high impedance grounding bank)
   d. To ground through resistance
3. Harmonic analysis of power system wave shape with the neutrals of the wye-delta transformer banks at Saginaw and Alcona connected:
   a. Isolated
   b. To ground through Petersen coils
   c. Directly to ground (high impedance grounding bank)

Tests were made with the transmission lines operating at voltages from 70 to 140 kv with various Petersen coil taps, different values of neutral impedance, etc.

Electrical Characteristics of Test Systems

The electrical characteristics of that portion of the system set apart as the Petersen coil system are shown in Fig. 2. It will be noted that this is a 226-mile portion of the 140-kv network isolated from the remainder of the system through delta-delta transformer banks. During the staged tests this section was taken out of service and energized from

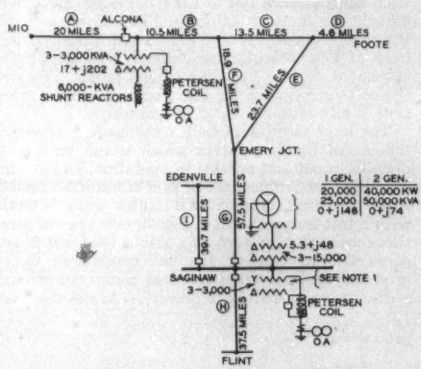


Fig. 2. Electrical characteristics of the test system

Line Section	R + jX1 Ohms	Z1 Ohms	Conductor Size	Conductor Spacing
A	10.6 + j17.5	20.5	110,000 cir mils	15.4 ft
B	5.59 + j 9.19	10.8	110,000 cir mils	15.4 ft
C	7.19 + j11.8	13.9	110,000 cir mils	15.4 ft
D	2.45 + j 4.02	4.71	110,000 cir mils	15.4 ft
E	12.6 + j20.8	24.4	110,000 cir mils	15.4 ft
F	10.1 + j16.5	19.3	110,000 cir mils	15.1 ft
G	30.6 + j50.3	58.9	110,000 cir mils	15.4 ft
H	19.1 + j32.6	37.9	110,000 cir mils	15.4 ft
I	17.5 + j34.2	38.4	No. 2/0	15.1 ft

Note 1. Transformer impedance equals 76 + j638 with high voltage windings connected in series; and 30 + j159 with high voltage windings connected in parallel

Measured line capacitance equals 0.0087 μf per mile

Ohms impedance given on 140-kv base

an independent power source located at Saginaw and consisting of either 1 or 2 20,000-kw turbine-generators. The majority of the transmission line conductors on this 226-mile portion consisted of 110,000 cir-mil copper. All circuits except the Saginaw-Edenville line are of single circuit construction arranged in triangular configuration without ground wires.

Test Equipment Set-Up

As it was desired to make measurements at a number of points on the system, the set-up of recording equipment was necessarily quite complicated. Because quantities to be measured were likely to vary rapidly with time, and as fault conditions were to be of very short duration, practically all records were made by means of oscillographs operating at reasonably high film speed, supplemented in a few cases by recording ammeters.

At Alcona no potential transformers were available for the measurement of 140-kv line-to-ground potentials. Use was therefore made of 50-ft water hose potentiometers similar to those previously used with entire satisfaction on similar test work.[4] At all other locations measurements were made through conventional current and potential transformers.

The test schedule required the use of a neutral grounding resistor and a fault resistor to be used in simulating a fault to a tower of high footing resistance or other condition in which considerable resistance was present in the fault-current circuit. These requirements necessitated the use of a resistance varying from 100 to 1,000 ohms and capable of carrying as high as 300 amp. The device used for this purpose consisted of 2 inverted U-shaped sections of 4-in. sluicing hose through which brine was circulated rapidly by a centrifugal pump. Varying the concentration of the brine made possible a selection of any required value of resistance.

The large number of fault tests made necessary a scheme of fault initiation which would be safe to operate, rapid and reliable in operation, and of such a nature that faults could be synchronized accurately with the oscillographs. All faults were initiated with a test frame shown in Fig. 3. As may be seen, this consisted of a horn gap, one side of which was connected to one of the line conductors to be grounded and the other side was connected through a disconnecting switch to ground. Across this horn gap was placed a 2-amp fuse wire when arcing faults were required, and a copper jumper when a solid fault was required. With the disconnecting switch open, the system was free of grounds and operated normally. At a given signal, rung over telephone lines, all oscillographs were started and at the test frame, a trap was sprung, permitting a weight to fall. This weight was attached to the disconnecting switch through a slack rope and after about 0.5-sec time delay, tightened up the rope and snapped the disconnecting switch shut very quickly, grounding the line. Because of its high speed of closing, the disconnecting switch was undamaged by several hundred operations in which fault current was as high as 400 amp.

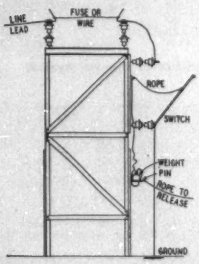


Fig. 3. Test rack

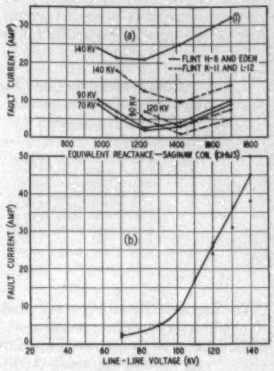


Fig. 4. Fault currents, showing (a) fault tuning tests and (b) fault current with Petersen coils in tune

Petersen Coil Tests

The reactance tap at which the Petersen coils tune with the system capacitance was determined by calculations and by tests under both normal conditions and fault conditions. Ammeter tuning tests, fault tuning tests, and tests to determine the effect of corona are described in the following sections.

Ammeter Tuning Tests

In Fig. 1(*a*) is represented a simple transmission system with its neutral grounded at one point through an inductance, and in Fig. 1(*c*) is shown the equivalent single-phase circuit to ground of this same system. In any polyphase system there is always some residual voltage to ground due to dissymmetry between phases and to ground. The voltage E_r in Fig. 1(*c*) represents this unbalanced voltage and with perfect tuning the current in the series circuit due to this voltage would be a maximum. In other words, when the inductance of the Petersen coil plus that of the grounding bank is tuned with the system capacitance to ground, the current in the neutral circuit will be a maximum

and will be limited only by the resistive losses in the circuit.[5]

These facts were used in the ammeter method to determine the tuned tap with the system in normal conditions by noting the magnitude of the neutral current when the coil was operated on various tap positions. With the Saginaw coil connected to the Flint-Edenville lines (sections H and I in Fig. 2) the tuning was relatively sharp at tap 3 with a neutral current of 4.6 amp. The neutral current was much steadier when the test system was synchronized with the remainder of the system than when it was operated isolated, possibly due to somewhat closer control of frequency. With the Alcona coil connected to the lines north of Saginaw (sections A to G, inclusive) the tuning was broad, between taps 8 and 9, which is close to the minimum value of coil reactance obtainable. With the Mio section of line off, the tuning point was tap 6 with a neutral current of approximately 7 amp.

Fault Tuning Tests

Fault tuning tests were made by placing a solid fault-to-ground on one of the conductors with the Petersen coils on one tap position and measuring the current in the fault. The fault was then cleared manually, the Petersen coils set on a different tap

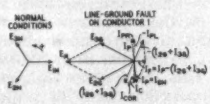


Fig. 5. Petersen coil system, showing complete vector relations at point of fault

E_{NG} = neutral-to-ground voltage
E_{1G}, E_{2G}, E_{3G} = line-to-ground voltages at fault (E_{1G} = 0)
E_R = residual voltage to ground = $E_{1G} + E_{2G} + E_{3G}$
I_0 = charging current to ground from sound phases 2 and 3
I_{COR} = equivalent leakage current to ground due to corona
$I_{2G} + I_{3G}$ = resultant line-to-ground current from phases 2 and 3
I_{PL} = inductive component of Petersen coil current
I_{PR} = resistive component of Petersen coil current
I_P = Petersen coil current, ground to neutral
I_F = fault current

and the test repeated. The coils were considered to be "in tune" when the fault current was a minimum. Curve 1 of Fig. 4(a) shows the results of tuning tests made at 140 kv with the Saginaw coil connected to the Flint H-8 and the Edenville lines. In this curve the variation of fault current is shown as a function of the equivalent neutral reactance. This equivalent neutral reactance is equal to the reactance of the Petersen coil plus one-third of the transformer reactance and is thus equal to one-third of the zero sequence reactance. This curve shows the Saginaw coil to be in tune at 1,230 ohms (tap 3) with a fault current of 21 amp. The Alcona coil, with the Au Sable section of line, tuned at 623 ohms (tap 8) with a fault current of 31 amp at 140 kv. The entire 226-mile test section was in tune with the Alcona coil on tap 8 and the Saginaw coil on tap 4. Under these conditions the fault current varied from 40 to 50 amp during different tests.

Tests were also made to determine the effect of different fault locations on the coil tuning. It was found that a change in fault location caused no definite change in tuning with operating voltages ranging from 70 to 140 kv. The tuning of the coil was the same regardless of which conductor was faulted. It also was found that the results were practically the same irrespective of whether or not the test system was synchronized with the remainder of the system through delta-delta transformer banks at Saginaw. However, with the system synchronized, the fault current contained a number of harmonics, particularly the third, fifth, and seventh.

Effect of Corona

It may be seen from the above that although the changing of the coil taps caused a change in the magnitude of the fault current, the minimum value of fault current obtainable on the 226-mile system was surprisingly high in value. In order to determine the cause of this high current, tests were made at various operating voltages ranging from 70 to 140 kv line-to-line. In Fig. 4(b) is shown the minimum values of fault current obtained with the entire test system operating at these voltages and with the coils operating on the tuned taps. This curve shows that the fault current was not directly proportional to the voltage, but rather varied as some higher power of the voltage and suggests that the difficulties encountered may be due to corona. The tuning curves for different coil operating taps were of the same general shape as those shown in Fig. 4(a). The wave shape of the fault current was in general more irregular for faults at 140 kv than at 70 kv, probably due to the presence of harmonics caused by corona at the higher voltages. The equivalent coil reactance required for the tuning at 140 kv was 415 ohms as compared to 455 ohms at 70 kv, indicating that the system capacitance to ground was greater at the higher voltage. The results of these tests are further illustrated by Table II.

Table II—Summary of Fault Tuning Tests, Saginaw and Alcona Coils

Sag. Bus Voltage	Tuned Taps	Fault Current (I_f)	Remarks
140 kv	S3, A8	38–50 amp	Tuning curve flat
130 kv	S3, A8	31–36 amp	Tuning curve flat
120 kv	S3, A8	24–27 amp	
70 kv	S1, A8	Approx. 2 amp	Tuning curve sharper than at 140 kv

The critical corona voltage on a 110,000-cir-mil 3-phase line is of the order of 125 kv rms line-to-line with the system operating normal, and about 100 kv with one conductor grounded. A considerable amount of corona might therefore be expected under line-to-ground fault conditions at 140 kv and would be evidenced as fault current since the in-phase component of corona current to ground adds directly to the resistive losses in the circuit. That this uncompensated current is produced by some form of system loss is further substantiated by the fact that the fault current to ground ($-I_f$) was found

to be practically in phase with the residual voltage as illustrated by Fig. 5. As a further check on this possibility, tests at various voltages were made, using the Saginaw-Flint K-11 and L-12 lines in place of the Flint H-8 and Edenville lines with the Saginaw coil. The K-11 and L-12 lines comprise a twin circuit line of No. 000 copper conductors with one ground wire and have a total circuit length of 87.6 miles. These lines, with their larger conductors, consequently have less corona loss than the Flint H-8 and Edenville lines. The curves of Fig. 4(a) show the variations of fault current with tap setting and voltage as determined by graphic ammeter records and checked by oscillograms. It may be seen that the effect of a change in wire size was much more pronounced at 140 kv than at the lower voltages. The K-11 and L-12 lines have a slightly greater total circuit length than the other pair of lines, but the expected increase in capacitance due to this was apparently more than offset by the decrease in capacitance resulting from the K-11 and L-12 lines being on the same towers. The K-11 and L-12 lines tuned on tap 2 with a much lower value of fault current, particularly at the higher voltages than the Flint H-8 and Edenville lines. The effect of varying voltage or wire size, the phase relation between fault current and residual voltage and calculations of critical corona voltage all indicated that the high values of fault current were the result of excessive corona loss under fault conditions.

Tests With System Neutral Isolated, or Grounded

A number of single-line-to-ground fault studies were made on the test system with the neutral isolated or grounded by means of a grounding bank, directly or through resistance. Part of these tests were made to compare the performance with that observed with the Petersen coils in operation; some were made to study other problems, taking advantage of the conveniences of the Petersen coil test setup. The transformer bank used in the "grounding bank" tests had a relatively high impedance (76 + j638 ohms) and this test condition therefore cannot be termed solidly grounded even though the neutral of the bank was directly grounded. In all these tests, conditions were somewhat abnormal in that the amount of generating capacity and transformer capacity as compared to the length of the test system was only approximately one-half normal, and at the instant of fault the generators were operating at practically no load and with very low values of excitation. Table III shows a comparison of the performance of this system with the various forms of neutral connections. The simplified system connections and the vector relations for the isolated and grounded neutral conditions are illustrated by Fig. 6 and Fig. 7, respectively.

During the isolated neutral tests at 140 kv the fault currents ranged from 355 to 455 amp with zero ohm faults. These currents were considerably higher in magnitude than had been indicated by preliminary calculations, which neglected corona currents. Moreover, in the isolated neutral tests, abnormal generator conditions (described above) became particularly important because of the large amount of charging current to ground which appeared as a capacitive load on the generators, tending to increase the excitation during faults. While this was somewhat counteracted by the eventual reduction in speed due to the large unbalanced load, the generator voltage rose considerably during the early period of faults. It therefore may be concluded that the increase in fault current over what might normally be expected was evidently due largely to corona on the unfaulted conductors and to the increased charging current to ground, both of which were materially affected by the high voltage between the unfaulted conductors and ground.

The grounding tests were made with the neutral of the 9,000-kva wye-delta transformer bank at Saginaw grounded either solidly or through resistance ranging from 100 to approximately 1,000 ohms. This bank was originally designed for 30-cycle operation and its impedance was therefore relatively high at 60 cycles. The bank when solidly grounded tended to act similarly to a Petersen coil approximately 50 per cent out of tune. During the neutral resistance tests the bank was connected first with the high voltage windings in series (Z = 76 + j638) and then in parallel (Z = 30 + j159). It was rather striking to note that the residual voltage and fault current increased while the neutral current decreased with increasing neutral resistance, contrary to what might at first be surmised. These results were due to the effect of the transmission line capacitance to ground on the total circuit impedance. The zero sequence capacitive impedance of the test system acted in parallel with the equivalent impedance of the grounding bank and neutral resistance in limiting the fault current, and with neutral resistances above approximately 160 ohms the system capacitance became controlling. The

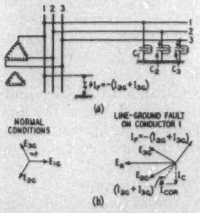


Fig. 6. Isolated neutral system showing (a) system connections, and (b) vector relations

Symbols same as shown for Fig. 5

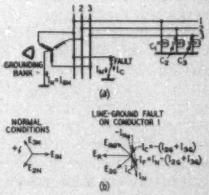


Fig. 7. Grounded neutral system showing (a) system connections, and (b) vector relations

Symbols same as shown for Fig. 5 except as follows:
I_N = current in neutral = I_{GN}
I_C = charging current to ground from sound phases 2 and 3 assuming corona current negligible

Table III—Comparative Typical Values of Currents and Voltages for Solid Low Resistance Faults at 140 Kv

Equiv. Neut. Impedance[1] (Ohms)	Neutral Resistance (Ohms)	Fault Current (Amp)	Current in Neutral (Amp) Saginaw	Current in Neutral (Amp) Alcona	Saginaw Residual Voltage (Kv)	Maximum Line-Ground Voltage (Times Normal[2])	Shock to Power System
Petersen coil tests							Slight
	0	40–50	30–60	130–180	250–290	2.0 (2.7)	
Isolated neutral tests							Severe
		350–450			390–410	2.9 (3.5)	
Grounding bank							Severe
25 + j213	0	110–120	180–200		130–140	1.4 (2.0)	
Neutral resistance (high voltage windings in series)							Severe
160 + j213	135	140–150				1.6	
375 + j213	350	170–180				1.9	
545 + j213	520	230				2.1	
Neutral resistance (high voltage windings in parallel, power suplied by 2 generators)							Severe
110 + j53	100	290	250		240	1.3	
380 + j53	370	270	160		200	1.9	
830 + j53	820	320	110		290	2.3	
1010 + j53	1000	310	100		310	2.4	

1. Value of neutral impedance given includes impedance of grounding bank and is expressed as one-third of the "per phase" value.
2. Times normal is equal to the maximum observed crest value divided by the normal crest value prior to the fault. Some of the maximum voltages listed were obtained during arcing faults.

Values in parentheses are based on surge recorder records, others on oscillograms.

Table IV—Relative Magnitudes of Induced Voltages

Neutral isolated	1.0
Petersen coils	0.4
High impedance grounding bank	0.7
Neutral resistance	1.4

resultant zero sequence impedance then had a capacitive reactance component which was neutralized to some extent by the inductive reactances of the positive and negative sequence impedances.

One of the most interesting features of the comparative tests was the observation of shock to the generators at the time of faults. With the Petersen coils in service there is practically no discernible effect. The severity of the shock was greatest when the neutral was isolated and somewhat less when the neutral of the grounding bank was grounded through a resistance.

Behavior of Arcs

It may be observed from Table III that with the Petersen coils in service the fault current was very much less than with the system neutral isolated or grounded. Obviously, an arcing fault on this Petersen coil system, because of its lower current, would be much less damaging to insulators, line conductors, and hardware, than would a similar fault on the other types of systems. A few tests were made with the system neutral isolated, grounded or connected to the Petersen coils to study experimentally the effect of circuit characteristics on the tendency of the arc to be self-extinguishing. Although the number of tests was too limited for definite conclusions, the tendency seemed to be for arcs of low current value to be less stable than those of higher value.

Inductive Influence Tests

The toll circuits of the Michigan Bell Telephone Company parallel the Saginaw-Emery Junction-Foote 140-kv transmission lines north of Saginaw for considerable distances at various separations, ranging from 65 ft to approximately 3 miles. Harmonic analyses and measurements of induced voltages and noise were made on the toll circuits in conjunction with the tests on the power system. The relative magnitudes of the low frequency voltages induced during the different power system operating conditions are given in Table IV for faults at Alcona. These relative values of induced voltages would be altered, of course, for other situations according to the separation between the circuits, fault location, etc. For convenience in comparing the values, the induced potential with the system neutral isolated has been used as a reference.

The higher induced voltage for the neutral resistance condition is explained by the increased fault current over that for the grounding bank condition. This increase is due to the capacitive nature of the zero sequence impedance which is comparable in magnitude with other reactive impedances of the circuit.

The results of the harmonic analyses showed that under normal operating conditions the harmonic content of voltages to ground, residual to ground and neutral current of the power system, was practically the same for the various neutral connections. The most prominent frequencies observed were 180, 300, and 420 cycles. The noise observed on the telephone circuits was about equal for the various neutral connections.

Overvoltage Conditions

As a part of this investigation a study was made of the voltages produced on the line conductors by various types of faults under different system conditions. Table V shows the maximum voltage between conductor and ground recorded by the oscillographs at the time of faults of the type indicated. As may be noted voltages on the isolated neutral system were the highest of the group, voltages on the Petersen coil system next, and those of the resistance or solidly grounded system were lowest.

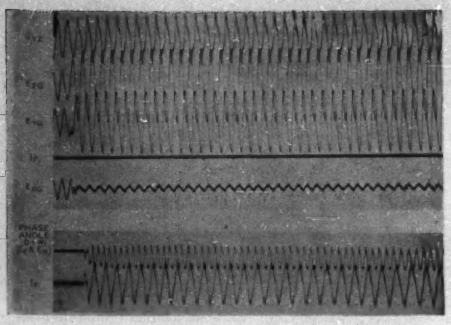


Fig. 8. Oscillogram of solid fault to ground with isolated neutral system

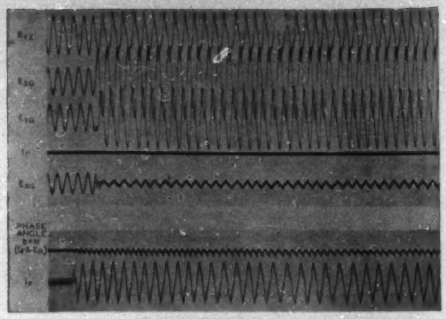


Fig. 9. Oscillogram of arcing fault with isolated neutral system

Table V—Conductor to Ground Voltages (Times Normal)

Type of System	Oscillographic Record Solid Fault	Oscillographic Record Arcing Fault	Surge Recorder Record Solid Fault	Surge Recorder Record Arcing Fault
Petersen coil	2.0	2.0	2.7	2.2
Isolated neutral	2.9	2.8	3.2	3.5
Grounding bank	1.4	No tests	2.0	No tests
Neutral resistance	2.4	2.3	2.5	2.5

It is of interest to note that voltages resulting from arcing faults are of the same magnitude as those resulting from solid faults and that in no case did they exceed 3.5 times normal (2.9 times normal by oscillograms). In all the tests made, either with solid or arcing faults, the voltage between sound conductors and ground was predominately 60 cycles, sometimes with some third or fifth harmonics superposed. (See Figs. 8 and 9.) In no case was there evidence of cumulative overvoltages due to restriking of the arc. These data, with other information previously presented,[4] seem to discredit the many theories based upon arc extinction which have been proposed regarding arcing ground faults and which, on isolated neutral systems, predicted overvoltages of as high as 7 times normal. All these theories have required that the arc break and restrike at certain parts of the cycle, resulting in an accumulation of voltage which according to certain theories had high frequency characteristics.

Clearing of Permanent Ground Faults

Petersen coils can, of course, be effective as regards the extinction of arcs only in case of faults which are of a momentary nature, such as flashovers. Other faults, such as exist when conductors lie in contact with ground, are of a permanent nature and cannot be cleared by Petersen coil operation. In such cases the line involved must be deenergized by circuit breaker operation, either manually or automatically by protective relays. Directional ground relays, such as are commonly used for transmission line protection, depend for their operation upon the magnitude and phase relations of the currents and voltages existing during fault conditions. A study of these quantities as determined during the staged tests indicates that with permanent faults it would be very difficult, if not impossible, to obtain proper relay selectivity with the Petersen coils in service. The most feasible means of clearing such faults when they have developed appears to be to short out the coil by a suitable relay, thus effectively grounding the system, and then to select the faulted circuit by the use of ordinary ground relays. Numerous complications are involved in the application of such a relaying scheme to a network where several coils are installed at widely separated localities. Studies have indicated that practicable solutions to this problem may be effected by one or more methods.

Petersen Coil System Operating Record

Following the staged tests, the Petersen coils were put into regular operation on the system on August 27, 1931, and remained in service until October 17, 1931, when their operation was discontinued because no more serious lightning storms were anticipated that year. The coils were again put in service on February 13, 1932, and have been in continuous service during the remainder of 1932 and all of 1933. In 1933, one more line between Saginaw River Steam Plant and Flint was added to the Petersen coil system, increasing the total length of lines connected to 276 circuit miles. During the entire time the coils have been in operation, their performance has been recorded by a 6-element automatic oscillograph and 2 high-speed curve-drawing ammeters. The ammeters, one located at Saginaw and one at Alcona, record the current through the respective coils. The automatic oscillograph, located at Saginaw, records the voltages of the X, Y, and Z conductors with respect to ground, residual voltage, Petersen coil current, and residual current in the H-8 line north of Saginaw. From these instruments it has been possible to get a very

complete story of the nature of the faults, their duration, the nature of the transient at the time the fault is cleared, and other important information.

Table VI gives a summary of the performance of the Petersen coil system for its entire period of operation up to the end of August, 1933. As may be seen, practically every single-line-to-ground fault has been eliminated without circuit breaker operation and subsequent outages to the lines. As line to line faults are unaffected by the Petersen coils, faults of this nature in most cases required breaker operation for their elimination.

The length of time required for ground faults to clear themselves is shown by Fig. 10. From this curve it may be seen that 50 per cent of all ground faults cleared in less than 20 cycles and 70 per cent cleared in less than 60 cycles. The maximum length of time required for a fault to clear was 14 sec. The location of this 14-sec fault was definitely determined and the damage to insulators and line hardware found to be insignificant, indicating that arcs constituting ground faults on this Petersen coil system are not very damaging in effect. Up to date (August 31, 1933), only one record has been obtained indicating that a fault which started as a ground fault developed into a short circuit before being cleared. As indicated in Fig. 10 a large number of ground faults have been entirely eliminated in less than 5 cycles. That the rapid elimination of the faults is a characteristic of the Petersen coil system is evidenced by the fact that automatic oscillographic records taken on the balance of the Consumers Power Company's 140-kv system operating with isolated neutral (length approximately 600 miles, ground fault current approximately 900 amp) show no faults clearing in less than the time required for relaying and breaker operation. The limited value of fault current on the Petersen coil system possibly prevents the establishment of even a semi-stable arc in a large percentage of the cases.

An oscillographic record of a typical ground fault is shown in Fig. 11. It may be noted that during the period of this fault, the voltage waves were very little distorted from sine waves with the exception of that on the faulted conductor, which was the voltage of the arc. At the start of the fault, the sound conductor voltages rose to line-to-line voltage with no evidence of excessive magnitudes due to arcing grounds. (The maximum voltage recorded by the oscillograph since the coils went into operation is 2.8 times normal.) As the arc was increased in length by the wind, the faulted conductor voltage rose gradually while the sound conductor voltages decreased accordingly. When the arc was extinguished, all voltages returned to normal within a few cycles without any unusual behavior. On a few oscillograms, restriking of the arc has been indicated. Faulted conductor voltage rose to almost normal value, apparently as the arc was increased in length by the wind and voltage values approached normal. Then as the arc restruck, and its length substantially decreased, voltage conditions again became characteristic of line to

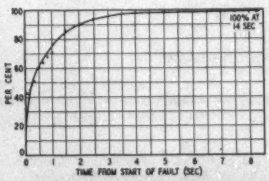


Fig. 10. Percentage of ground faults self-cleared in various lengths of time. Total number of faults 52

Table VI—Summary of Petersen Coil Operation

	1931, Aug. 27–Oct. 17	1932, Feb. 13–Dec. 31	1933, Jan. 1–Aug. 31	Total
Cause of Faults				
Lightning	12	27	46	85
Sleet	0	3	0	3
Unknown and other causes	1	2	10	13
Total	13	32	56	101
Type of Fault and Method of Clearing				
Line to ground faults	6	16	31	53
Self-clearing, no line interruption	5	16	30	51
Cleared by breaker operation	1[1]	0	1[2]	2
Short circuits	1	9	6	16
Self-clearing, no line interruption	0	1	0	1
Cleared by breaker operation	1	8	6	15
Faults which could not be definitely classified as to nature[3]	6	7	19	32
Self-clearing, no line interruption	4	4	15	23
Cleared by breaker operation	2	3	4	9
Per cent of all faults cleared without interruption to line	69	66	80	74

1. Line failure, insulator string parted
2. Developed into a short-circuit
3. Includes faults which because of lack of oscillograms or difficulty of interpretation could not be definitely classified as short circuits or ground faults

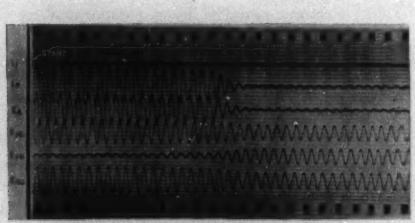


Fig. 11. Oscillogram of typical ground fault

I_r = residual current in Saginaw-Emery Junction line
I_P = Petersen coil current
E_R = residual voltage to ground
E_{XO}, E_{YO}, E_{ZO} = line-to-ground voltage

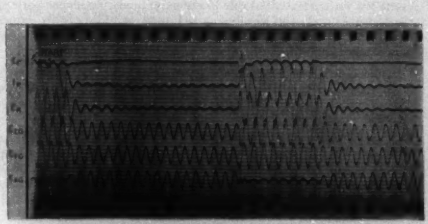


Fig. 12. Oscillogram of recurring fault

Symbols same as shown for Fig. 11

ground faults. The transition between these 2 conditions occurred without abnormal voltage on any of the conductors, although irregular waves of moderate value were recorded in the record of Petersen coil current and residual current.

A type of fault which has been recorded in a few cases is shown in Fig. 12. This oscillogram indicates that a ground fault on the X conductor was cleared in less than 5 cycles. Normal conditions were established on the system, but at the end of 17 cycles the fault recurred on the X conductor and was again cleared after 9-cycles duration. Faults of this type have a similarity in that the second disturbance began within 30 cycles of the start of the first and affected the same conductor, with no evidence of overvoltage being recorded by the oscillograph. It has been suggested that these repeating faults have been caused by multiple strokes of lightning, the first stroke establishing a fault which was quickly cleared, only to be followed by another established by a second stroke of lightning, possibly at the same tower. That multiple strokes of lightning going to earth at the same point are rather common in occurrence has been well established by pictures made with revolving cameras.[6]

Conclusions

The following conclusions may be drawn from the results of the staged tests and the subsequent operating experience:

1. The shock to the system during line to ground faults is very small with the Petersen coils in service, being considerably less than with the neutral either isolated or grounded through a high impedance grounding bank.

2. The ground fault current with the Petersen coils in service is relatively small.

3. The tuning of the Petersen coils for a given system may be determined either by calculations, by ammeter tuning, or by fault tuning. The operation of the coils when in tune was not affected by the location of the fault or by the particular conductor selected for the fault.

4. Successful operation of the coils as regards arc extinction requires that the uncompensated fault current be kept to a moderately low value, probably less than 50 amp. The magnitude of the fault current is vitally affected by the length of the connected system and the amount of leakage current to ground, including corona. It is very important that the line conductor sizes and the transmission voltage be properly correlated so that the corona current will not be excessive during fault conditions.

5. The maximum overvoltages recorded during the staged tests were approximately 3 times normal. In no case were there any excessive voltages attributable to arcing grounds, resonance between the Petersen coils and the line capacitance, or to any other causes. The voltage conditions during arcing and solid fault conditions were practically identical.

6. The clearing of permanent line to ground faults by automatic relay operation involves certain complications on a Petersen coil system, but it appears that these may be taken care of in a practical manner.

7. Operating experience on the 276-mile section of this system has demonstrated that the Petersen coils successfully eliminate a large percentage of interruptions due to line to ground faults. In 96 per cent of the cases of ground faults (74 per cent of all faults) the arc has been extinguished and the fault cleared without line interruptions.

8. Faults of the current magnitude experienced in this section (approximately 50 amp or less) require various lengths of time for extinction. Some apparently do not develop into a stable condition and are extinguished within a very few cycles, while others continue for several seconds. The local arc damage has been found to be insignificant.

9. The Petersen coils do not affect or handicap the normal routine operation of the system, except to require change of tap setting with changes in length of connected transmission lines.

Acknowledgment is made to the Joint Subcommittee on Development and Research of the Edison Electric Institute and the Bell Telephone System, to The Michigan Bell Telephone Company, and to the General Electric Company, for the extremely valuable assistance rendered by these organizations. Special recognition is due to A. C. Connell, I. R. Dohr, J. M. Dunham, A. F. Gramm and J. K. Peck, and others of the participating organizations, for their excellent assistance in the conduct of these tests and analyses of the data.

Appendix

The design characteristics of a ground fault compensating coil and the effect of such a coil on the magnitude and distribution of current under fault conditions, as compared to operating with the neutral isolated or grounded, may be determined analytically from a knowledge of the electrical characteristics of the transmission system.

Principles of Ground Fault Compensation

It has been previously explained in this paper that a ground fault compensating coil consists of an inductance L which is designed to be connected in the neutral circuit of a system and tuned with the capacitance to ground C_G of the transmission circuits so that:

$I_L = I_{CG}$ and, neglecting losses

I_F = zero

To accomplish this compensation of the ground fault current, the inductance L of a Petersen coil together with its associated transformer bank, and the capacitance to ground of the system, must be such that:

$$2\pi f L = \frac{1}{2\pi f C_G} \quad \text{and}$$

$$\text{inductance} \quad L = \frac{1}{(2\pi f)^2 C_G} \text{ henries, and}$$

$$\text{inductive reactance } X_L = \frac{1}{2\pi f C_G} \text{ ohms} \tag{1}$$

where

C_G = zero sequence capacitance to ground of transmission system with one conductor grounded (farads)

f = frequency

I_{CG} = charging current to ground through capacitance C_G (amp)

I_L = current to ground through inductance L (amp)

I_F = fault current (amp)

L = zero sequence inductance of coil and transformer bank (henries)

X_{CG} = zero sequence capacitive reactance to ground of transmission system (ohms)

X_L = zero sequence inductive reactance of coil and transformer bank (ohms)

X'_L = inductive reactance of coil and transformer bank to residuals (ohms)

X_{Coil} = inductive reactance of coil alone (ohms)

$X_{Transf.}$ = inductive reactance of associated transformer bank (ohms)

With a Petersen coil connected in the neutral of a wye-delta transformer bank and considering the zero sequence network:

$$\text{Zero sequence reactance } X_L = 3X_{Coil} + X_{Transf.} \tag{2}$$

Viewed from the standpoint of reactance to residuals then:

Residual reactance $X'_L = X_{Coil} + X_{Transf.}/3$ (3)

$X_L = 3X'_L$ (4)

In considering the application of such compensating coils to a system, the maximum and minimum lengths of line which are to be controlled by a single coil must first be decided. Then, after determining the capacitance to ground or the charging current to ground of these line sections, the inductance of the coil may be found. Knowing the wire size, configuration, spacing, height of conductors above ground, number of ground wires, etc., of the transmission lines, the capacitance between wires and ground may be determined by the formulas given by Clem[7] or by the method described in the article "Protection Against Earth Faults."[8]

Typical Example

For example, consider that it is desired to apply a Petersen coil to a 132-kv transmission system where the total length of line sections for a single coil will be between 75 and 150 miles and where the transmission line sections will consist of single circuit lines on steel towers with one ground wire, the conductors 3/0 copper with an equivalent spacing of 15 ft and at an average height of 40 ft above ground. The calculated zero sequence capacitance to ground C_G will be found to be 0.008 μf per mile

$$\text{Capacitive reactance } X_{CG} = \frac{1}{2\pi f C_G} \text{ ohms} \quad (5)$$

$$X_{CG} = \frac{10^6}{(2\pi)60(0.008)} = \text{Approx. 330,000 mile-ohms (zero sequence)}$$

$$\text{Charging current } I_{CG} = \frac{3E_N}{X_{CG}} \text{ amp} \quad (6)$$

$$I_{CG} = \frac{3\ (76{,}200)}{330{,}000} = 0.69 \text{ amp/mile}$$

Now assume further that the wye-delta connected transformer bank to be used with the coil is rated 132–13.2 kv, 15,000 kva and has an impedance of 200 ohms at 132 kv. The coil characteristics may then be determined as follows:

	75 mile	150 mile
$X_L = X_{CG}$ by eq 1	4,400 ohms (330,000/75)	2,200 ohms (330,000/150)
X_{Coil} by eq 2	1,400 ohms ($4{,}400 = 3X_{Coil} + 200$)	666 ohms ($2{,}200 = 3X_{Coil} + 200$)
Maximum coil Current $I_{Coil} = E_N/X'_L$	52 amps [76,200/(1,400 + 66)]	105 amps [76,200/(666 + 66)]
Voltage across coil = $(I_{Coil})(X_{Coil})$	72.8 kv (52 × 1,400)	69.4 kv (104 × 666)

A Petersen coil to be used in the neutral under such couditions therefore must have a reactance ranging from 666 to 1,400 ohms. The selection of coil taps or steps between these maximum and minimum reactance values will be governed by the intermediate lengths of line sections for which the coil is to tune.

A rough approximation of the required coil reactance may be obtained from the magnitude of the normal charging current to ground of the system on the assumption that the fault current is approximately equal to the charging current to ground under fault conditions. The current under fault conditions and neglecting corona, will be approximately 1.5 times the normal charging current to ground.[9]

$$\text{Thus } X_L \text{ (approx.)} = \frac{3E_N}{(\text{line length})(1.5)(\text{normal } I_{CG})} \text{ ohms} \quad (7)$$

For example the previously cited:

$$X_L = \frac{3(76{,}200)}{(150)\ 1.5\ (0.69)} = 1{,}470 \text{ ohms by eq 7, and}$$

$$X_{Coil} = \frac{1{,}470 - 200}{3} = 424 \text{ ohms by eq 2 for the 150-mile section}$$

Calculation of Fault Current

Following the staged tests it was desired to study the magnitude and distribution of fault current analytically for the various operating conditions. The symmetrical component method of circuit analysis lent itself readily to this type of problem.[10] The following assumptions were made in connection with these calculations, based upon the experimental data obtained during the tests:

1. The capacitive reactance to ground X_{CG} of the Petersen coil system is equal in magnitude to the inductive reactance X_L of the Petersen coils together with their associated transformer banks, with the coils in tune (minimum fault current).
2. The fault current present on the Petersen coil system with a solid low resistance ground is due entirely to corona, neglecting other losses.
3. The corona voltage limit is exceeded by practically the same amount regardless of the fault location or the Petersen coil operating tap (within reasonable limits), i.e., the voltage to ground on the sound phases is unaffected by fault location or operating tap.

The calculation of the current during single-line-to-ground faults with Petersen coil or isolated neutral system necessitated consideration of a method for evaluating the component of the fault current due to the corona current to ground, i.e., a simple circuit representation which would simulate the effect of corona. The equivalent leakage resistance to ground representing corona was determined from the measured fault current by neglecting the positive and negative sequence impedances as follows:

$$\text{Leakage resistance } R_G = \frac{E_R}{I_F \cos\theta} \text{ ohms} \quad (8)$$

where

E_R = residual voltage = $(3E_N)$ volts
I_F = fault current amp
θ = phase angle between fault current $-I_F$ and residual voltage E_R

This method is not strictly true since it neglects the effect of other resistance in the circuit. However, it was found sufficiently accurate for this purpose. This leakage resistance for use in the equivalent zero sequence network has been considered to be in parallel with the capacitive reactance to ground of the system.

The specific values of circuit constants used in the analytical study are shown in Table VII.

Solution of Networks

The procedure followed in analyzing the Petersen coil, isolated neutral, etc., systems, was to set up the positive, negative, and zero sequence networks in ohms on a common voltage base and then to solve these networks in the customary manner[10]. Starting at the most remote points the impedances were combined up to the point of fault using delta-wye transformations where necessary. In the zero sequence network it was recognized that the capacitances to ground of the various line sections may be united at a common point (ground). After the positive, negative, and zero sequence impedances at the point of fault had been determined, the fault currents were found by the following formula:

$$I_F = \frac{3E_N}{Z_1 + Z_2 + Z_0 + 3R_F} \text{ amp} \quad (9)$$

Table VII—Summary of Test System Characteristics, One Conductor Grounded

Neutral Connection	Petersen Coil	Isolated Neutral	Directly Grounded	Neutral Resistance
Capacitance to ground C_G μf/mile/phase	0.01	0.01	0.0088	0.01
Capacitance reactance X_{CG} mile-ohms	265,000	265,000	300,000	265,000
Charging current I_{CG} amps/mile	0.92		0.81	0.92
Leakage resistance due to corona R_G mile-ohms/phase	1,370,000	750,000	Considered zero	1,370,000

where

E_N = normal line-neutral system voltage (volts)
I_F = fault current (amp)
R_F = fault resistance (ohms)
Z_1, Z_2, Z_0 = positive, negative, and zero sequence impedances, respectively, at the point of fault (ohms)

When the system is grounded by means of a Petersen coil the sum of the positive and negative sequence impedances $(Z_1 + Z_2)$ is small compared with Z_0 and therefore it may be considered that:

$$I_F = \frac{3E_N}{Z_0} \text{ approx. amp.} \qquad (10)$$

With the neutral of the system isolated the only path for the fault current was through the distributed admittance to ground of the transmission system. The current was therefore a maximum at the point of fault and decreased uniformly along each circuit away from the fault. The solution of the networks and the calculations of the fault current in this case were made similarly to those previously described, using the proper values for the circuit constants. The analysis of the sequence networks and the computations of fault current with the system neutral grounded directly by the transformer bank at Saginaw were made in the manner customary for grounded neutral systems.

An example of the solution of the networks for a solid low resistance fault at Saginaw with the Petersen coil system may serve to make this procedure clear. The positive and negative sequence networks for this example are shown in Fig. 2 and it will be noted that the positive and negative sequence impedances at the point of fault consist only of the Saginaw generator and the 45,000-kva transformer bank. The equivalent zero sequence network is illustrated in Fig. 13. The zero sequence impedance of each circuit at the point of fault was found by combining the impedances (using complex notation) from the remote end in toward the Saginaw bus. These impedances were then combined as indicated in Table VIII.

The solution of the network between Emery Junction, Loud, and Foote was accomplished by first transforming the series impedances of the lines from their delta connection to an equivalent wye. In a similar manner the delta mileage was transformed into an equivalent wye mileage and the mileage of each branch of the wye was then multiplied by the ratio of the total delta to the total wye mileage so as to make the total mileage of the wye equal to the original total mileage of the delta. The capacitive reactance and the leakage resistance per mile were divided by the corrected wye mileages and the resultant impedances considered concentrated at the mid-points of the wye branches of the series impedances. This was an approximation, but it was sufficiently accurate because the series impedances were small compared with the shunt impedances.

Distribution of Fault Current

The distribution of fault current in the various circuits was determined by starting at the point of fault where the zero sequence impedance looking in each direction was known, and computing the currents in each branch at that point which add up to equal the total fault current. The product (fault current × total zero sequence impedance looking in at the fault) equaled the product (residual current in each branch × zero sequence impedance of that branch looking at the point of fault). The zero sequence impedance at each point of discontinuity in the network had previously been computed and the currents in each of the other branches therefore could be readily determined. In Fig. 14 is shown the calculated distribution of residual current for a single-line-to-ground fault at Saginaw with the Petersen coils in tune.

References

1. Directional Ground Relay Protection of High Tension Isolated Neutral Systems, J. V. Breisky, J. R. North, and G. W. King. A.I.E.E. Trans., v. 46, 1927, p. 853–67.

2. Operating Performance of Petersen Earth Coil, J. M. Oliver and W. W. Eberhardt. A.I.E.E. Trans., v. 42, 1923, p. 435–45.

3. The Neutral Grounding Reactor, W. W. Lewis. A.I.E.E. Trans., v. 42, 1923, p. 417–34.

4. Experimental Studies of Arcing Faults on a 75-Kv Transmission System, J. R. Eaton, J. K. Peck, and J. M. Dunham. A.I.E.E. Trans., v. 50, 1931, p. 1469–79.

5. Relation of Petersen Coil System of Grounding Power Networks to Inductive Effects in Neighboring Communication Circuits, H. M. Trueblood. *Bell Sys. Tech. Jl.*, July 1922, p. 49–51.

6. Physics of the Air, Humphres. McGraw-Hill Pub. Co., Chapter XVIII.

7. Arcing Grounds and Effect of Neutral Grounding Impedance, J. E. Clem. A.I.E.E. Trans., v. 49, 1930, p. 970–89.

8. Protection Against Earth Faults, A. van Gastel. *The Brown Boveri Rev.*, Nov. 1930, p. 335–54; Dec. 1930, p. 376–83.

9. Transmission Line Engineering, W. W. Lewis. McGraw-Hill Book Co., p. 248.

10. Symmetrical Components, Wagner and Evans. McGraw-Hill Book Co.

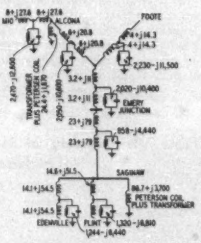


Fig. 13. Equivalent zero sequence network for determining impedance for fault with the Petersen coil system

Impedances expressed in ohms on 140-kv base
Equivalent corona leakage resistance = 1.37×10^6 mile-ohms per phase
Capacitance to ground = 0.01 μf per mile per phase

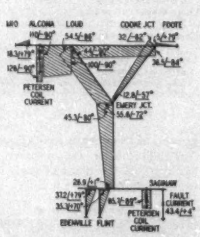


Fig. 14. Calculated values of residual current distribution for fault at Saginaw during 140-kv Pejersen coil tests

Calculated fault current = 43.4 amp
Measured fault current = 38 to 43 amp

Table VIII—Fault Current Calculations, Petersen Coil System, With Fault at Saginaw

Section		Petersen Coil System (Taps S4, A8)
Positive Sequence Network		
Saginaw generator		0 + j146 ohms
Saginaw transformer		5.3 + j 48 ohms
	Z_1 =	5.3 + j194 ohms
Negative Sequence Network		
Consider $Z_2 = Z_1$	Z_2 =	5.3 + j194 ohms
Zero Sequence Network		
Avg fault current I_F		40 amp
Leakage resistance R_G (eq 8)		6,080 ohms
Leakage resistance (6,080 × 226)		1,370,000 mile-ohms
Saginaw coil & transf. residual react. X'_L (eq 3)		1,080 ohms
Alcona coil & transf. residual react. X'_L (eq 3)		623 ohms
Equiv. coil & transf. residual react. X'_L (eq 3)		395 ohms
Equiv. coil & transf. Zero Seq. React. X_L (eq 4)		1,180 ohms
Capacitance C_G (eq 1)		0.01 μf/mile
Cap. react. X_{CG} (eq 5)		265,000 mile-ohms
Charging current I_{CG} (eq 6)		0.92 amp/mile
Mio line at Alcona		2,480 − j12,800 ohms
Alcona coil and transformer		24.4 + j1,870 ohms
Alcona at wye tap		309 + j2,710 ohms
Foote at wye tap		2,230 − j11,500 ohms
Alcona and Foote at wye tap		710 + j3,430 ohms
Au Sable line at Saginaw		8,280 − j2,370 ohms
Edenville line at Saginaw		1,260 − j6,380 ohms
Flint line at Saginaw		1,340 − j6,760 ohms
Saginaw coil and transformer		86 + j3,250 ohms
Total Z_0 at Saginaw	Z_0 =	5,580 − j606 ohms
Total $Z = (Z_1 + Z_2 + Z_0)$	Z =	5,590 − j218 ohms
Fault current I_F (eq 9)		43.4 ∠4 deg amp

An Experimental Ignitron Rectifier

Experiments aimed at the elimination of the backfire tendency of arc-rectifiers have led to a device termed the "ignitron." Equipment, methods, and test data are discussed in this paper.

By
L. R. LUDWIG
ASSOCIATE A.I.E.E.

A. H. TOEPFER
ASSOCIATE A.I.E.E.

F. A. MAXFIELD
ASSOCIATE A.I.E.E.

All of the Westinghouse Elec. & Mfg. Company, East Pittsburgh, Pa.

DURING the early development of the mercury arc rectifier, the serious defect in its operation known as backfire or arc-back, quickly became apparent. These erratic failures, amounting to complete loss of valve action of the device, necessitated a large expenditure of effort on the part of engineers and physicists before practical rectifiers could be built. At the present time entirely satisfactory rectifiers are available commercially, but the problem of backfire continues to hamper the designer. Grids, shields, disadvantageous spatial relationships, costly anode constructions, force their way into his structures because reliable valve action requires them. To make clear the advantages in these respects of the apparatus described, a brief summary of the factors affecting backfire is given.

Many investigators[1] have associated the backfire or accidental formation of a cathode spot on the anode, when it is bearing negative voltage with the back current. By back current, one means the positive ion current collected by the anode bearing negative voltage, as a result of diffusion of ions to the anode region, or as a result of a self-maintained discharge of the glow type. Slepian and Ludwig[2] defined the conditions favorable for backfire and cited experiments made by D. E. Marshall in which backfires were produced by striking a negative electrode with some kind of small particle. It was found that backfires would result only if ionization existed, causing back current to the negative electrode.

In the normal multi-anode rectifier this back current may arise in 3 ways:

1. Throughout the nonconducting period of a particular anode there is a continuous back current flow to it as a result of diffusion of ions from arcs to other anodes in the same tank, which are active during this period.

2. Immediately following the "transition point" that is the point at which the current reaches zero and negative voltage is applied rapidly to the anode, a very high initial back current will flow for at least a short time because of the high density of ionization present in the anode region due to current flowing just previous to this transition point.

3. In case conditions become such that a self-maintained glow discharge can exist with its cathode upon the negative anode, then a comparatively high back current can exist for a long period of time.

The vapor density of the mercury in the vicinity of the anode also has been found to have a considerable effect on the backfire probability. This effect is not necessarily distinct from the association of backfire probability with back current, because clearly the transition back current just described as well as fulfillment of the condition under which a self-maintained glow may exist, largely depends upon the vapor density.

In any practical rectifier a self-maintained discharge during a nonconducting period may be avoided by holding the gas density and the dimensions of the rectifier within limits such that the available voltage will not maintain the discharge. Furthermore, the length of time during which the transition back current will flow may be minimized by keeping the gas density low so that the residual ions will be lost rapidly by diffusion. It also is possible to minimize the continuous diffusion back current by surrounding a negative anode with shields and grids and by placing it far away from other conducting arcs. The shields and grids also are effective with respect to the other 2 forms of back current.

Such an analysis shows why multi-anode rectifiers have been designed having rather large dimensions, necessitated by a tortuous arc path, grids and shields, large internal coolers and in fact all those factors of design which prevent the use of a simple conducting arc having a low drop, and which consequently causes the rectifier to be expensive and inefficient compared with what might be expected if backfires could be avoided in a more direct manner.

In order to keep the average backfire rate of a rectifier low and at the same time to use a small structure in which the anode is placed directly above the cathode without interfering grids and shields, more suitable means are required for keeping the back current sufficiently low. These desirable characteristics are attainable readily in the following way:

If a rectifier having a single anode and mercury pool cathode within a separate small tank were to be built, no continuous back current could flow to the anode when it is negative, because the tank would contain no source of ionization and would remain entirely inactive during the nonconducting period. However, some means for restarting the arc would be required when the device is to become conductive again. A continuously burning "keep-alive" would be satisfactory for restarting the arc, but it would completely defeat the purpose, which is to avoid any source of ionization during the period of nonconduction. An intermittent "keep-alive," or "make-alive" is required. An entirely suitable ignition means has been described by Slepian and Ludwig,[3] and it can be

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–27, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 22, 1933. *Not published in pamphlet form.*

1. For numbered references see end of paper.

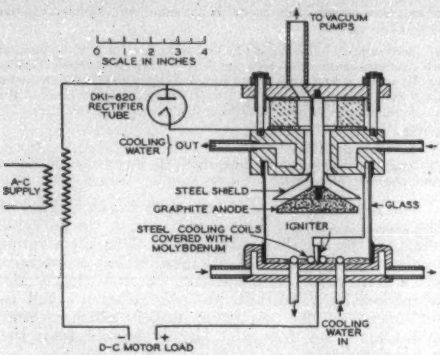


Fig. 1 A single anode experimental ignitron

used in the single anode tanks without causing continuous back current.

Thus the continuous back current need be of no more concern, but to obtain backfire immunity a self-maintained glow discharge also must be avoided during the nonconducting period. Furthermore it is essential rapidly to deionize the gas space between the electrodes at the transition interval. Sufficient and proper cooling alone, has been found adequate to accomplish both of these purposes.

Thus one is led to the adoption of single anode tanks, properly cooled and with built-in igniters, to escape the complexity and comparative inefficiency of the conventional rectifier. The new structure has been termed an "ignitron."

Experiments With Small Ignitrons

The essential components of a small ignitron are shown diagrammatically in Fig. 1. The anode was made of graphite and placed 2 in. above a mercury pool cathode. For experimental purposes the side wall was of pyrex glass sealed to the cathode and to the anode structure. The anode was insulated from the plate sealed to the top of the glass by porcelain. Rubber gaskets were used to secure vacuum tightness at the junction of the porcelain and the iron and the upper part of the assembly were bolted together. The upper end of the igniter was connected to the cooled upper plate, which was connected electrically to the anode through a rectifier tube. This unit was tested in a single-phase half-wave rectifier circuit and the output direct current power was supplied to a rotating machine. Tests were made at 300 volts and 50 amp direct current. During these initial tests no special cooling was used, the cathode itself and the upper plate served entirely for condensation of the mercury evaporated at the cathode. During the initial tests several backfires occurred. It was interesting to note, however, that none of these backfires seemed to be associated with mercury drops thrown from the cathode against the anode, or mercury drops falling from the anode when it was run cold. In the usual type of rectifiers such conditions would cause practically continuous backfire, because almost every drop impinging against the anode would produce an arc back immediately. This observation seems to bear out the previous test obtained by D. E. Marshall which requires back current in order for impinging particles to produce backfire, and at the same time these particles show that throughout most of the nonconducting period the back current in this ignitron must have been quite small.

In another ignitron similar to the one described, except larger, tests made by Dr. D. Silverman indicated that the backfires obtained did occur at the transition interval. The circuit used for these tests was the same as that shown in Fig. 1 except that a condenser was connected in parallel to the ignitron. This condenser was sufficiently large so that approximately 400 microseconds was required before it could be charged to a potential greater than 100 volts by the current flowing into it through the reactance placed in series with the ignitron. Consequently negative voltage was not impressed suddenly on the ignitron anode as is usual in case of a rectifier circuit. During the test made with the condenser, no backfires occurred, although the backfire rate was very high with the same current and voltage when the condenser was removed. The fact that both of these ignitrons operate backfire free in a single phase circuit when a resistance load is used also indicates that the backfires are occurring in the transition region because the negative voltage is applied slowly to the anode with the resistance load and the ions have ample time practically to vanish before considerable voltage is present.

During tests with the ignitron shown in Fig. 1, it was found that if the temperature of the ingoing cooling water was increased from 18 to 30 deg C the backfire rate would be increased very considerably. At the same time a glow could be detected during the nonconducting period by looking into the vessel through a stroboscope. At the lower water temperature no light at all was visible during a nonconducting period.

In order to make the device less critical to ingoing water temperature and also to improve conditions at transition, a special cathode cooling means was de-

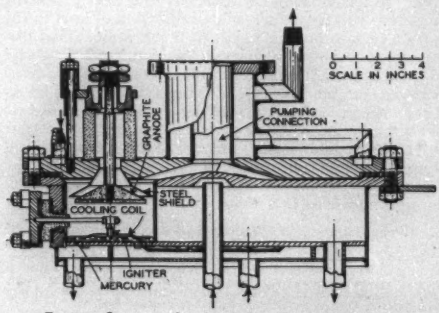


Fig. 2 Section of a 6-anode polyphase ignitron

vised. This consists in fixing the cathode of the arc directly on a cooling coil. Actually iron pipes arranged to carry water were covered with molybdenum and placed in the cathode such that the mercury level extended about half the height of the pipe. It may be seen from this construction (shown in Fig. 1) that approximately half the cooling coil extends above the mercury. The igniter, which in this case is a crystal of carborundum, is so placed as to touch this cooling coil at one particular spot along this length. The igniter also is surrounded completely with a glass covering except for a vertical strip of its outer surface which contacts with the mercury and the spot fixing coil. In this way the arc is started directly on the well cooled fixer.

During tests with this arrangement it was found that 50 amp at 600 volts direct current machine load was carried for one week without backfire. Ingoing water temperature during this test was 27 deg C. The arc drop as observed from an oscillogram had an average value somewhat less than 10 volts.

A still further check on the applicability of the ignitron principle to rectifiers was made by building another unit similar to the one shown in Fig. 1, but with the following changes. The glass walls and steel cathode structure were replaced by a steel cup so that the walls as well as the cathode could be cooled. The cooling coils in the cathode were omitted. A hollow iron anode insulated from the walls and cathode by glass sealed to 2 pieces of "kovar" (an iron alloy, developed by H. Scott, which may be sealed to glass) was used instead of graphite. The igniter lead was brought in through the side by means of another kovar-glass seal. The physical dimensions of this unit essentially were the same as those of Fig. 1. With this ignitron it was possible to supply a rotating machine load of 50 amp average and 600 volts direct current through a half wave rectifier connection for $19^1/_2$ hours without backfire. With an average of 75 amp and 600 volts dc supplied for $15^1/_2$ hr, only 3 backfires occurred. It was possible to carry this load in the absence of

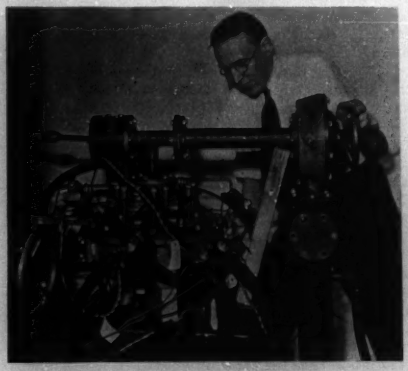


Fig. 3 View of polyphase ignitron

Fig. 4 Oscillogram showing typical ignitron operation for double 3-phase connection; motor load 320 amp at 260 volts

cooling coils in the cathode because of the much more effective cooling obtained with steel walls. Another factor which aided in giving satisfactory operation of the ignitron was the fact that this unit practically had no leaks. The gas pressure rose only about 2 microns an hour with the unit trapped off and carrying a 50-ampere d-c load. The arc drop again was slightly under 10 volts.

These tests seem to show that with sufficient cooling to avoid a self-maintained glow and to speed up the deionization at the transition, the ignitron principle may be adapted to rectification with results vastly improved over any present form of mercury pool cathode device.[4]

The Polyphase Ignitron

In following up this idea a polyphase ignitron was built for test in a 6-phase or double 3-phase circuit. This experimental ignitron shown in Fig. 2, consists of 6 units each similar to the ignitron in Fig. 1, except that the glass wall is replaced by steel. The 6 units are mounted in a steel tank which provides a common water-cooling system for the walls and another for the cathodes and a common evacuating system. This assembly is very compact. It is only $9^1/_4$ in. high and 16 in. in diameter. There is no need for insulating the cathodes or restricting the motion of the cathode spot. At the beginning of every cycle the arc starts always at the igniter and tends to fix on the molybdenum covered cooling pipe. Rarely does it move more than $1^1/_2$ in. from the igniter. All the cathodes are interconnected to permit free flow of mercury from one pool to another, assuring equal distribution of mercury among the 6 pools.

This ignitron was operated in 2 types of rectifier circuits—a double 3-phase of the usual kind and a 6-phase obtained by short circuiting the interphase transformer.

Figure 4 shows a typical oscillogram taken when the rectifier was supplying 325 amperes at 265 volts direct current. The total cathode current as indicated by this oscillogram has more of a ripple than is

permissible with commercial rectifiers since no reactor was placed in the cathode lead to provide smoothening. The condition in which 2 anodes are carrying current at the same time is shown clearly. It can be seen readily that after a conduction period, the voltage rises suddenly to about 300 volts which is typical of power rectifier circuits. Also it can be seen that the voltage required to strike an arc in the rectifier by means of the igniter is only slightly more than 40 volts and that the maximum current required is only about 10 amperes. The time of application of this voltage and current is very short being only about 3 per cent of a cycle or about 10 electrical degrees. The average current through the igniter is somewhat less than 0.1 ampere, consequently the power input is very low.

Figure 5 shows the nature of the arc drop. The process of measuring it necessitated putting a rectox unit in series with the oscillograph element, hence the deflection is not linear nor is it the same on both sides of the zero line. It can be seen though that the average arc drop is slightly more than 9 volts.

At the time of writing, this ignitron had been operated for more than 49 hours in a 6-phase circuit supplying 300 amperes at 300 volts dc or 90 kw to a rotating machine load. During this time no backfires occurred nor was there any other indication that the unit had reached its maximum capacity. These tests still are in progress, but the data obtained thus far in actual rectifier operation seem to demonstrate that the ignitron is quite practical.

The authors wish to acknowledge the creative guidance of Dr. J. Slepian in the development which has been described and to credit him with many contributions fundamental to the ignitron.

References

1. v. Issendorf, Schenkel, Seeliger, *Wiss. Veröf. aus dem Siemens-Konzern*, v. IX, 11, p. 73, 1930.

Mercury Arc Rectifier Research, Hull and Brown. Trans. A.I.E.E., June 1931, v. 50, p. 744.

Mercury Arc Rectifiers and Circuits, Prince and Vodges. *McGraw-Hill*, p. 67.

Mercury Arc Power Rectifiers, Marti and Winograd, *McGraw-Hill*, p. 37. M. Leblanc and Demontvignier. *Rev. Gen. Elec.*, June 6, 1931.

2. Backfires in Mercury Arc Rectifiers, Slepian and Ludwig. Trans. A.I.E.E., March 1932, v. 51, p. 92.

3. A New Method for Initiating the Cathode of an Arc, Slepian and Ludwig. Trans. A.I.E.E., June 1933, v. 52, p. 693.

4. See also D. D. Knowles, Electronics, June 1933, p. 164.

Fig. 5 Oscillogram showing ignitron arc drop for double 3-phase connection; motor load 325 amp at 260 volts

Inductor Alternators for Signaling Purposes

Recent developments of the inductor alternator for the generation of modulated high frequency currents for telephone or telegraph signaling or carrier purposes are given in this paper. Several novel arrangements of the electric and magnetic circuits and certain principles and special details of design and construction are described.

By
F. W. MERRILL
MEMBER A.I.E.E.

General Elec. Company,
Fort Wayne, Indiana.

GENERALLY speaking, inductor alternators designed for the generation of special tones for signaling or telegraph carrier purposes on communication lines are of small output, ranging from a few hundredths of a watt to 40 watts, and in frequency from about 135 cycles to 2,300 cycles, for the uninterrupted or pure tones. These tones may be used in their pure form for certain applications, or may require modulation at some low frequency rate for the production of other characteristics. In some cases it is desired to interrupt the tone completely at some such rate as 20 or 30 cycles; and again the signal may require only the variation of the voltage or amplitude of the high frequency current at a periodic low frequency rate without complete interruption.

It is not the function of this paper to discuss the applications of these tones in detail, as that phase of the subject is outside the experience of the author, but some of the applications are mentioned to establish a practical connection.

In leading up to the special designs required for the production of the interrupted, or otherwise varied, tone signals it is essential first to understand the general type of inductor alternator that has been found most suitable in these small sizes for the generation of uninterrupted high frequency currents. These simpler machines are interesting in themselves, illustrating as they do the fundamental principles of generation, and an arrangement of parts which is capable of modification to produce the more complicated designs which are the principal subject of this paper. In this connection an arrangement of especial interest is described in which 12 plain inductor alternators each giving a different fre-

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. winter convention, January 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 25, 1933. *Not published in pamphlet form.*

quency, are assembled into a single "multifrequency" unit which has to meet very exacting requirements for both voltage and frequency.

In addition to its superiority as a generator of the higher frequencies the inductor alternator has several other advantages.

1. It has no moving conductors.
2. It requires neither brushes nor collector rings.
3. It can be operated at a higher flux density for a given core loss because the flux does not reverse but merely rises and falls between maximum and minimum values.
4. It can be operated at higher speeds because there is no winding on the rotor.
5. It has a lower cost of attendance and maintenance due to the absence of brushes and collectors.
6. It can be designed for the *direct* generation of interrupted or modulated high frequency output.

Frequency Range of Fractional Horsepower Inductors

The expression "high frequency" is relative, and as used in connection with the subject matter of this paper is defined as any frequency high enough to warrant the construction of an inductor alternator in preference to the conventional type of salient pole a-c generator. Due to the small physical size of fractional horsepower frames, it is surprising how low this so-called high frequency may be and still meet the above definition.

Standard fractional horsepower d-c motors are bipolar, hence revolving armature type a-c generators built in these frames also are bipolar. The larger induction motor stators are slotted so as to permit 4, 6, and 8 pole windings, and presumably revolving field rotors could be built up to 8 poles for use with these stators. As a matter of fact, however, a 6-pole field design is about the economical limit for the largest fractional horsepower frame, and it is preferable, when considering the next step, to use an inductor alternator having a 4-tooth rotor instead of a revolving field system having 8 poles.

Either the 8-pole alternator or the 4-tooth inductor generator would give 120 cycles at 1,800 rpm but the ampere turns per pole permissible in the restricted winding space of the 8-pole revolving field system would be considerably less than those obtainable with the bipolar stator excitation of the 4-tooth inductor alternator. For this reason the air gap flux density of the inductor machine would be enough higher than that of the 8-pole revolving field alternator to make it preferable from an output standpoint, if for no other reason. Therefore, 120 cycles at 1,800 rpm may be taken as approximately the correct point in fractional horsepower frames to change over from the conventional a-c generator to the inductor alternator. For frames of larger size this change-over point would occur at a higher frequency, the value of which would continue to rise with the absolute size of the machines under consideration.

The approximate upper limit of frequency obtainable in fractional horsepower frames with the type of construction described is between 4,000 and 5,000 cycles at 1,800 rpm giving a practicable frequency range, *at a definite speed*, for inductor alternators in these small sizes of about 40 to 1. The speed of 1,800 rpm, is, of course, low for such small frames, and with proper design and construction may be increased 4 times, giving an absolute upper frequency limit of 15,000 to 20,000 cycles for these small machines.

The power output, of course, drops off at the higher frequencies but can be maintained very well up to the upper limits given by suitable tuning of the output and by the proper choice of materials.

Construction—Electric and Magnetic Circuits

The fractional horsepower inductor alternators usually are designed as indicated in Fig. 1.

The coils in which the high frequency a-c output is generated are wound around the 12 stator teeth as shown and all connected in series so as to add their voltage, terminating in leads L_1 and L_2. The excitation is bipolar and is provided by the 2 field coils on the stator element terminating in leads F_1 and F_2. The exciting flux passes from the 6 stator teeth of 1 polar group through the rotor into the teeth of the opposite polar group and returns by way of the 2 halves of the yoke, the magnetic circuit being, in this respect, exactly like that of any 2-pole generator.

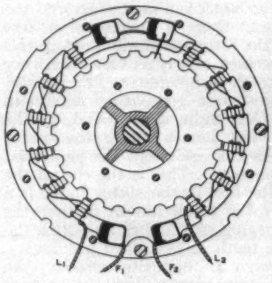


Fig. 1. Cross section of stator and rotor assembly, showing arrangement of teeth and windings of a typical inductor alternator for generating uninterrupted current—illustrating fractional pitch of stator teeth

In the alignment of stator and rotor teeth in Fig. 1, there are $1^1/_2$ rotor tooth pitches for 1 stator tooth pitch. With an *even* number of stator teeth in each exciting polar group this *fractional* pitch alignment places half of the stator teeth directly in line with rotor teeth and the other half in line with rotor slots. The stator teeth in line with the rotor teeth carry *maximum* flux, those in line with the rotor slots carry *minimum* flux. If the rotor is revolved one half a rotor tooth pitch the flux shifts in half the stator teeth from maximum to minimum and in the other half from minimum to maximum. The total flux, however, which passes through the field coils and around the yoke remains *constant*. Therefore, in the construction shown in Fig. 1, which is fundamental for all of the fractional horsepower frame inductors, constancy of the main exciting flux through the field coils and yoke is secured by means

of: (1) an even number of stator teeth per exciting polar group and (2) stator teeth spaced a *fractional* number of rotor tooth pitches apart.

In general, with this fractional pitch as a basis of design, the stator teeth may be spaced, $^1/_2$, $1^1/_2$, $2^1/_2$, $3^1/_2$, etc., times the rotor tooth pitch. The higher the frequency and the finer and more numerous the rotor teeth, the larger would be the number of rotor tooth pitches that would have to be allowed for one stator tooth pitch in order to secure sufficient winding space for the a-c generating coils. The number of stator teeth, however, affects only the total voltage generated, while the frequency depends wholly upon the *rotor tooth pitch* and the speed of the rotor.

It should be noted also that the arrangement of teeth shown in Fig. 1, in which half of the teeth are in the position of maximum flux while the other half are in the position of minimum flux, is equivalent to displacing half of the stator coils 180 elec deg with respect to the other half. As a result of this connection all even harmonics cancel out, but the fundamentals add. For this reason a fractional pitch arrangement of the stator teeth as shown gives a much better wave shape than would be obtained by an integral pitch spacing even if this latter were not objectionable from the standpoint of pulsating the main exciting flux through the field coils.

Frequency. When any rotor tooth exactly is in line with a stator tooth, the flux through the a-c coil around that stator tooth is a maximum and the voltage is zero, because there is no change in flux at that instant. As the rotor tooth moves from this position, the flux decreases, slowly at first, then very rapidly as the rotor tooth completes the first quarter of its full pitch movement generating maximum voltage in the coil, then more slowly, and, as the center of the rotor slot comes under the stator tooth, the decrease in flux ends and the generated voltage again becomes zero. This is the end of the first half cycle and the flux in the stator tooth is a minimum. As the rotor tooth moves further the flux increases at a varying rate, depending upon the exact position of the tooth as described previously, generating the a-c wave of opposite polarity, the flux again becoming a maximum and the voltage zero when the next rotor tooth exactly comes in line with the original stator tooth.

Therefore, *one cycle* is completed for a movement of *one* rotor *tooth pitch*. If the rotor has a *full number* of *equally spaced* teeth uniform frequency will be generated.

If

f = frequency in cycles per second
P = number of rotor teeth in full circumference
S = revolutions per second.

Then

$$f = PS$$

If P = the number of poles of a revolving field system, then $f = \frac{P}{2} \times S$. Hence one inductor rotor tooth is equivalent in frequency generation to a pair of poles of the conventional type alternator. Another thought is that one inductor rotor tooth pitch = 360 elec deg, whereas, a pole pitch of the conventional type alternator field = 180 elec deg.

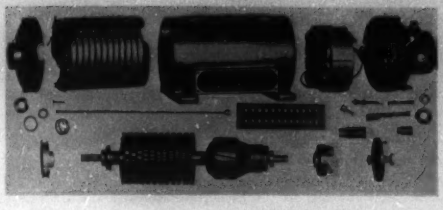


Fig. 2. Component parts of a multifrequency set

Voltage. The voltage of the entire a-c winding is proportional to the rate of change of flux and to the number of turns in series. The flux change per stator tooth is equal to the difference between the maximum and the minimum flux in the 2 extreme positions of the rotor tooth as described. This difference in flux per *stator* tooth is called the "useful flux."

If

T = total turns in series on *all* stator teeth
ϕ = useful flux per stator tooth
E = effective voltage generated in entire a-c winding.

Then

$$E = 2.22 f \phi T 10^{-8}$$

The derivation of this formula is not given, as this may be obtained from various textbooks on the subject.

It is easy to assign definite values to all of the terms of the above voltage formula except ϕ. The determination of this useful flux is important and somewhat difficult. It may be found, however, within a fair degree of accuracy, by means of large scale flux plots of the teeth in the maximum and minimum positions. It should be noted that such determinations will be less accurate in the case of the higher frequency inductors having narrow tooth widths and relatively large values of minimum flux. The useful flux then is equal to the difference between 2 relatively large quantities, and small errors in the determination of either one of these, causes a much larger percentage of error in their difference.

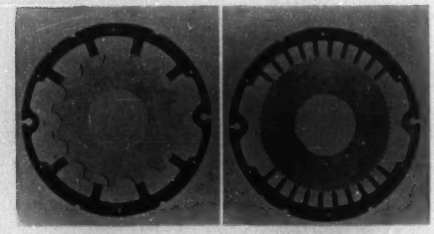
Percentage Rotor Tooth Width. The graphical method of determining the useful flux just referred to assumes that the dimensions of the rotor and stator teeth already have been established. The choice of these dimensions, however, must very carefully be made, particularly the width of rotor tooth as compared to rotor tooth pitch. In starting with a very narrow rotor tooth, say 20 per cent of the tooth pitch, the maximum flux and the useful flux both will be quite small. As the percentage tooth width is increased (the stator tooth being kept the same width as the rotor tooth), both the maximum and useful flux increase up to a certain point. If the tooth width is increased still further the maximum flux continues to increase but the useful flux

begins to decrease, because the *minimum flux* now is increasing faster than the maximum flux causing the difference between the 2 values—the useful flux—to diminish. When designing an inductor alternator care should be taken to choose a width of tooth that will give the greatest value of useful flux.

Saturation. In the graphical determination of the useful flux it has been assumed that there is no rotor or stator tooth saturation. If the ampere turns of an inductor alternator (similar to Fig. 1) are increased, and the yoke section is heavy enough so that saturation occurs first in the stator or rotor teeth, the "maximum flux" will be held at a certain point by this saturation while the "minimum flux" will continue to increase, as neither the rotor nor stator teeth will saturate in the minimum position, the extra ampere turns all being absorbed in the large gap. The result of this is a decrease of useful flux and of generated voltage. A saturation curve taken on an inductor alternator with this kind of a magnetic circuit will show increasing no-load voltage with increasing field current up to a certain point, beyond which the generated voltage will decrease with increased excitation. This same effect also is noted in the paper, "A 10-kw, 20,000-Cycle Alternator," by M. C. Spencer, JL. OF THE A.I.E.E., July 1927, p. 681. This puts a definite limit on the amount of voltage that can be obtained by field control. This condition of tooth saturation generally should be avoided, and if saturation must be had in order to minimize the effect of varying exciting voltage, temperature changes, etc., on the generated voltage, it would be better to saturate the yoke in the constant flux zone and thus retain some field control to cover manufacturing variations among individual machines. Locating the saturated section of the magnetic circuit in the constant flux zone also prevents the excessive iron losses that might occur if this section were subject to the same high frequency variations which occur in the stator and rotor teeth.

THE MULTIFREQUENCY SET

The multifrequency set shown disassembled in Fig. 2, is an inductor alternator generating 12 fundamental frequencies at the same time. The generator end really is 12 inductor alternators combined into 1 unit. The 12 stators differ in mechanical details, and have different windings, but all are assembled in 1 block, and excited by a common set of field coils. Each stator is composed of the same number of silicon steel punchings so that the axial length is the same for each unit. Different punchings, however, are required for the respective stators. These stator elements are separated axially by nonmagnetic (brass) spacers to prevent frequency interference between adjacent channels. The block of 12 stators with windings complete is assembled in an aluminum case, it not being permissible to use a cast iron case on account of frequency interference.



Figs. 3 and 4. Stator and rotor punchings of a multifrequency set, (left) 15-tooth rotor channel, and (right) 81-tooth rotor channel

The assembled rotor is composed of 12 different rotors, mounted on a brass spider and separated by brass spacers. This assembled rotor is mounted on the shaft so that its respective channels line up exactly with the corresponding stator channels. The number of rotor teeth begins with 15 and proceeds upward by arithmetical progression, having a common difference of 6, until the highest number of teeth, 81, is reached. Figs. 3 and 4 show the stator and rotor punchings of the 15 tooth and 81 tooth channels, respectively. This inductor is built into a 2 bearing set having a 20/24-volt d-c speed-regulated motor as the other unit. The rating of each channel is 0.7 volt, 0.04 amp—the frequency ranging from 425 to 2,295 cycles at a speed of 1,700 rpm. The speed is held within about plus or minus $^1/_2$ per cent by the centrifugal speed regulator for the above battery range and for all variations of load and temperature.

The multifrequency sets are used for sending telegraph messages on the longer lines, such as those between Boston, New York, Chicago, and the West Coast. These machines make it possible to send 12 messages over 1 circuit at the same time, filters being used to tune in the messages at the receiving end.

The first model multifrequency sets were designed by H. M. Stoller of the Bell Telephone Laboratories and built in New York under his supervision.

FIRST METHOD OF PRODUCING INTERRUPTED SIGNALING CURRENTS

In 1922 a demand arose for a special 1,000-cycle signaling tone for use on long telephone toll circuits. The customer's specification requested a speed-regulated, battery-driven, 2-bearing set, the inductor alternator of which should generate 1,000 cycles, and be fitted with a mechanical interrupter which would interrupt completely the 1,000-cycle tone at a 20-cycle rate, that is, $^1/_{40}$ sec on, $^1/_{40}$ sec off. The 1,000-cycle signaling pure tone also was required for testing purposes in carrier systems. This set originally was known as the "voice frequency signaling set." A schematic diagram of the set with its d-c speed regulated motor, and mechanical interrupter is shown in Fig. 5. It will be noted that the inductor alternator generates an uninterrupted current, which is interrupted by 2 mechanical interrupters so as to supply the 1,000/20 tone to 2 independent circuits. Oscillograms of the pure tone

and of the interrupted tone from this type of set are shown in Fig. 6. A disassembled view of the set, Fig. 7, clearly shows the inductor and mechanical interrupter parts. Several of these sets were manufactured and gave good service except that the interrupter rings and brushes required considerable maintenance and the efficiency was not good due to the friction loss of the 6 interrupter brushes. The rating of the generator end of this set is 6 volts, 0.035 amp, 1,000 cycles, 1,175 rpm, ± 2 per cent. The inductor rotor has 51 teeth. (19.6 rps × 51 = 1,000.)

Direct Generation of Interrupted Currents

As stated previously: "one *cycle* is completed for a movement of *one rotor tooth* pitch. If the rotor has a *full number* of *equally spaced* teeth, uniform frequency will be generated."

After a few of the mechanically interrupted sets had been built the idea was conceived that it would be possible to generate the 1,000-cycle tone for half the time by using a rotor having one-half of the circumference smooth and the other half notched with teeth of the same circumferential pitch as that of the 51 tooth rotor of the original set. This idea was tried out and found to work perfectly. As a result, it was possible to eliminate the entire interrupter of the original set, reduce the first cost, eliminate maintenance of the mechanical interrupter and increase the efficiency. Fig. 8 shows the disassembled view of this new type of set. Comparing this with Fig. 7 it will be noted that only 3 brushes are required instead of the 9 brushes used on the original set. The stacking of the partly toothed rotor has been increased to raise the flux per stator tooth to make up for the fact that the number of teeth available for the generation of voltage has been reduced from 12 to 2.

Fig. 9 shows a cross section view of this special inductor. Comparing this with Fig. 5 it will be noted that the winding L_1, L_2 supplies interrupted circuit No. 1 and winding L_3, L_4 supplies interrupted circuit No. 2. By connecting L_1, L_2, L_3, and L_4 in series an approximately continuous 1,000-cycle tone is generated, each winding supplying this tone for half the time. Fig. 10 shows 3 oscillograms taken from this first machine. Oscillograms 1 and 2 show the result of connecting the 2 interrupted windings in series. In oscillogram 1 the overlapping portions of the active generating periods of the 2 windings add their voltage, while in oscillogram 2 these overlapping portions are in opposition. Oscillogram 3 is representative of either one of the interrupted circuits taken alone. This signal, while not so sharply interrupted as some which have been produced by inductors of later design, proved to be an entirely satisfactory substitute for the mechanically interrupted pure tone.

Examination of Fig. 9 shows that in this first attempt to generate an interrupted current the stator teeth were spaced $2^1/_2$ rotor tooth pitches apart. The rotor has 25 teeth and 26 slots on half the circumference (equivalent to 52 teeth and 52 slots for a full circumference). When this type of

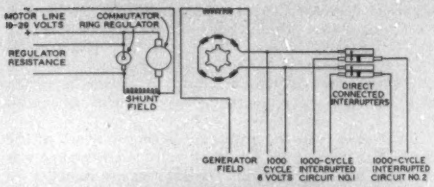


Fig. 5. A 1,000-cycle voice frequency signaling set of mechanical interrupters

Fig. 6. Oscillograms of the tones of the set shown in Fig. 5

(Above) 1,000 cycles uninterrupted
(Below) 1,000 cycles interrupted at 20-cycle rate

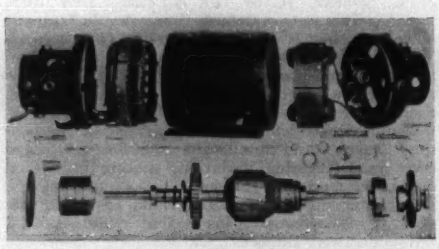


Fig. 7. Component parts of the 1,000-cycle set shown diagrammatically in Fig. 5

rotor is revolved at 19.23 rps, 1,000 cycles are generated in each alternate circuit for one-half the time. It is evident, therefore, that the generated frequency is not equal fundamentally to the number of teeth on the rotor multiplied by the revolutions per second, but that it is equal to the peripheral velocity of the rotor surface in feet per second, divided by the circumferential pitch of the rotor teeth in feet (any other units of length or angle may, of course, be used).

Fig. 11 illustrates an improved up-to-date design of rotor and stator structure for producing a 500/20-cycle signal. In this case, there are 11 teeth and 12 slots equivalent to 12 rotor tooth pitches (as the beginning of the smooth portion is equivalent to another tooth), but located on less than half the rotor circumference. In this case, the circumferential pitch of the rotor teeth $= \frac{\text{Circumference}}{25^1/_2} = \frac{3.64 \text{ in.} \times \pi}{25^1/_2} = 0.449$ in. Peripheral velocity at

19.6 rps = 3.64 in. $\times \pi \times$ 19.6 = 224.5 in. per sec, $\frac{224.5}{0.449}$ = 500 cycles per sec: rotor diameter being 3.64 in. This method of calculating frequency fundamentally is more correct than the usual formula $f = PS$, which assumes a full number of equally spaced teeth. Another advantage of using a partly toothed rotor is that there is no single step limitation to the tone frequency. For example, with a full number of teeth, either 25 or 26 teeth would have to be used, but with a partly toothed rotor the exact tone frequency of 500 cycles, at 19.6 rps, corresponding to $25^1/_2$ teeth, is just as easy to obtain as some other frequency corresponding to an integral number of teeth for the entire circumference.

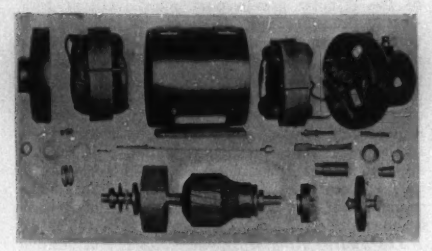


Fig. 8. An inductor alternator set for generating 1,000/20-cycle tone directly—no mechanical interrupters

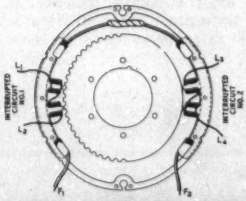


Fig. 9. Cross section of stator and rotor assembly, showing arrangement of teeth and windings of inductor alternator for generating 1,000/20-cycle tone directly

Fig. 10. Oscillogram of interrupted output generated by the special machine shown in Figs. 8 and 9. Also oscillograms of the 2 interrupted circuits of this generator connected series cumulative and series opposed

1. Cumulative connection 2. Opposed connection
3. One interrupted circuit

The detail of particular interest to be noted in Fig. 11, however, is the fact that the stator teeth have been converged so as to be spaced only $^1/_2$ rotor tooth pitch apart. The effect of this is to interrupt the tone sharply, and to prevent the shading and interference so evident in the oscillograms of Fig. 10. An oscillogram of the interrupted output of this up-to-date 500/20-cycle generator is shown in Fig. 12.

The Generation of Modulated Signaling Currents

Tone Alternator. For many years a large percentage of telephone ringing machines have been fitted with so-called "high speed interrupters" for the generation of special tones. This high speed interrupter is a cylindrical drum containing several interrupter rings which are fitted with alternate live and dead segments contacting with brushes located in such a way as to interrupt battery current at a rate that will produce the desired tones. Each interrupter ring unit of this interrupter produces a different kind of a tone for a special signaling purpose. The interrupter drum is mounted directly on a shaft extension of the ringing machine and operates at a speed of about 1,150 rpm. The tones produced are satisfactory, but the cost of maintaining the brushes and rings is high.

Following the successful generation of the interrupted tone signal, and the elimination of the mechanical interrupters from the voice frequency signaling set it was thought that a similar result might be possible in connection with the high speed interrupter.

This high speed interrupter produced 3 tones—high tone (411 cycles), low tone (137 cycles), and the audible ringing signal, which was a very special tone having a continuous frequency of 411 cycles—

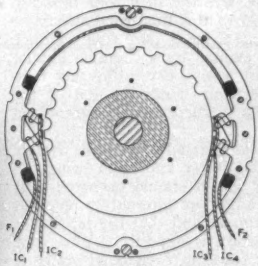


Fig. 11. A stator and rotor assembly, showing arrangement of teeth and windings of an improved type of inductor alternator for the generation of interrupted output

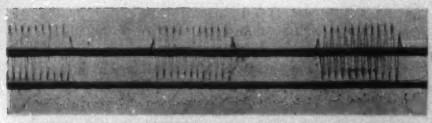


Fig. 12. Oscillogram of the sharply interrupted output of the inductor alternator shown in Fig. 11

the same as the high tone—but interrupted at a lower frequency rate so as to sound like a ringing signal. It was suggested by the telephone engineers that this tone could be duplicated by a sine wave of 411 cycles fundamental frequency varied in voltage

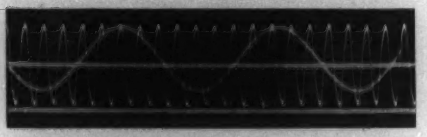


Fig. 13. Oscillogram of "high tone" with 60-cycle timing wave

in a 1 to 4 ratio at a 40-cycle rate. A method of generating such a modulated tone by inductor alternator was conceived and successfully accomplished in the first model. It was found, however, that the pure 137-cycle tone of the first model was not a satisfactory low tone as the wave, being nearly sinusoidal, lacked the quality of the mechanically interrupted tone to which the operators had become accustomed. It was thought necessary, therefore, to generate a low tone that would sound more like the mechanically interrupted tone. After considerable study the telephone engineers in charge of this investigation decided that a correct tone would be obtained if 660 cycles could be generated by an inductor alternator in such a way as to be varied in voltage or amplitude in a 1 to 4 ratio at a 120-cycle rate. At the same time the output requirements of this so-called tone alternator were increased several hundred per cent, the audible ringing tone was specified as 420 cycles modulated in a 1 to 4 voltage ratio at a 40-cycle rate, and the high tone raised to 500 cycles. The design of this final tone alternator consisting of 2 modulated and 1 pure tone channel, built into 1 unit and excited by a common bipolar field system brings out some very interesting relations of the a-c generating windings, and of the stator and rotor teeth. These are considered in detail as follows:

The High Tone. This channel is a simple design, the cross section of the stator and rotor being the same as shown in Fig. 1. It should be noted that the coils of the a-c winding are alternately reversed polarity all the way around, and that the top stator tooth in each polar group is opposite a rotor slot while the lower stator tooth in each polar group is opposite a rotor tooth and the winding is reversed in going from the top tooth of one polar group to the top tooth of the other polar group, because the polarity of the main field also reverses at this point. If the rotor had an even number of teeth, however, such as 24 or 26 instead of 25, the top stator teeth of the 2 polar groups would be opposite a tooth and a slot, respectively, and the winding would not be reversed in going from 1 polar group to the other. This is the result of the rule that an even number of stator teeth must be used in each polar group, spaced a multiple of $^1/_2$ rotor tooth pitch apart. An even number of stator teeth, such as N, covers a polar angle equal to $N-1$ stator tooth pitches. The rotor teeth covered by 1 polar group of stator teeth, therefore, are equal to $(N-1)^1/_2K$ in which K is an odd number (1, 3, 5 etc.—that is, $^1/_2$, $^3/_2$, or $^5/_2$ rotor tooth pitches). The rotor teeth covered by both polar groups $= 2(N-1)^1/_2K = (N-1)K$. Since $(N-1)$ and K are both odd, neither contains a factor 2, and the expression $(N-1)K$ always is odd, but integral, regardless of the total number of rotor teeth. If the total number of rotor teeth is odd the difference between this number and $(N-1)K$ must be even. Hence half this difference (in each interpolar space) is integral bringing adjacent top teeth of the 2 polar groups over rotor teeth or rotor slots at the same time. If the total number of rotor teeth is even, the difference between this total number and $(N-1)K$ will be odd. Half of this odd number difference, therefore, will be fractional putting adjacent stator teeth of the 2 polar groups over a slot and a tooth, respectively. This makes it necessary to place the a-c windings around these teeth in the same direction to add their voltage on account of the reversal of the main field flux in passing from 1 polar group to the other. An oscillogram of the "high tone" with a 60-cycle timing wave is shown in Fig. 13.

The Audible Ringing Signal. This is a modulated tone, being 420 cycles modulated by a 1 to 4 voltage variation at a 40-cycle rate. Its oscillogram is shown in Fig. 15 with a 60-cycle timing wave. Referring to the cross section shown in Fig. 14 of the stator and rotor punchings for this special inductor, it will be observed that there are 4 groups of 2 stator teeth each, spaced 90 deg apart. Two of these

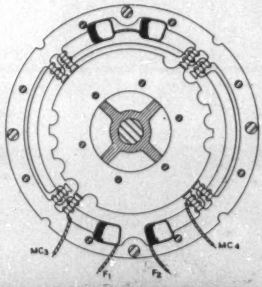


Fig. 14. A stator and rotor assembly, showing arrangement of teeth and windings of audible ringing tone channel of tone alternator

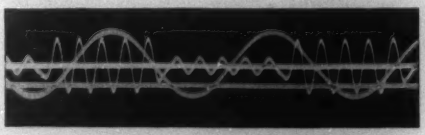


Fig. 15. Oscillogram of audible ringing tone with 60-cycle timing wave

groups come under each field pole. The rotor has 2 opposite toothed portions and 2 opposite smooth portions. The circumferential pitch of the rotor teeth is such that 420 cycles will be generated in any stator tooth winding while the toothed portion of the rotor is passing, if the rotor is revolved at 1,200 rpm (20 rps): $\frac{420}{20} = 21$, that is, if the rotor were completely filled with teeth of this same pitch, it would have 21 teeth. Each generating group of teeth contains 5 rotor slots and teeth exactly, but these are spaced diametrically opposite so that each smooth portion covers an angular space equal to $5^1/_2$ rotor tooth pitches.

In order to secure the modulated wave, the opposite stator tooth, groups 3 are wound with 4 times as many turns per coil as the other opposite groups marked 2. All of the stator windings, however, are connected in series. With this arrangement, as the rotor revolves, the toothed portions generate alternately on windings 2 and 3 producing voltage in a 1 to 4 ratio—because of the ratio of turns, and at a 40-cycle rate because there are 2 groups of teeth on the rotor turning at a speed of 20 rps.

The Low Tone. This is a very special modulated tone particularly difficult to generate because the rate of modulation is so high, being equal in frequency to 18.2 per cent of the fundamental tone. This tone is 660 cycles modulated at a 120-cycle rate. In the cross section shown in Fig. 16 there are 6 groups of 2 converging stator teeth each, and 4 single stator teeth. The single stator teeth are spaced 60 deg apart, plus half a rotor tooth pitch, while the groups of converging teeth are spaced 60 deg apart. The rotor tooth pitch is such as to generate 660 cycles, while the toothed portions are passing under stator teeth. If the same winding were placed on all the stator teeth, the 4 single teeth would generate one-third the voltage of the 12 converging teeth. The winding on the single teeth is reduced sufficiently, however, to make the voltage ratio 4 to 1 as specified. As the rotor revolves at 1,200 rpm, generation of 660 cycles occurs alternately in the 6 groups of converging teeth and in the group of 4 single teeth producing the wave train shown in Fig. 17.

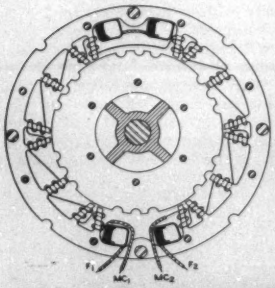


Fig. 16. Cross section of stator and rotor assembly, showing arrangement of teeth and windings of "low tone" channel of tone alternator

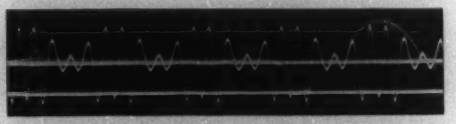


Fig. 17. Oscillogram of "low tone" with part of a 60-cycle timing wave

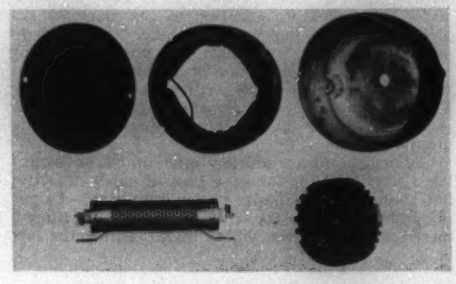


Fig. 18. A tone alternator shown disassembled

A view of the tone alternator disassembled is shown in Fig. 18. The 3 sets of rotor laminations for the 3 channels are mounted on a brass spider and riveted together, brass spacers being used between the steel punchings to prevent frequency interference. The 3 stators also are shown assembled in a single unit with the windings in place; a common set of field coils is used to excite the stators. The laminated stator structure then is assembled in the aluminum case shown at the right. The rotor is placed on the shaft extension of the ringing machine replacing the high speed mechanical interrupter, while the aluminum case containing the stator is rabbeted to the end of the ringing machine bearing bracket. This generator should require no maintenance whatever as it has not even added a bearing to the ringing machine assembly.

The pins shown on the end of the rotor are used for driving a coupling connected to a gear reduction which in turn drives the so-called low speed interrupters that are a part of many of the ringing machine units. The perforated cage encloses a resistance tube for connection in the field circuit of the tone alternator. This tube is adjusted on test so as to bring the no load and full load voltages of the high tone, low tone, and audible ringing channels within certain specified limits.

The output ratings of these 3 channels are as follows:

Low tone	1.0 volt,	4.0 amp
High tone	1.5 volts,	4.5 amp
Audible ringing tone	0.6 volt,	1.0 amp

Thermocouple instruments are used for measuring the output of these special machines. In some cases, voltmeter and ammeter are both used, but

more often a noninductive resistance carefully measured is connected across the output leads, a voltmeter then being the only instrument required.

Conclusion

It is difficult to predict just what course the future development of this special type of inductor alternator will take. In addition to the machines described in this paper many other combinations and arrangements, of course, are possible utilizing the fundamental principles of supplying only part of the rotor circumference with teeth and in winding different numbers of turns around groups of stator teeth periodically affected by the separate generating groups of rotor teeth.

Generators for producing interrupted or modulated tones built so far have been of small capacity, but there is no particular power limitation. Larger size inductor alternators could be designed, utilizing these same principles, which would deliver the low tone or any of the other tones in kilowatts instead of watts, if there were a demand for such greater power.

References

Theory and Calculations of Electrical Apparatus. Chas. P. Steinmetz. 1917—*Inductor Machines*, p. 274–87.

High Frequency Alternators (in French), M. Latour. *Revue Gen de L'Elec.* v. 5, p. 557–64, April 12, 1919.

High Frequency Alternators, C. M. Laffoon. *Elec. Journal*, v. 21, p. 416–20, Sept. 1924.

10-Kw 20,000-Cycle Alternator, M. C. Spencer. Trans. A.I.E.E., July 1927, v. 46, p. 681–87.

Progress in the Construction of Medium and High Frequency Machines (in German), K. Schmidt. *ETZ*, Oct. 25, 1928, v. 49, p. 1565–69.

Voltage and Magnetization in Two-Phase Inductor Type High Frequency Alternators (in Swedish), V. Olander. *ASEA Tidning*, Oct. 1928, v. 20, p. 138–44.

High Frequency Alternator Developments. *Elec. Rev.* (*Lond.*), April 12, 1929, v. 104, p. 674–75.

Method of Designing Medium and High Frequency Alternators With Special Reference to the Inductor Type, N. M. Oloukhoff. Oklahoma Agricultural and Mechanical Engg. Expt. Station, Stillwater, Okla. Publications Nos. 7 and 13, 1930 and 1932.

Heavy Surge Currents—

Generation and Measurement

There has been developed a generator for the production of heavy surge currents in excess of 100,000 amperes and of effective durations greater than 100 μsec. Methods of measuring these currents by the cathode ray oscillograph with good engineering accuracy also have been developed. Some features of lightning phenomena may now be investigated which were not possible of study with the high-surge-voltage generator.

By
P. L. BELLASCHI
ASSOCIATE A.I.E.E.

Westinghouse Elec. and Mfg. Co., Sharon, Pa.

FIELD investigations and experience have indicated that surge currents are important features of lightning phenomena, in some respects even more important than surge voltages. This consideration has led to the development of the heavy-surge-current generator which is described in this paper.

A prerequisite for the production of heavy surge currents is a surge-generator discharge circuit of low impedance; the maximum current discharged from such a circuit is inherently oscillatory. To secure an aperiodic wave, series resistance is inserted in the discharge circuit; this results however in a lowering of the maximum current output. Since the current generated bears a linear relation to both the charging volts and the capacitor voltage, it can be controlled in much the same way as the voltage of the surge voltage generator.

The accurate measurement of heavy surge current is beset by difficulties due not only to the magnitude of the current but also to its rapid time variation. To eliminate stray effects and errors in the measuring circuit due to surge currents in the ground, the generator is grounded at one point only—in this way suppressing currents flowing in the ground. At this grounded point a resistance shunt is inserted in the generator circuit. This shunt must be practically noninductive and must have a constant resistance independent of temperature and frequency effects. The voltage across the shunt is transmitted through a short segment of cable for measurement at the cathode ray oscillograph.

With the development of the heavy-surge-current generator and of the technique of heavy-surge-current measurement, surge currents in excess of 100,000 amp and of effective duration greater than 100 μsec have been produced. These currents have been measured with good engineering accuracy.

The physical characteristics of heavy surge currents produced in the laboratory are comparable in effect to those produced in the field by direct or near-direct lightning discharges, for example: the ex-

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 20, 1933; released for publication Nov. 21, 1933. *Not published in pamphlet form.*

plosive and destructive effects, the fusing of conductors, the sound and light produced, and other physical manifestations. One of the practical applications of the heavy-surge-current generator has been in connection with the testing and development of the deion gap for surge-proof distribution transformers.

Importance of Heavy Surge Currents

The early studies of the protection of high voltage lines against lightning strokes, which indicated that current was as important a characteristic of lightning phenomena as voltage, also showed that this was true particularly in its bearing on the design of ground wires and tower footing resistances where current discharges are involved.[1] Later, considerable attention was given to the protection of low voltage circuits against lightning[2] and growing out of this study a special form of protected distribution transformer[3] was developed. Following the installation of several thousands of these transformers, many of them in regions highly exposed to lightning, valuable field experience emphasizing the importance of lightning current in distribution circuits has been obtained. Among other things, these field data establish the fact that while heavy-lightning-current discharges occurring directly at or near the transformer are rare, yet they take place more often than was originally suspected on the strength of previous available experience.

Surge Currents Obtainable From High-Surge-Voltage Generator

At the time of the investigation of surge voltages,[4] studies were made of the currents obtainable from the 3,000,000-volt surge-voltage generator at Sharon, Pa., and subsequently laboratory tests were made. The results of these tests are summarized below, for they have served as a useful guide in the development of the heavy-surge-current generator design and operating technique.

1. For all numbered references see list at end of paper.

Fig. 1. Surge current waves produced by a 3,000,000-volt surge-voltage generator

Briefly: The maximum current obtainable with the voltage generator short-circuited and all inserted resistance removed is of the order of 20,000 amp. This current (Fig. 1*A*) is oscillatory, having a period of 5 μsec and a duration to half-crest value of 10 μsec. With 600 ohms inserted in the generator, an exponential discharge (Fig. 1*B*) of duration 4 to 5 μsec is

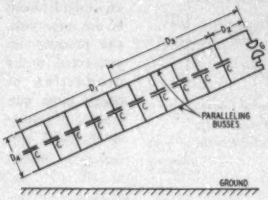


Fig. 2. Circuit diagram of one stair of the surge voltage generator with all capacitor groups reconnected in parallel

obtainable with a crest-value of about 3,000 amp. These current waves are generally characterized by an ill-defined front having superposed thereon high-frequency oscillations which are due to the effects of ground and to the short-circuiting lead from the high voltage terminal to ground.

With an inductance of 100 to 200 μh inserted in the generator circuit, the initial rate of current discharge is decreased and for both the oscillatory and exponential waves, the oscillograms (Figs. 1*C* and *D*) therefore become well-defined on the front, but the maximum current generated is reduced materially.

These preliminary investigations on the generation and measurement of surge currents definitely pointed out that as a prerequisite for the production of heavy surge currents it is essential that the surge-current generator circuit be of much lower impedance than prevails with the surge-voltage generator. They also suggested the desirability of eliminating the ground as part of the discharge circuit by confining the surge current to a definite path and emphasized the necessity in current measurement technique of the use of noninductive, constant-resistance shunts free from appreciable skin effect and unaffected by temperature.

Adaptation of the 3,000,000-Volt Surge-Voltage Generator for Heavy Surge Currents

In the early work on heavy surge currents it was found from analysis that by paralleling the 30 capacitor groups of the surge-voltage generator[5] and discharging them at the junction of the first and second stairs (see Fig. 6), it would be possible to produce currents of the order of 75,000 amp and of a fundamental period of 30 μsec and more. Simply stated, this analysis is as follows.

The equivalent circuit of the first stair of capacitors (10 groups) is represented in Fig. 2. The average distance of the 10 capacitances C from the discharge gap G is D_3. The 2 paralleling busses of effective radius r are set D_4 distance apart. The ef-

fective lumped inductance considered in series with the total capacitance $C_0 = 2.4$ μf is approximately

$$L_a = 0.28 \left(\log_{10} \frac{D_1}{r}\right) D_1 + 0.28 \left(\log_{10} \frac{D_2}{r}\right) D_4 \ \mu\text{h}$$

where the linear dimensions are in feet. On the basis of these simplifications the lumped circuit constants of the 3 stairs of capacitors are given in Fig. 3. The first and second stairs of capacitors are symmetrically disposed with respect to the discharge gap and therefore each of these contributes the same amount of current, calculated as follows:

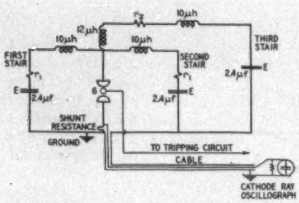


Fig. 3. Simplified equivalent circuit of the surge voltage generator reconnected for the production of heavy surge currents. Measurement circuit also shown

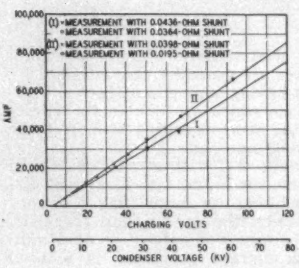


Fig. 4. Current output of surge voltage generator reconnected for the generation of current. The 30 capacitor groups are all connected in parallel

I. Paralleling strap conductors mounted on charging bus supports

II. Paralleling bus bars mounted on terminals of capacitors

Oscillation impedance $= \sqrt{\frac{L_a}{C_0}} = 2$ ohms

Period of oscillation, $T = 2\pi\sqrt{L_a C_0} = 31$ μsec

The effective series resistance of the leads, busses, etc., taking into account skin effect[6] at 30 kc but neglecting other possible losses in the capacitors, at the discharge gap, etc., is $r_1 = 0.1$ ohm. On this basis the fundamental oscillation would dampen from crest to half value in approximately $\frac{2\,L_a}{T r_1} \doteq 4$ oscillations. Then for a capacitor voltage $E = 75{,}000$ volts, the combined currents discharged at the gap from the first and second stairs of capacitors would be 70,000 amp. The third stair of capacitors is located well above the discharge gap, connecting thereto through a cable extension of 12-μh inductance. Accordingly, the third stair contributes a current of only about 20,000 amp and of 45 μsec period.

It was found that altogether a total current of approximately 75,000 amp at a period somewhat greater than 30 μsec could be produced. Therefore, a scheme of paralleling busses was devised so that the surge-voltage generator could be utilized to produce heavy surge currents. The calibration curves of current in Fig. 4 and the corresponding oscillograms in Fig. 5 show that the experimental data obtained are in substantial agreement with the analysis based upon the simplifying assumptions stated above. In Appendix I the circuit characteristics of surge current generators are treated more fully and in detail.

Fig. 5. Oscillograms of surge currents produced with surge voltage generator reconnected for the generation of current

Fig. 6. Laboratory view of surge voltage generator reconnected for current and of the adjunct current generator. Note the triple gap on platform

The operation of the surge-current generator is much the same as in surge-voltage technique.[7,8] The measurement of the currents are conducted as follows: Referring to Fig. 3, the generator circuit is connected to ground at one point only to eliminate current flowing therein; furthermore, the shunt is

inserted in the circuit at the grounded point and the voltage drop v_s across the shunt is transmitted to and measured at the voltage plates of the cathode ray oscillograph. Then from the resistance of the shunt R_s the current measured is $i_s = v_s/R_s$. With this arrangement of the surge current generator, the current measured at the oscillograph was found to be practically independent of effects due to ground; this is shown in the oscillogram of Fig. 5*A*.

In Table I are summarized pertinent data on the first group of shunts that were used to measure surge currents as large as 75,000 amp. It was found that in comparing any 2 or more shunts, the same connections for the busses, leads, discharge gap, etc., had to be used since any changes in them would alter the circuit inductance sufficiently to affect the current generated for a given charging voltage. For example, the calibration curves I and II in Fig. 4 show appreciable differences in the currents, these being due to alterations that had been made in the set-up of the busses. The 2 shunts compared with each other in curves I and II, respectively, while somewhat different from each other, both measure practically the same current. The characteristics of shunts for heavy surge current measurements are discussed in greater detail further on and also in Appendix II.

To render the wave form of the surge current aperiodic, or at least to simulate the aperiodic wave form, resistance is inserted in the current generator. In so doing the amplitude of the current is reduced. The characteristics of the current generated are given in the oscillograms of Fig. 7 and the relation between maximum current and inserted resistance are plotted in Fig. 8. It is of interest to note that the maximum current is independent of the arrangement of the resistors with respect to the discharge gap.

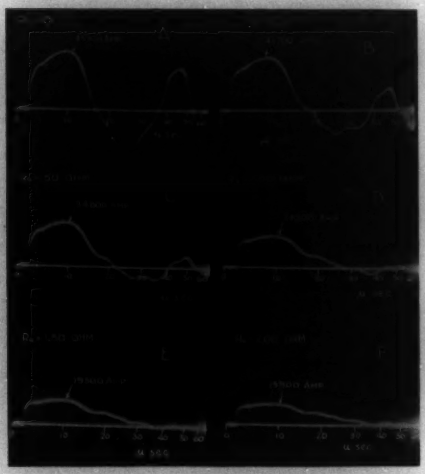


Fig. 7. Oscillograms of surge current with resistance (R_0) inserted in generator

Design and Characteristics of the Adjunct Surge-Current Generator

The purpose in providing an adjunct current generator for use in conjunction with the parallel-operated surge-voltage generator already available was to produce surge currents of the order of 100,000 amp or more. To accomplish this, the adjunct current generator had to be designed to have the

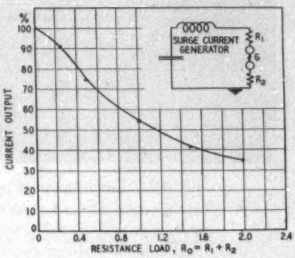


Fig. 8. Current output as affected by resistance inserted in generator. The 30 condenser groups are connected in parallel. Load resistance is at the discharge gap

Current output is given in per cent of maximum current for load resistance, $R_0 = 0$

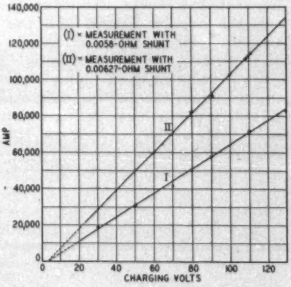


Fig. 9. Current output of surge current generator

I. Current output of adjunct surge current generator

II. Current output of surge current generator proper and adjunct surge current generator both connected in parallel

proper natural period and other electrical constants, to permit operating it successfully in parallel with the reconnected surge voltage generator. As shown in Fig. 6, the adjunct generator consists of 8 groups of 4 capacitors paralleled by 2 busses.

The total capacitance of the adjunct is $C_0 = 7.7$ μf. The equivalent series lumped inductance, calculated by the simplified method described previously, is $L_a = 4.3$ μh. Accordingly the characteristics of the circuit for a capacitor voltage of 75,000 volts are as follows: Oscillation impedance = 0.75 ohms; period of fundamental oscillation = $2\pi\sqrt{L_aC_0} = 36$ μsec; maximum current of fundamental oscillation = 75,000 divided by 0.75 = 100,000 amp. This calculated value of the maximum current generated by the adjunct does not take into account attenuation or the fact, as shown subsequently in Appendix I, that harmonic oscillations are

superposed on the fundamental, both factors reducing the actual maximum current to a value somewhat below that calculated above.

Curve I of Fig. 9 gives the relation between the charging volts and the crest value of the current

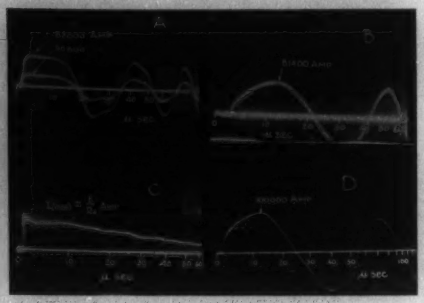


Fig. 10. Oscillograms of surge current

A. Surge current produced by the adjunct surge current generator

B, C, and D. Surge current for various conditions of load at discharge gap (2 generators in parallel)

generated, and Fig. 10*A* gives the oscillograms showing the natural period and the wave form of the current. From these it can be seen that experimental data are in substantial agreement with the above analysis even though this analysis is based upon certain simplifying assumptions. It should be noted, however, that the first loop of the oscillograms is of rectangular wave form, this being due to harmonic oscillations superposed upon the fundamental, as discussed at length in Appendix I.

Reconnected Surge Voltage Generator and Adjunct Current Generator in Parallel

To produce surge currents above 100,000 amp, the 2 generators mentioned above are operated in parallel. The laboratory arrangement and also the triple discharge gap located on the platform are shown in Fig. 6. The total capacitance of the 2 generators in parallel is 14.9 μf. The relation of the current output to the charging voltage is plotted in Curve II of Fig. 9. Oscillogram *B* of Fig. 10 gives the wave form and the period of the surge current. It should be noted that since the natural period of each of the 2 generators individually is between 35 to 40 μsec, the period for the 2 in parallel remains practically unchanged. However, the surge current output from the 2 generators in parallel is not the sum of the currents from each separately, but rather a value somewhat less; the reason for this is as follows: The discharge circuit comprising the discharge gap and common to both generators has an appreciable inductance relative to the total circuit inductance. Furthermore, this common inductance, being well lumped and in series with the rest of the circuit, results in a wave form of current as shown in the oscillogram of Fig. 10*B*, which can be seen to be substantially more sinusoidal than for the case when either of the 2 generators operates alone.

The other 2 oscillograms in Fig. 10 are worthy of study. When increasing the load resistance to approximately 3 ohms, the current output becomes practically equal to the voltage divided by the load resistance, and the wave form is then substantially exponential, rising abruptly to crest and receding to half crest value in nearly 40 μsec, as shown in oscillogram *C*. With zero resistance load and the length of the discharge path common to the 2 generators increased, the period of oscillation is increased as shown in oscillogram *D* and the output for a given charging voltage is somewhat decreased, due

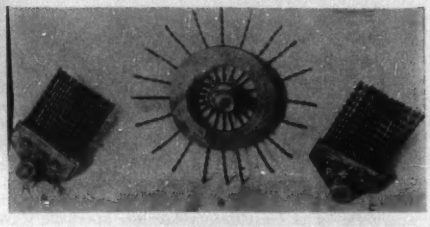


Fig. 11. Resistance shunts for the measurement of heavy surge currents

to the obvious fact that the total series inductance of the discharge circuit is increased thereby.

Shunts for the Measurement of Heavy Surge Currents

As can be seen from Fig. 3, the technique of heavy surge-current measurement consists essentially of recording the voltage drop across a resistance shunt at the voltage plates of the cathode ray oscillograph. Since the voltage that can be measured at the oscillograph is of the order of 1,000 volts, the product of the crest current and of the shunt resistance must be of this order.

The requirements of a resistance shunt, intended to measure heavy surge currents with good engineering accuracy, are best understood by references to specific examples of shunt performance. The shunt must be practically noninductive. It must have a constant resistance independent of temperature and its conductor elements should be practically free from skin and proximity effects[6] within the range of frequencies measured. Furthermore it should carry the current without excessive heating.

Conductors of No. 20 A.W.G. manganin wire, for example, twisted together noninductively as shown in Fig. 11, were found to satisfy the above requirements in a good measure. The maximum surge-current carrying capacity of No. 20 manganin wire for the oscillatory waves (Fig. 5) is in the order of 10,000 amp, so that the shunts with 20 elements in parallel, shown in Fig. 11, can carry 200,000 amp

satisfactorily. Shunts, described in Table I, were subjected to heavy surge currents up to the fusing point of the conductors; even then their resistance was found to remain substantially constant, as was the case, for example, with the shunts in Fig. 4. These shunts, although differing in construction, recorded practically the same current values.

A strictly noninductive shunt is difficult to realize. However, the inductive drop can be reduced practically to a small amount relative to the ohmic drop by a disposition of conductor elements as shown in Fig. 11. For shunt resistances of the order of milliohms, the inherent inductance permissible should be limited to a value of the order of millimicrohenries, in order that the shunt may record surge currents of the time-characteristics under consideration within a few per cent deviation from true value.

No less important in the construction of the shunt is the proper location of its potential terminals. It is essential that the leads from the core and sheath of the cable shall be as short as possible and that they connect directly to the terminals without open loops, since loops would inevitably entail mutual couplings with the discharge circuit and thus result in errors of measurement. The method of inserting the shunt in the discharge circuit is also important; for example, it will be noted in Fig. 11 that the current is made to enter at right angles to the plane of the shunt elements. Furthermore, if various shunts are to be compared with each other, for performance, the effective inductance of the generator discharge circuit must not be altered appreciably with the insertion of any one of the various shunts being compared since the comparison should be made on the basis of equal charging voltage applied to the current generator.

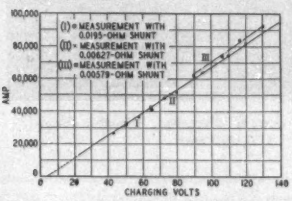


Fig. 12. Comparison of current measurements made with different shunts. The 30 capacitor groups are connected in parallel

Table I—Data on Shunts

Shunt Resistance[1] —Ohms	Current Measured per Inch Deflection on Film —Amperes	Description of Shunt[2]	Max. Current-Carrying Capacity[3] —Amperes
0.0436	19,500	Six elements of No. 20 manganin wire in parallel, each element 12 in. long	65,000
0.0364	23,400	One element of No. 12 manganin wire 5 in. long	Greater than 40,000
0.0398	21,400	Three elements of No. 20 manganin wire in parallel, 7 in. long	33,000
0.0195	43,600	Six elements of No. 20 manganin wire in parallel, 7 in. long	65,000

1. D-c resistance measured with the Kelvin bridge. Skin and proximity effects at 30 kc for manganin conductors here considered increase d-c resistance inappreciably

2. Each element of wire is extended to half-length and twisted back onto itself noninductively

3. Current that produced excessive heating of conductor and diffusive burning of insulation. Wave form of current as in oscillograms of Fig. 5

Shunt *B*, Fig. 11, was found, both theoretically and experimentally, to conform with the cited requirements for a shunt good for very heavy surge-current measurement. Curve II in Fig. 12 is the current calibration of the generator with shunt *B* (0.00627 ohm). Shunt *A* measured values for current which were higher by a small percentage, as indicated in curve III. Curve I corresponds to a higher resistance shunt (0.0195 ohm) which had already been found in good agreement with other shunts of still higher resistance.

Oscillograms *A* and *B* in Fig. 13 were recorded with the 0.00627-ohm shunt (shunt *B*) and the 0.0195 shunt (Table I), respectively. These 2 oscillograms are practically identical in period, damping, and wave form. Oscillogram *C* was taken with shunt *A* (0.00579-ohm). This shunt has potential terminals at the ends of the copper plates. Shunt *C* is similar to *A* except that the 2 potential terminals are located on opposite copper plates, thus entailing a loop of the cable terminals in connecting. Oscillogram *D* was recorded with shunt *C;* it shows an even higher overshoot than oscillogram *C*, and accordingly a still higher measurement of current than with shunt *A*.

Résumé of Investigations of Discharges and Their Physical Characteristics

Extensive tests have been made with heavy surge currents and there are good reasons indicating that these currents are fairly representative of the heavy surge currents that are found in the field. This statement does not preclude the possibility of even more intense and still more rare, direct-stroke lightning-current discharges. These are the reasons.

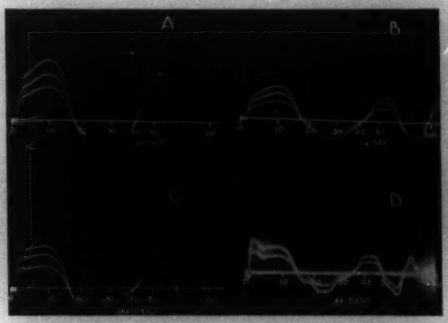


Fig. 13. Oscillograms of surge currents taken with different shunts to illustrate their performance

First: The very heavy surge currents produced in the laboratory readily explode a No. 14 copper wire.

In this connection, a simple experiment conducted by Prof. E. C. Starr of Oregon State College is illuminating. He erected a lightning rod on the top of a mountain peak and connected it to conductors laid along the sides of the peak. In this path, which completed the lightning discharge to earth, he inserted sections of different-sized copper wires connected in series, making it possible to determine the fusing effects of the very heavy currents in a direct stroke. The conclusions from this experiment and from similar observations of the kind are that the current in a direct lightning-stroke can be expected to fuse copper wires of No. 14 and smaller, but that larger conductors will ordinarily conduct the current successfully to ground. Similar data have been obtained by the author with a lightning stroke at Sharon, Pa., where No. 10 copper wire of a radio antenna was beaded at the point of contact with the stroke, but not fused. Observations by other investigators are in substantial agreement with these findings.[8,10,11]

The following relationship of the current for a single lightning discharge that would produce fusing of a copper conductor is of great interest, since it makes possible an estimate of the current in a lightning stroke from observations on the fusing of conductors:

$$I_{(max)} = 320{,}000 \frac{A}{\sqrt{T}}$$

The formula is deduced directly from the curves of Fig. 14, which were determined experimentally in the laboratory. (On account of skin effect, the effective area A used should be somewhat less than its physical value for $T = 20$ to 60 μsec and for large size solid conductors of 1.3 mm diameter and greater.) The symbols are defined in Appendix III, where the expression is arrived at with good approximation from theoretical considerations.[12] Similar expressions have been obtained for other wave forms of current and for conductors of other materials, the constant being a function of the wave form and of the material. The expression for fuse links as ordinarily used in distribution systems is in substantial agreement with the data published by other investigators.[13]

Second: Field experience has revealed valuable information on direct or near-direct strokes of lightning at distribution transformers provided with deion gap protection. The plugs or electrodes of the deion gaps discharging these heavy surge currents were marked on their faces with a "klydonograph" figure or record. These figures when compared with similar figures obtained on deion gaps tested with known heavy surge currents in the laboratory showed marked similarities in all respects, indicating that the currents in the laboratory were closely comparable to those that have occurred in the field.

Third: It is well known that in cases of a direct or near-direct strokes of lightning at distribution transformer installations, fuse cutouts and similar apparatus have been completely destroyed and shattered.

Fig. 15. Surge current discharge, slightly above 100,000 amp

Similar effects have been produced in the laboratory with heavy surge current tests and with heavy surge current tests combined with power excitation.

The light produced by these heavy surge-current discharges is intense in brilliancy and blinding, much the same as when looking directly at the sun. The sound produced by the arc discharge, although the arc is only several feet long, is uncomfortable and even painful to the ear. The diameter of the incandescent part of the arc is of the order of one foot and more. In Fig. 15 is illustrated a heavy surge-current discharge of 100,000 amp.

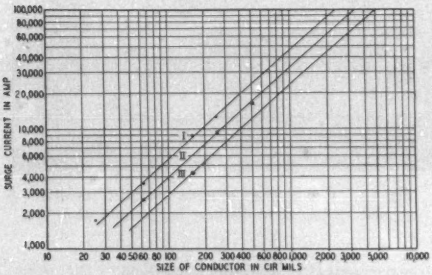


Fig. 14. Fusion characteristics of copper conductors with surge currents

I. Steep front 9-μsec surge (exponential tail)
II. Steep front 18-μsec surge (exponential tail)
III. Steep front 40-μsec surge (exponential tail)

Appendix I

The circuit of the surge current generator of Fig. 2 is represented in Fig. 16A as an ideal network with distributed constants. Neglecting for the moment the effect of resistance and other losses, traveling waves of voltage and current are then set up as given in Fig. 16B. The voltage and current at any point n are plotted in Fig. 17A and B as functions of time t. The equations of current

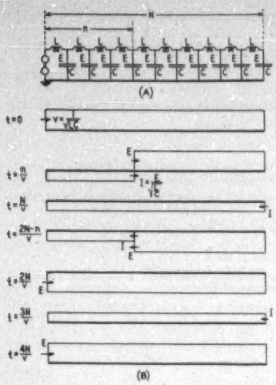


Fig. 16. Surge current generator with distributed constants

A. Circuit of surge current generator having distributed constants

B. Traveling waves of current and voltage in the distributed circuit

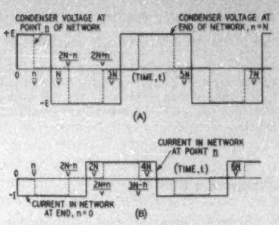


Fig. 17. Voltage and current as functions of time for the distributed circuit of Fig. 16A

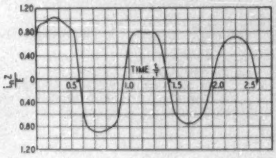


Fig. 18. Damping of current at the discharge gap for the distributed circuit of Fig. 16A

and voltage as a function of time then can be arrived at conveniently from the Fourier integral theorem. Expressed in their final solution, they are as follows:

$$i_n = -\frac{4}{\pi}\frac{E}{Z}\sum_{k=1}^{k=\infty}\frac{1}{k}\cos\left(\frac{k\pi n}{2N}\right)\sin\left(\frac{2\pi kt}{T}\right) \tag{1}$$

and

$$e_n = \frac{4}{\pi}E\sum_{k=1}^{k=\infty}\frac{1}{k}\sin\left(\frac{k\pi n}{2N}\right)\cos\left(\frac{2\pi kt}{T}\right) \tag{2}$$

where $k = 1, 3, 5$, etc.

$$L_0 = NL \text{ and } C_0 = NC$$

Fundamental period, $T = \frac{4N}{v} = 4\sqrt{L_0C_0}$ since $v = \frac{1}{\sqrt{LC}}$

Surge impedance, $Z = \sqrt{\frac{L}{C}} = \sqrt{\frac{L_0}{C_0}}$

It can be demonstrated readily that eqs 1 and 2 satisfy the general differential equations:

$$\frac{\partial e_n}{\partial n} = -L\frac{\partial i_n}{\partial t}; \text{ and } \frac{\partial i_n}{\partial n} = -C\frac{\partial e_n}{\partial t}$$

Next, considering the dissipative characteristics of the distributed circuit in Fig. 16*A*, with particular reference to the current at the discharge gap, and denoting the total distributed resistance as r_0, then in accordance with the classical theory[14,15] the waves in Fig. 17*B* would decay at substantially an exponential rate, i. e.,

$$\epsilon^{-\frac{r_0}{2L_0}t}$$

But the resistance of large-section copper conductors, as well as losses in the dielectric of the capacitors, are both functions of the frequency of oscillation. As an illustrative example, let it be assumed that the effective resistance increases in direct proportion with the frequency, then the fundamental and harmonic oscillations in eq 1 would dampen from crest to half-crest value in the same number of oscillations. Considering the case where the amplitude of the oscillations dampen to half-crest value in 3 oscillations, then introducing damping factors in eq 1 and dropping the negative sign for convenience, the current discharged at the gap is plotted in the curve of Fig. 18. This curve clearly indicates that on account of the rapid damping of the higher-frequency oscillations, the current assumes practically a sinusoidal wave form after a few oscillations. On the basis of still greater damping with frequency than stated above, the current would assume still more rapidly practically a sinusoidal form. To be sure, the exact determination of the damping factors at high frequencies involves many complications; however, a close determination of these factors is not of vital importance here and therefore further detailed analysis is considered to be beyond the scope of the present work.

In practice, the capacitor bank connects to the discharge gap through leads of appreciable length, shown as D_3 in Fig. 2, thus introducing at the discharge gap in Fig. 16*A* an appreciable lumped inductance relative to the total distributed inductance L_0. Furthermore, the capacitor groups C are not uniformly distributed but lumped into a finite number of groups. In addition, each group of capacitors connects to the 2 paralleling busses through leads which are short but which nevertheless entail some inductance and resistance in series with each C. Considering these modifications introduced in the ideal distributed network in Fig. 16*A*, the combined effect is to round off the otherwise rectangular shape even of the first loop of the current as can readily be seen from the oscillograms shown. In fact, the total effect, due to these practical considerations, is to modify the ideal distributed network by the introduction of lumped constants of appreciable magnitude, so that practically speaking the resultant network can be analyzed with reasonably good approximation as an equivalent capacity-inductance-resistance series circuit. The good approximation obtained from this simplification is well borne out by the 2 examples in the early part of this paper.

The following observation is of further practical interest. In the case of the ideal distributed network, Fig. 16*A*, with a load resistance $R_0 = Z$ at the discharge gap, the current at the gap would be a single rectangular discharge of duration $0.5T = 2\sqrt{L_0C_0}$ and amplitude $E/2Z$. This point is illustrated in the oscillograms of Fig. 7, but due to modifications in the distributed circuit produced by lumped circuit constants the end of the rectangle does not drop abruptly but is drawn out in an approximately exponential form.

Appendix II

Referring to Fig. 3, let the resistance of the shunt be R_s, the self and mutual inductance L_s; then, the voltage drop across the shunt set up by a current $i = f(t)$ which rises from zero to crest value and recedes gradually to zero, is

$$e = R_sf(t) + L_s\frac{d}{dt}f(t) \tag{3}$$

In general, the current rises more rapidly to crest than it recedes from crest to zero value. Then, denoting the average rise of the front as taking place in time T', for practical purposes the ratio of inductive drop superimposed on the ohmic drop is $\frac{L_s}{R_sT'}$. There-

fore to eliminate a possible overshoot on the current oscillogram due to the inductive drop, the time constant $\frac{L_s}{R_s}$ of the shunt should be kept substantially smaller than the time T'. For example, in measuring a surge current rising exponentially to crest value at the initial rate of rise to crest of one microsecond, the permissible inductance for a 10 milliohm shunt should not exceed 5 millimicrohenries.

Appendix III

The surge current required just to produce fusion of a conductor is here derived from fundamental considerations. Let

$$i = I_{(max)} \in^{-\frac{0.693}{T}t},$$ be the surge-current discharge where,

t = time in microseconds
$I_{(max)}$ = crest value of current in amperes
T = duration of current discharge from crest to half-crest value in microseconds;

and,

A = cross-sectional area of conductor in square millimeters
θ = melting point of conductor in degrees C
d = specific density of conductor
ζ = mean resistivity of conductor from zero degrees C to θ deg C
s = mean specific heat of conductor from zero degrees C to θ deg C
J = Joule's mechanical equivalent of heat = 4.18

Then from the law of conservation of energy, equating the amount of heat generated per unit length (one centimeter) of conductor by the passage of the surge current to the amount of heat per unit length of conductor required to raise its temperature from zero degrees C to θ deg C,

$$\int^{\infty} \frac{100\zeta}{A} I^2_{(max)} \in^{-\frac{1.386}{T}t} dt = \frac{100\zeta}{A} \frac{I^2_{(max)}\, T \times 10^{-6}}{1.386} = \frac{J\theta Asd}{100}$$

$$I_{(max)} = \sqrt{(580)\frac{\theta ds}{\zeta}}\,\frac{A}{\sqrt{T}} \qquad (4)$$

For example, introducing the physical constants[12] of copper in the equation: $\theta = 1{,}080$; $d = 8.93$; $s = 0.117$; $\zeta = 5.30 \times 10^{-6}$

$$I_{(max)} = 350{,}000\,\frac{A}{\sqrt{T}}$$

which agrees quite well with the expression obtained experimentally:

$$I_{(max)} = 320{,}000\,\frac{A}{\sqrt{T}}$$

References

1. Lightning and Its Effects on Transmission Lines, C. L. Fortescue. Internl. Elec. Congress, Paris, 1932.

2. A.I.E.E. Trans., v. 51, 1932, p. 234–85:
   Interconnection of Primary Lightning Arrester Ground and the Grounded Neutral of the Secondary Main, C. Francis Harding and C. S. Sprague.
   Lightning Protection for Distribution Transformers, K. B. McEachron and L. Saxon.
   Lightning Protection for Distribution Transformers, A. M. Opsahl, A. S. Brookes and R. N. Southgate.
   Studies in Lightning Protection on 4,000-Volt Circuits—III, D. W. Roper.
   Lightning Protection for Distribution Transformers, T. H. Haines and C. A. Corney.
   Distribution System Studies, H. A. Dambly, H. N. Ekvall and H. S. Phelps.

3. Surge-Proof Distribution Transformers, J. K. Hodnette. *Elec. Jl.*, Feb. 1932, p. 69–70.

4. Characteristics of Surge Generators for Transformer Testing, P. L. Bellaschi. A.I.E.E. Trans., v. 51, Dec. 1932, p. 936–45.

5. New Surge Generator for Testing Transformers, O. Ackermann. *Elec. Jl.*, Feb. 1932, p. 61–3.

6. Electric Power Transmission and Distribution, L. F. Woodruff. John Wiley & Sons, 1925, Chap. VII.

7. High-Voltage Surge Oscillography, J. J. Torok and F. D. Fielder. *Elec. Jl.*, July 1929, p. 320–4.

8. The Measurement of High-Surge Voltages, P. L. Bellaschi. A.I.E.E. Trans., v. 52, June 1933, p. 544–52.

9. Einige Untersuchungen Über den Blitz, L. Binder. *E.T.Z.*, v. 49, 1928, p. 503–7.

10. Code for Protection Against Lightning—Appendixes A and B. Handbook No. 17, Bureau of Standards, Washington, D. C.

11. La Foudre et ses effets sur les bâtiments en Suisse au cours des étés 1931 et 1932, Ch. Morel. *A.S.E.*, May 12, 1933, p. 209–16.

12. Lightning, G. C. Simpson. *I.E.E. Jl.*, v. 67, Nov. 1929, p. 1279–81.

13. Impulse Characteristics of Fuse Links, E. M. Duvoisin and T. Brownlee. *Gen. Elec. Rev.*, May 1932, p. 260–6.

14. Electric Power Transmission and Distribution, L. F. Woodruff. John Wiley and Sons, 1925, Chap. XVI.

15. Operational Circuit Analysis, V. Bush. John Wiley & Sons, 1929, Chap. XII.

A New Demand Meter

A new demand meter has been developed which is suitable for attaching to either a single-phase or polyphase watthour meter, and which appears to have an accuracy and all around serviceability approaching that of the watthour meter itself. It has a definite law for averaging loads, and is smooth in operation.

By
B. H. SMITH
ASSOCIATE A.I.E.E.

Westinghouse Elec. and Mfg. Co., Newark, N. J.

VERY early in the development of the electrical industry, the watthour meter was produced. Its record for ease of maintenance and for doing continuously just what it is supposed to do is unsurpassed by any other piece of apparatus in the electrical or any other field. Millions of these meters have been manufactured and installed and kept running year after year with a minimum of maintenance cost and with unparalleled accuracy. Now, in addition to a charge for watthours, which

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Nov. 9, 1933; released for publication Dec. 5, 1933. *Not published in pamphlet form.*

is based upon the measurements of the watthour meter, it is necessary to make a charge for "ability to serve" on a "demand" basis, especially to users of large amounts of electrical energy.

The subject of demand measurement has been expounded to the fullest extent by many authors, particularly by P. A. Borden (see "The Measurement of Maximum Demand and the Determination of Load Factor," A.I.E.E. TRANS., v. 39, 1920, p. 1847–83) and by Prof. P. M. Lincoln (see "Rates and Rate Making," A.I.E.E. TRANS., v. 34, 1915, p. 2279–318, and "The Character of the Thermal Storage Demand Meter," A.I.E.E. TRANS., v. 37, 1918, p. 189–210).

A number of different types of demand meters have been developed and have been commercially successful, but none of them has approached the ideal set by the watthour meter itself. Such an instrument should follow a definite law embodying the average loads for a given billing period and should avoid the mechanical difficulties of periodically tripping and resetting mechanisms. A new demand meter which embodies these principles is described in this paper. The record of the performance of this meter already obtained and a study of its mechanical construction indicates that it will register demand with great accuracy and, perhaps, approach the high ideal of good service set by the watthour meter.

OPERATION OF MECHANISM

The meter is suitable for attaching to either a single-phase or polyphase watthour meter. The conventional pointers for registering watthours are accompanied by a 300 deg demand scale with demand pointer and maximum hand. A representation of the principal parts of the mechanism with its connection to a watthour meter disk is given in Fig. 1, and a view of the mechanism is shown in Fig. 2. In Fig. 1, A and B are small bevel or crown gears which with a planetary gear G form a differential which through the relative speeds of its parts controls the angular position of the planetary gear G which carries with it an involute cam C. The cam C is mounted on a shaft which connects with the demand pointer D. A solid aluminum ball rests against the edge of the cam and is positioned between a driving disk E and a driven drum or roller F. At the "zero" position of the cam, the demand pointer is at zero on the scale and the ball is held at the exact center of the driving disk E. The gear A of the differential is driven by the watthour meter with a proper reduction in speed, and the gear B is driven by the drum F of the ball mechanism. As long as there is no load on the watthour meter, and if the ball is at the zero position, as mentioned above, the differential remains at rest and the driving disk E simply rotates at a constant speed due to a connection with the synchronous timing motor, but no motion is imparted to the ball and the demand pointer remains on zero.

Now, if a load is applied to the watthour meter, its side of the differential is driven at a speed proportional to this load, the cam begins to move, and since the drum F is tilted at a slight angle, the ball follows the cam and moves a little away from the center of the disk E. Immediately the ball begins to rotate about an axis which is parallel to the drum and which passes through the contact point between the ball and cam so that there is no friction at this point to prevent free rotation. Since the ball is resting on the drum F and rotating about a parallel axis, the drum is driven at the same surface speed as the ball and in turn drives the gear B in a direction which is arranged to be opposite to that of gear A. Thus the motion of the planetary gear G with the cam C is equal to the difference between A and B; therefore, if for any position the speed of B is equal to A, the cam remains in that position. Referring again to the position of the ball against the driving disk E, it is evident that the rotational speed of the ball and, consequently of the drum F is proportional to the distance of the ball contact point from the center of the disk E, which distance is exactly proportional to the angular position of the cam since the radius or "rise" of an involute cam is exactly proportional to its angular position. Then for any given load and corresponding rotational speed of A, there is a definite position of cam which will give an equal and opposite speed of B; therefore, the cam simply moves until this balance point is reached and remains there until the load on the watthour meter changes to a new value.

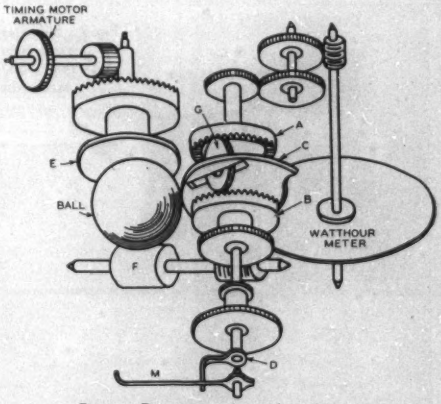


Fig. 1. Perspective view of mechanism

A. Watthour meter side of differential
B. Timing side of differential
C. Involute cam carried by center of differential
D. Demand hand
E. Ball driving disk
F. Drum driven from ball
G. Planetary gear of differential
M. Maximum hand

Since the *rate* at which the cam with the demand pointer D moves is equal to the difference in speed between A and B, it is evident that this

rate starts off at a relatively high value then becomes less and less as A minus B approaches zero, and the time to reach the balance point fully is very long. Thus the advance of D over the demand scale is rapid at first but becomes less and less as the final position is approached. For the same change in load, the descending rate as the demand pointer returns to zero is exactly the same as the ascending rate. Thus if the watthour meter stops, the gear B simply continues to rotate and carries the cam in the reverse direction at a slower and slower speed until finally the ball is again at the center of the disk E and all motion stops.

Determining Length of Demand Period

All of the above is analogous to a thermal meter where the pointer moves at a constantly decreasing speed or rate until the escape of heat just balances the heat input due to the watts in the circuit being measured. In both cases the time element to reach the 90 per cent point is given by the equation $t = T \log \frac{1}{1 - 0.9}$ or $t = 2.302\,T$, where T is the time which would be required to reach the former balance point in the thermal meter if there were no escape of heat. Since it is impossible to avoid the escape of some heat, the time element of a given design of thermal meter may be determined and adjusted only by experiment after first building a model and operating it with various adjustments until the desired value of t is found from which the value of T may be calculated. In the new mechanical logarithmic meter under discussion, however, we may simulate the desired condition by simply stopping the synchronous motor. Then the watthour meter will carry the cam with its attendant demand pointer forward at a constant speed and will reach a given point in a time which is determined by the gear ratio between the watthour meter and the demand pointer, and which is the value of T in the above equation. As an example, suppose that a 30-min meter is desired. Then if gears are selected by which the watthour meter at full scale speed brings the pointer to full scale in 30 divided by 2.302, or 13.02 min, there results what may be called a 30-min logarithmic meter; that is, if a steady load is applied with the synchronous motor running the pointer will reach 90 per cent of its final reading in exactly 30 min. Likewise, if it is required to design a 15-min meter, the gears must be such that the pointer will reach full scale in 6.51 min with the synchronous motor stopped. For the descending or cooling curve, if the watthour meter stops, the gearing from the synchronous motor through the ball mechanism to the differential must be such that with the ball mechanism held at full scale position, the pointer will return to zero in 13.02 min and 6.51 min, respectively. Tests on this time characteristic show that this type follows the law with precision while in thermal meters there are small discrepancies due to certain physical limitations of available material and also due to the fact that heat escape is not exactly proportional to temperature.

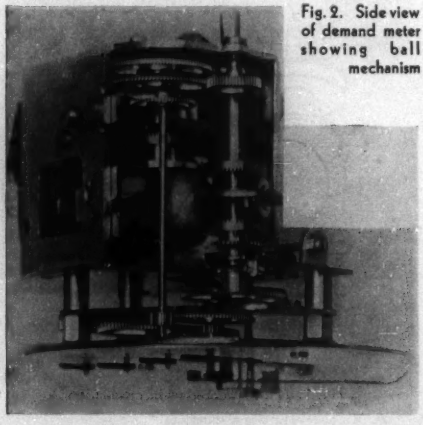


Fig. 2. Side view of demand meter showing ball mechanism

Ease of Checking, and Operation

Another interesting feature is the ease of checking the time element and general condition of meters in service. This new demand meter may be manually reset to zero at will and the time necessary to reach a given indication measured with a stop watch. Thus is avoided a long wait which would be necessary if the meter had to be disconnected from the load and allowed to return itself to zero along its normal logarithmic curve.

From a mechanical standpoint, the construction of the mechanism is very attractive. The operation is smooth and continuous; there is no tripping or sudden resetting or parts which might cause them to get out of order. The load on the timing motor is very small. The added load on the watthour meter can hardly be detected and is approximately the same as a standard watthour gear train. The question might be raised as to whether there is ever any slipping of the ball. In order to make certain that no slipping occurs even under the worst conditions, tests were made with the maximum hand friction adjustment tightened up until the torque required to move it was many times normal, yet there was no measurable error in the rotational speed of the ball side of the differential.

It should be apparent from the description of this instrument that the operation involves only well-known mechanical elements, such as gears, pinions, differentials, etc., a friction drive ball element such as has been in successful use for many years in a kilovoltampere demand meter, and a low speed type of synchronous motor. Therefore, it is believed that the result should be comparable in life and reliability to its associated device—the watthour meter itself.

An Economic Study of Suburban Distribution

Results of a recently completed study of methods of increasing the distribution facilities in Somerville, Mass., are presented in this paper. The economic study included several different plans covering a 10-year period, and as a result a plan is proposed which permits modification to suit future conditions.

By
A. H. SWEETNAM
MEMBER A.I.E.E.

C. A. CORNEY
MEMBER A.I.E.E.

Both of The Edison Elec. Illum. Co. of Boston, Mass.

METHODS of providing for the relief of an existing radial substation in Somerville, Mass., a city of 105,000 population and comprising an area of approximately 4 sq miles, were recently subjected to study. Several plans for providing additional transmission, substation, and distribution facilities were considered; these included one or more of the following possibilities enlarging the present substation, building a new attended or an automatic substation, and installing a primary network with a number of different possible transformer arrangements. The 10-yr period from 1933 to 1942, inclusive, was used as a basis for the study, and consideration was given to engineering features as well as to economics.

As a result of this study, it is proposed to install initially one 2-transformer network unit at a load center in East Somerville, supplying 3 radial circuits. It is also proposed that when the load has increased sufficiently, a second 2-transformer unit be installed at another load center, with a possible interconnection of part of the radial circuits from the original and second units. A valuable feature of this plan is that still further expansion may be secured with a network system involving 2-transformer units, or by forming a network supplied by single-transformer units. The latter plan involves removing the second transformers from the original units and using them with new switching units at new locations.

Existing Facilities

The position of the existing radial substation in Somerville is shown in Fig. 1. This substation, which is located about 0.7 of a mile from the present load center, is relatively old, and contains considerable equipment which has reached the limit of its load carrying and short-circuit interrupting capacity. The firm capacity of this substation is 8,000 kva with the largest transformer bank out of service. The load is approximately 9,000 kva.

The substation is an attended station supplied by 8 13.8-kv transmission lines having a firm capacity of 30,000 kva. This excess transmission line capacity is due to the fact that initially 5 lines served the entire northern district from the L Street generating station, but with the advent of a new 110-kv substation located in this area, the load was served from the new station by means of 3 new transmission lines.

The distribution system consists of 9 4-kv 3-phase 4-wire lighting circuits having an average capacity of 1,400 kva per circuit and 4 4-kv 3-phase 3-wire power circuits with an average capacity of 1,200 kva per circuit.

Plan 1—Enlarge Present Substation

The first alternative considered was to increase the firm capacity of the present substation to 14,000 kva by the installation of another transformer bank.

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 22, 1933. *Not published in pamphlet form.*

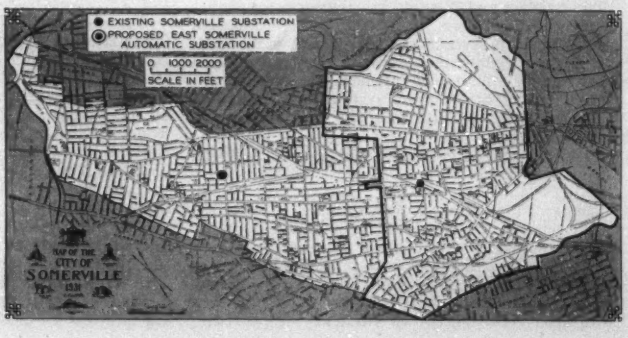


Fig. 1. Map of the city of Somerville, Mass., with East Somerville area shown outlined

In connection with this work it would be necessary to replace the existing 4-kv circuit breakers with a more modern type having a higher interrupting capacity, and to rebuild the existing 4-kv bus structure to accommodate additional distribution circuits. The ultimate development of this plan would provide for a second transformer bank to increase the firm

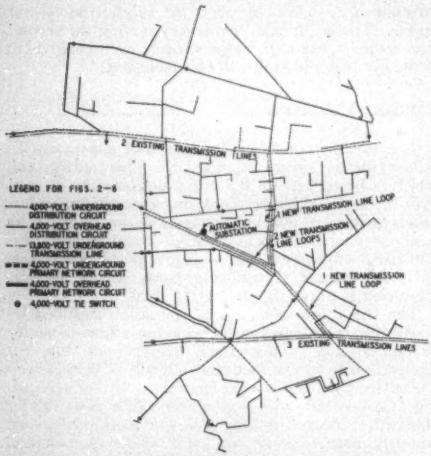


Fig. 2. Transmission and distribution systems for automatic substation (initial and ultimate installation, plan 3)

capacity to 23,800 kva. At this time it would be necessary to add another 13.8-kv bus section and to replace the existing 13.8-kv circuit breakers with a more modern type having a higher interrupting capacity, but it would not be necessary to add any more transmission lines. Another section would be added to the 4-kv bus to provide for additional distribution circuits.

Transmission and distribution diagrams for plan 1 are not presented here, as initially the transmission and distribution systems would remain unchanged, and in the ultimate development the transmission system would still remain unchanged, and the expansion of the distribution system would depend upon the location and nature of the load growth.

Plan 2—Abandon Present Substation and Build New Substation

The second alternative provided for a new, attended substation located at the estimated future load center which would contain one new 7,500-kva transformer bank in addition to 2 5,250-kva banks taken from the present substation, thereby giving the new substation a firm capacity of 12,000 kva based upon zero degrees C ambient temperature, under which condition the 7,500-kva banks were given an overload rating of 9,800 kva, and the 5,250-kva banks were given an overload rating of 6,000 kva.

Transmission lines feeding the present substation would be extended to the new location, there terminating in 2 13.8-kv bus sections equipped with 350,000-kva circuit breakers.

Initially there would be 3 4-kv bus sections equipped with 150,000-kva circuit breakers and accommodating 21 distribution circuits, 16 of which would be completely equipped. The distribution circuits themselves would consist of 350,000-cir-mil feeder cables installed from the substation to pick up the existing distribution circuits.

The ultimate development provides for the installation of another 7,500-kva transformer bank to increase the firm capacity to 21,800 kva. The 13.8-kv busses would not be altered, but another section would be added to the 4-kv bus thereby providing for a total of 28 distribution circuits, 23 of which would be completely equipped. The necessary 4-kv circuits would consist of 350,000-cir-mil feeder cables run out to their respective load centers from which point the distributors would be extended to pick up the load.

Transmission and distribution diagrams for plan 2 are not presented here, for the same reasons that they were omitted for plan 1.

Plan 3—Build New Automatic Substation

The next alternative considered was to maintain the existing substation at its present capacity of 8,000 kva initially, and to supplement it with a new automatic substation, located approximately 1.5 miles from the first. It was proposed to install 2 7,500-kva transformer banks and 2 13.8-kv bus sections in the new station supplied from loops of 2 nearby transmission lines. This would give the new substation a firm capacity of 9,800 kva, and in order to distribute this energy it was proposed to install 1 4-kv bus section to provide for 7 distribution circuits, 4 of which would be completely equipped. The 4-kv circuits would consist of 350,000-cir-mil feeders installed out to load centers as shown in Fig. 2.

The ultimate development would provide for the installation of a new 7,500-kva transformer bank in the present substation which would necessitate the changing of the existing 4-kv breakers to a more modern type. This would increase the firm capacity of the system to 23,800 kva, 9,800 kva of which would be in the new substation, and 14,000 kva in the old substation. Under these conditions, 2 new 350,000-cir-mil 4-kv feeder cables would be installed to their respective load centers in order to pick up the additional load.

The completion of this work would provide 2 modern substations with combined firm capacity to supply the 10-year ultimate load in Somerville, with consequent increased reliability of service, decreased distribution costs, and reduced interrupting duty on all circuit breakers.

Plans 4 and 5—Primary Network Scheme

The Boston Edison Company has had in operation since February 1932, a primary network system supplied from 3 1,500-kva network units in the Brighton and Brookline area which was installed after an extensive study had shown it to be the most suitable method of providing relief for the existing overloaded substation supplying this area. In view of its highly successful operating experience with this network, and also as a result of comparative studies made for supplying service to an entirely new area both by means of a radial substation and by a primary network system, in which the network showed a saving of approximately 20 per cent over the radial system, it was decided to make a study of the possibility of relieving the existing Somerville station of some of its load by the installation of a primary network.

An area comprising approximately 1.5 sq miles in East Somerville was chosen for this study. This is the area enclosed with the heavy line in Fig. 1. The peak load in this area, which is approximately 3,700 kva is now supplied by 4 3-phase 4-wire lighting circuits and 3 3-phase 3-wire power circuits, with a total of 10.6 circuit miles of overhead construction and 5.6 circuit miles of underground construction.

It was proposed to install network units which would have a normal rating of 2,000 kva with blower equipment and a rating of 2,500 kva under ambient conditions of zero degrees C, either in underground vaults, or above ground on concrete mats, depending upon local conditions. On this basis the installation of 3 primary network units would provide a firm capacity of 5,000 kva with one unit out of service, which would take care of the initial demands and provide considerable spare capacity. Preliminary costs showed, however, that the increased cost of this street work over that of a similar 4-unit network, due to the less favorable locations of the units with respect to existing copper, would nearly offset the additional cost of the fourth unit, and as a 4-unit network has certain inherent advantages over one with 3 units, no diagrams or further studies were made for the latter scheme.

A transmission and distribution system diagram for the initial network installation is given in Fig. 3, showing the location of the 4 primary network units, transmission lines, network mains, taps, and tie connections to existing radial circuits. A similar diagram for the ultimate network installation supplied from 6 primary network units is given in Fig. 4. Taps from the network mains have been omitted from this diagram due to the uncertainty of the location and nature of the load growth.

In practically all cases sufficient conductors were available to form a 4-wire main between units by combining existing power and lighting circuits and removing the extra conductors. In no case was it necessary to increase the size of any of the conductors, as No. 1/0 was the smallest size encountered and previous studies have indicated that this size is sufficient for all network needs. Very little rephasing was required as the single-phase circuits were taken over intact and the 3-phase transformers cut over where necessary.

Plans 6 and 7—Radial Circuits Supplied From Network Units

During the progress of the network study it became more and more apparent from the nature and the location of the load, and from the location and

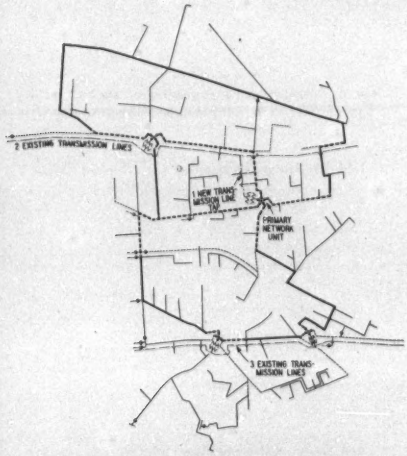


Fig. 3. Transmission and distribution systems for 4 single-transformer network units (initial installation, plan 5)

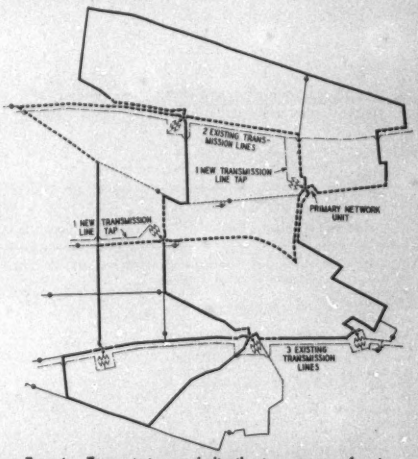


Fig. 4. Transmission and distribution systems for 6 single-transformer network units (ultimate development, plans 5 and 6)

arrangement of the existing transmission lines and 4-kv distribution circuits, that there was sufficient justification to warrant the making of a study for supplying the load in this same area by means of radial circuits supplied from primary network units.

It was proposed to add a second transformer to a standard network unit and connect it to the 4-kv bus through one of the feeder circuit breakers, thereby leaving 3 breakers available for distribution circuits. This second transformer would be supplied from a separate transmission line so that each 2-transformer unit would have a firm capacity with one line out of service of 2,500-kva.

These 2-transformer units would be installed above ground, either on concrete mats using weather-proof units, or the switch units themselves might be installed in a small building.

One very attractive feature of this plan lies in the fact that an existing radial system can be relieved of approximately 2,500 kva of load at a relatively small cost by the installation of one of these 2-transformer units at some load center where short 4-kv feeders can conveniently be run out to pick up existing distributors. As the load continues to grow, a second 2-transformer unit can be installed at another load center, as in Fig. 5. Two of the circuits out of this unit can be arranged for interconnection with 2 circuits out of the first unit, if short-circuit studies show that satisfactory relaying

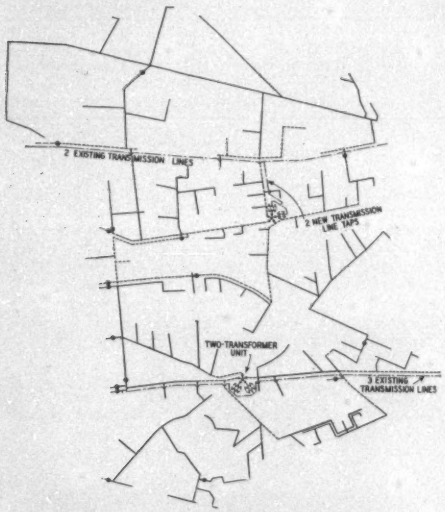


Fig. 5. Transmission and distribution systems for 2 2-transformer units (initial installation, plans 6 and 7)

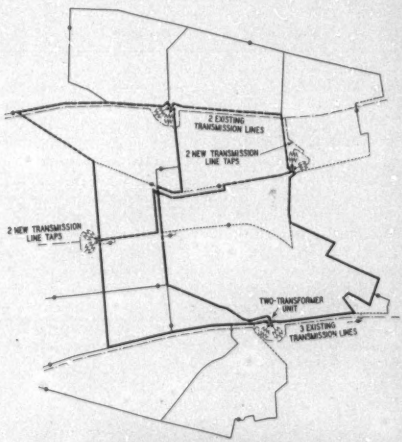


Fig. 6. Transmission and distribution systems for 4 2-transformer units (ultimate development, plan 7)

Table I—Initial Capacities and Initial Costs

Method of Providing Capacity	Firm Capacity	Cost*	Per Cent of Plan No. 2
1. Enlarge and rebuild present substation	14,000 kva.	$182,250	30.6
2. Abandon present substation and build new substation	12,000 kva.	596,750	100.0
3. Maintain present substation and build new automatic substation	17,800 kva.	335,700	56.2
4. Maintain present substation and install primary network with 3 single-transformer units	13,000 kva.	212,050	35.6
5. Maintain present substation and install primary network with 4 single-transformer units	15,500 kva.	235,500	39.4
6. Maintain present substation and install primary network starting with one 2-transformer unit	10,500 kva.	77,000	12.9
7. Maintain present substation and install primary network starting with one 2-transformer unit	10,500 kva.	77,000	12.9

* These cost figures include land costs as well as costs for station and street work.

Table II—Ultimate Capacities and Ultimate Costs

Method of Providing Capacity	Firm Capacity	Cost*	Per Cent of Plan No. 2
1. Enlarge and rebuild present substation	23,800 kva.	$433,750	56.0
2. Abandon present substation and build new substation	21,800 kva.	773,000	100.0
3. Maintain present substation and build new automatic substation	23,800 kva.	520,000	67.4
4. Maintain present substation and install primary network (grown from 3 to 6 single-transformer units)	20,500 kva.	379,550	49.1
5. Maintain present substation and install primary network (grown from 4 to 6 single-transformer units)	20,500 kva.	362,000	46.8
6. Maintain present substation and install primary network (grown from one 2-transformer unit to 6 single-transformer units)	20,500 kva.	362,000	46.8
7. Maintain present substation and install primary network (grown from 1 to 4 2-transformer units)	23,000 kva.	330,000	42.7

* These cost figures include land costs as well as costs for station and street work.

Table III—Plan No. 1, Enlarge Present Substation

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$182,250			$182,250	$ 22,800	$ 22,800	$ 22,800
1934					22,800	21,300	19,800
1935					22,800	19,900	17,230
1936					22,800	18,600	15,000
1937					22,800	17,400	13,080
1938	32,000		$20,000	234,250	29,300	20,900	14,580
1939					29,300	19,500	12,680
1940					29,300	18,250	11,000
1941	179,500		20,000	433,750	54,200	31,550	17,700
1942					54,200	29,500	15,380
					$310,300	$219,700	$159,250

Table IV—Plan No. 2, Abandon Present Substation and Build New Substation

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$491,750	$15,000	$90,000	$596,750	$ 74,500	$ 74,500	$ 74,500
1934					74,500	69,600	64,800
1935					74,500	65,100	56,300
1936	126,250		50,000	773,000	96,600	78,800	63,500
1937					96,600	73,700	55,400
1938					96,600	68,900	48,200
1939					96,600	64,400	41,800
1940					96,600	60,200	36,350
1941					96,600	56,300	31,600
1942					96,600	52,600	27,500
					$899,700	$664,100	$499,950

Table V—Plan No. 3, Maintain Present Substation and Build New Automatic Substation

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$208,700	$35,000	$94,000	$335,700	$ 41,900	$ 41,900	$ 41,900
1934					41,900	39,200	36,450
1935					41,900	36,600	31,700
1936					41,900	34,200	27,550
1937					41,900	32,000	24,000
1938			55,000	390,700	48,850	34,800	24,350
1939					48,850	32,550	21,150
1940					48,850	30,400	18,350
1941	167,000		5,000	562,700	70,350	41,000	23,000
1942					70,350	38,350	20,000
					$496,750	$361,000	$268,450

Table VI—Plan No. 4, Maintain Present Substation and Establish Primary Network (3 Units Originally)

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$126,000	$13,000	$73,052	$212,052	$ 26,500	$ 26,500	$ 26,500
1934					26,500	24,800	23,050
1935					26,500	23,150	20,000
1936					26,500	21,600	17,400
1937	42,000	4,500		258,552	32,350	24,650	18,500
1938					32,350	23,050	16,100
1939					32,350	21,550	14,000
1940	42,000	2,000	16,500	319,052	39,850	24,800	15,000
1941					39,850	23,250	13,030
1942	42,000	1,800	17,000	379,552	47,450	25,850	13,500
					$330,200	$239,200	$177,080

would result, thereby forming a network supplied from 2 5,000-kva units with a firm capacity of 7,500-kva. This system later can be expanded into either a network supplied from several 2-transformer units as in Fig. 6, or one of the transformers may be removed from each of the existing units, combined with a new switching equipment and relocated to form a network supplied from single-transformer units, as previously shown in Fig. 4.

Method of Economic Comparison

From an economic standpoint the network scheme offers marked advantages, as may be seen from Table I, which is based upon accurate estimates obtained from the construction bureau of the company for the station and street work in accordance with the description of each as given in this paper. The costs of distribution transformers, secondary services, and other common costs are omitted for each plan.

The first step in this economic study consisted of extending the peak kilovoltampere load curve to 1942, giving the proportionate amount of weight to such factors as rate of increase of population, increase in the number of customers, and in the number of houses assessed, houses wired and the building trend; from this curve it was estimated that the load would increase approximately at the rate of 7 per cent per year over that period. However, in view of the uncertainty of predicting load growth, and realizing the importance of its effect on the installation of additional capacity, studies were made for load growths of 5, 7.5, and 10 per cent, but as each study showed the same relative order of magnitude for each scheme, only the study for the 7.5 per cent load growth is included in this paper.

Each of the alternatives shown in Table I was carried to its ultimate (1942) capacity, which would be approximately 20,000 kva based upon a 7.5 per cent load growth, by the addition of capacity when needed. For convenience, these ultimate capacities and costs are tabulated in Table II.

The tabulations for each plan, shown in Tables III to IX, inclusive, which are presented primarily to show the annual costs incurred by each investment, are separated into 4 columns, as follows:

1. New investment.

2. Annual costs. These are the fixed charges based upon a certain percentage of the new investment. The rate was taken at 12.5 per cent and includes interest, taxes, and depreciation. No account was taken of energy losses or maintenance, as it was felt that the differential in costs for these items would not be sufficient to affect the relative magnitude of the total costs for the several plans appreciably.

3. Present worth of yearly costs. In order to make proper allowance for the effect of interest in comparing yearly costs occurring in different years, the annual costs have been discounted at 7 per cent compounded annually, and these figures are shown as the present worth of yearly costs.

4. Discounted present worth of yearly costs. In view of the unknown effect of future occurrences on the outcome of present plans, it was felt that the results would be progressively less accurate for the later years, and therefore in making any choice between the various alternatives, the later years should be given less weight than

Table VII—Plan No. 5, Maintain Present Substation and Establish Primary Network (4 Units Originally)

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$168,000	$17,500	$50,000	$235,500	$ 29,400	$ 29,400	$ 29,400
1934					29,400	27,500	25,580
1935					29,400	25,700	22,200
1936					29,400	24,000	19,320
1937					29,400	22,450	16,830
1938					29,400	20,950	14,600
1939					29,400	19,600	12,700
1940	42,000	1,500	18,000	297,000	37,100	23,100	13,950
1941					37,100	21,650	12,120
1942	42,000	3,000	20,000	362,000	45,250	24,650	12,870
					$325,250	$239,000	$179,570

Table VIII—Plan No. 6, Maintain Present Substation and Establish Primary Network (2-Transformer Radial Units Originally)

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$ 55,000	$ 2,000	$20,000	$ 77,000	$ 9,625	$ 9,625	$ 9,625
1934	55,000	3,500	25,000	160,500	20,050	18,700	17,400
1935					20,050	17,500	15,180
1936					20,050	16,350	13,200
1937	58,000	12,000	5,000	235,500	29,400	22,450	16,850
1938					29,400	20,950	14,620
1939					29,400	19,600	12,710
1940	42,000	1,500	18,000	297,000	37,100	23,100	13,960
1941					37,100	21,600	12,110
1942	42,000	3,000	20,000	362,000	45,250	24,650	12,880
					$277,425	$194,525	$138,535

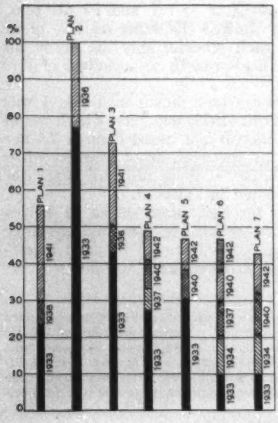


Fig. 7. Initial, increment, and ultimate investment costs for supplying city of Somerville, 1933–1942

Annual load growth assumed 7.5 per cent

the earlier years. The figures which take this factor into consideration are prepared in the same manner as the figures for "present worth of yearly costs," except that a factor of 15 per cent per year compounded annually was used, 7 per cent of which was for interest and 8 per cent for relative inaccuracy.

The one outstanding fact which is forcibly brought out by a careful study of these tabulations is that

Table IX—Plan No. 7, Maintain Present Substation and Establish 2-Transformer-Unit Primary Network (2-Transformer Radial Units Originally)

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$ 55,000	$ 2,000	$20,000	$ 77,000	$ 9,625	$ 9,625	$ 9,625
1934	55,000	3,500	25,000	160,500	20,050	18,750	17,420
1935					20,050	17,500	15,180
1936					20,050	16,350	13,200
1937					20,050	15,300	11,500
1938					20,050	14,300	10,000
1939					20,050	13,350	8,670
1940	55,000	7,500	25,000	248,000	31,000	19,300	11,660
1941					31,000	18,100	10,130
1942	55,000	2,000	25,000	330,000	41,250	22,450	11,730
					$233,175	$165,025	$119,115

Table X—Summary of Annual Costs

Plan No.	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1	$310,300	$219,700	$159,250
2	899,700	664,100	499,950
3	496,750	361,000	268,450
4	330,200	239,200	177,080
5	325,250	239,000	179,570
6	277,425	194,525	138,535
7	233,175	165,025	119,115

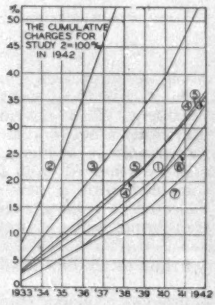


Fig. 8. Cumulative annual carrying charges for various methods of supplying city of Somerville, 1933–1942

Annual load growth assumed 7.5 per cent
Annual carrying charges 12.5 per cent

any scheme which makes maximum use of existing capacity and adds capacity in small increments will have the lowest initial cost and also the lowest annual carrying charges. This is shown graphically in Figs. 7 and 8. A summary of the annual costs is given in Table X.

Conclusions

As a result of the foregoing considerations, both engineering and economic, it is proposed to provide initially for the relief of the existing substation supplying Somerville by means of one 2-transformer network unit located at a load center in East Somerville and supplying 3 radial circuits. Plans 6 and 7 are based upon this initial arrangement. Later, when the load justifies it, a second 2-transformer

unit is to be installed at another load center nearby, and 2 of its radial circuits will be so arranged that they may be interconnected with 2 of the circuits from the original unit if found practicable. Beyond this point, the decision to expand the system into a network by the installation of additional 2-transformer units, or by removing the second transformers from the original units and combining them with new switching units at new locations to form a network supplied by single-transformer units, will be governed by conditions which may arise at that time.

The ability to expand this system by the method which will be most advantageous at such time as any expansion may become necessary, appears to be the most valuable feature of this proposed plan.

The authors wish to acknowledge the valuable assistance rendered by J. F. Maxwell, L. J. Weed, and St. G. T. Arnold in assembling and arranging the material for this paper.

The Pitt-Westinghouse Graduate Program

Recognizing that some of the highest types of graduate engineering instruction is to be found in a few of the larger research and industrial organizations, the University of Pittsburgh (Pa.) and the Westinghouse company during the past several years have coöperated in a joint program of graduate study for certain designated employees of the company. Besides being of distinct benefit to the individual employee, this work has had a highly stimulating influence upon the faculty members of the university connected with it, and the results have been most gratifying to the industry.

By
H. E. DYCHE
MEMBER A.I.E.E. University of Pittsburgh, Pa.

R. E. HELLMUND
FELLOW A.I.E.E. Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.

TO THOSE who have been identified with engineering education in the Pittsburgh (Pa.) district for the past 25 years, the formal presentation of the University of Pittsburgh-Westinghouse graduate program in 1927 was a logical step forward in higher education. It is interesting to note that in 1910 2 highly significant events took place: (1) The University of Pittsburgh introduced the coöperative system of undergraduate engineering education on a plan somewhat different from that in use at the University of Cincinnati; (2) Mr. B. G. Lamme, then chief engineer of the Westinghouse Electric and Manufacturing Company, was formulating an intensive program of educational work for the highly selected group of engineering graduates received by the Westinghouse company each year. These 2 ideas, apparently unrelated, have been adopted during the years by many educational and industrial institutions. It seemed, therefore, an obvious move to correlate these activities under the general direction of the graduate school of the University of Pittsburgh, and it is now widely known in educational circles as the University of Pittsburgh-Westinghouse graduate program.

The following quotation is taken from a recent publication of the graduate school of the University of Pittsburgh:

"... it is realized that a general undergraduate education was never designed, and never should be designed, to prepare individuals for immediate, highly specialized service. First must be laid the broad foundation without which graduate work would be but a mockery. But the foundation once laid, the peculiar services which a graduate school can render become self-evident."

This quotation is cited primarily to show the breadth of view held by Dr. L. P. Sieg, dean of the graduate school of the University of Pittsburgh since 1925. Doctor Sieg maintains that some of the highest type of graduate instruction is to be found in a few of the larger research and industrial organizations. As already indicated, this idea has been accepted for years by many engineering faculties in undergraduate training, in some form of coöperative work. It remained, therefore, to work out a similar plan to assimilate some of the higher grade industrial instruction available in the Pittsburgh district. Considering the usual method of pedagogic administration in many graduate schools, it is not surprising that this plan has created widespread discussion.

It is realized that there are not many places equally favored by the circumstances cited and it therefore is not possible to establish a similar practice at all universities; but the salient features of the arrangement so eminently are suited to meet the basic requirements of a postgraduate engineering

Full text of a paper recommended for publication by the A.I.E.E. committee on education, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Dec. 5, 1933. *Not published in pamphlet form.*

education that similar plans elsewhere, even on a smaller scale, should be well worthwhile.

In discussing the fundamentals of an adequate engineering education, it is well to recognize the fact that the requirements for the engineering profession are different from those of some of the older professions. Frequently the latter are regarded as being essentially professions of learning; and since the methods of the universities are naturally the outgrowth of practices evolved in the older professions, there is an inclination to overemphasize the importance of book learning in engineering training. Now, regardless of how important knowledge may be in any walk of life, including engineering, of course, it nevertheless should be recognized clearly that the engineering profession is primarily a profession of creation and accomplishment and that the training of engineering students and of the younger engineers therefore should be directed toward developing in them above all else a desire and ability to create and accomplish. It is extremely important, then, that in addition to imparting the necessary knowledge, particular stress be laid upon developing in the student during the most formative period of his life such traits as initiative, action, imagination, analytical ability, and independence of thought; in other words, accomplishment through knowledge rather than knowledge in itself should be stressed throughout the entire course, beginning even during the undergraduate program as far as at all possible. However, no matter how carefully the curriculum may be planned and how thoroughly the college work carried out, it will have to be admitted that it is at best very difficult to give to the student in a purely university atmosphere that training in developing initiative, resourcefulness, action, and responsibility which is required in actual practice. Consequently, there is a distinct danger in extending the engineering college course beyond the usual 4-yr program, except for those who expect to make research or teaching their life work. The inevitable conclusion is that postgraduate work on subjects that cannot be covered adequately during the undergraduate course should be carried on by engineers after entering the profession.

Although many universities have established postgraduate evening courses, seldom is it found that the individual student avails himself of more than 1 or 2 courses, or that such work is extended over a very long period after graduation. The only way in which this condition can be improved is by offering proper incentives for postgraduate work, preferably in the form of additional university degrees. If these incentives are to be effective and accomplish the maximum results, they must be such as to stimulate an appreciable number of engineers to greater effort than that involved in 1 or 2 casual graduate courses. In this connection, there is one fundamental which should govern the establishing of standards for offering degrees or similar incentives of any kind, and that is that the standards should be such as to bring about the maximum total effort in the profession and therefore result in maximum accomplishment as a whole. It is all very well to establish a high standard; but if the standard is so high that only exceptional students can reach it, little good will be accomplished. The same is true if the conditions are such that the possibilities are open only to students in favorable financial circumstances. In short, the conditions and standards governing the obtaining of degrees should be such that the goal is possible of attainment by a reasonably large number of the abler members of the profession. Furthermore, degrees in engineering should be conferred as rewards for originality and accomplishment rather than for the accumulation of knowledge alone, if they are to take cognizance of the requirements of the engineering profession.

The University of Pittsburgh-Westinghouse graduate program recognizes these fundamentals, as shown in the following regulations published by the graduate school of the University of Pittsburgh:

"By agreement between the Westinghouse Electric and Manufacturing Company and the graduate school, certain courses in the educational program of the company are identified with the school. Those in charge of the administration and of the instruction of these courses have regular appointments on the staff of the University of Pittsburgh, and hence credits earned in these courses are recorded under the regulations as resident credits. Regardless of the number of credits earned in the Westinghouse courses, there must be gained for the master's degree a minimum of 10 credits in regular University courses and 6 thesis credits.

"1. Courses are open, except by special permission, only to designated employees of the Westinghouse Electric and Manufacturing Company who are graduates of accredited colleges or universities.

"2. Registration, including the payment of fees, shall be effected at the University of Pittsburgh.

"3. No student may take any of the Westinghouse courses for credit in the graduate school, unless he has in advance the approval of the dean of the graduate school and of the head of his major department.

"4. A registration fee of $5 for each registration is required regardless of the number of courses taken. For the Westinghouse courses, there is no tuition charged, but for the courses offered by the resident staff of the University of Pittsburgh, the regular tuition charges are levied. Upon the granting of a degree, the regular graduation and publication fees are also assessed.

"5. Credits earned through the Westinghouse courses are recorded as resident credits.

"6. A minimum of 30 resident credits is required for any degree from the University, of which, in this particular arrangement, a minimum of 16, if the thesis is worked out on the campus, must be earned in campus courses.

"7. The research work leading to a thesis may be conducted with the consent of the head of the department, under the direction of any of the Westinghouse lecturers."

As indicated in these regulations, there are at present 30 Westinghouse lecturers actively identified with this program. As such, they are recognized members of the graduate faculty of the University, meeting from time to time as a group with the resident faculty.

The 30 credits required for the master's degree normally would take at least 5 or 6 years of evening work even under the most ideal conditions, assuming that suitable evening courses were available during such an extended period of time. Such sustained effort and continued financial sacrifices for tuition and the like, particularly during early life, makes the obtaining of a master's degree impracticable, if not impossible, in the majority of cases. With

the plan described, it is quite possible with reasonable effort outside of business hours and under moderate financial obligations to obtain this degree in about 3 years. At the same time, the total requirements in the way of university credits have not been lessened in the least and the thesis requirements have been increased.

With reference to the thesis, it must be considered that the laboratory facilities now existing in the larger industries will permit the carrying on of work of a character often impossible with the facilities available in the colleges; consequently, the thesis results accomplished are likely to be of a character often impossible with the facilities available in the colleges, and therefore are likely to be, but not necessarily, of a higher order and of greater usefulness. The fact that the work carried on in industry is to serve as the basis for a thesis will prove an incentive for the use of a higher order of analytical work and originality. Consequently, the results will be of greater value to the industry, and the engineer himself will profit because of the necessity for greater accomplishment and for carrying such additional studies as are required for his thesis. Appendix II gives a list of these subjects so far completed as a part of this program. As a rule, the thesis work is carried on under available research or development appropriations of the company, although at times small special appropriations are made for the purpose; therefore, no expense to either the student or the university is involved. Where appropriations for experimental work cannot be made available, a purely analytical study often is chosen for the thesis. The work usually is supervised by one of the University of Pittsburgh-Westinghouse lecturers after formal approval has been granted by the department of electrical engineering of the university.

Dr. E. A. Holbrook, dean of the schools of engineering and mines of the University of Pittsburgh, says:

"During the past 4 years I have reviewed a number of the theses presented by candidates for the master's degree under our Westinghouse coöperative graduate program. Uniformly, these theses show more professional maturity and higher research technique than the usual postgraduate master's theses in engineering. I make this comparison, having in mind not the University of Pittsburgh alone, but also the graduate theses I have read in the several colleges with which I have been connected."

A general idea of the character of the courses of study can be obtained from Appendix I. Many of these consist of lecture courses and problem work, although in several the problem work predominates. In general the courses are conducted in a manner quite similar to the regular university courses, except that most of them are given during working hours and some of them at night. The course *E.E. 151–152W* on electrical theory and engineering practice, which is an outcome of the so-called engineering school of the Westinghouse company, is somewhat different from the ordinary course. It consists of weekly assignments of a relatively large number of questions which the students are called upon to answer during an extended quiz at the end of the week. The questions represent broadly a survey of the present state of the electrical art and accumulated experience in the application of fundamental principles to engineering problems. They involve the study of designs, materials, methods of construction, testing, application, and maintenance of a wide variety of electrical appliances and equipment, as well as significant excursions into the history of the development of the art. This part of the graduate program, as well as many other features, has grown out of the pioneering work in advanced engineering education by Mr. B. G. Lamme; some of Mr. Lamme's fundamental ideas along this line are set forth in his publications. (See "Technical Training for Engineers," *Electric Journal*, Sept. 1916, p. 404.)

Among the courses instituted during the more recent years, special attention might be called to *E.E. 193W* by Doctor Slepian on conduction of electricity in gases, *E.E. 181–182W* by Doctor Lewis on symmetrical components, and *M.E. 161–162W* by Doctor Nadai on applied elasticity. Complying with an urgent demand, these courses and also the one on electrical theory and engineering practice have been made available to students outside of the Westinghouse company and an appreciable number of engineers connected with the utilities and also instructors and postgraduate students of the university have availed themselves of this opportunity.

Special attention is called to the fact that credits can be obtained only by successful completion of these various courses. No credits whatsoever are obtained for any of the shop, testing, drafting, or engineering work done by the students during working hours. The experimental work for the theses is conducted, of course, in the laboratories of the company during working hours, and frequently the engineering work of the company benefits from the solution of the problems in connection with the theses.

The entire work of the students is done under the broad guidance of the school of engineering of the university, and the university assumes the responsibility for the adequacy of the program. However, since a great many of the engineering subjects required for the master's degree are given by the Westinghouse staff, the evening courses covered by the university staff relate essentially to such subjects as advanced physics, mathematics, economics, and the like, so that a properly balanced curriculum will be maintained. The degree conferred is that of Master of Science, usually with the major in electrical or mechanical engineering.

In 1930 the plan was extended to include the doctor's degree, the requirements for which, although in the first stages similar to those for the master's degree, are more extensive both in quantity and quality of work to be covered. For the doctor's degree great care is exerted to select candidates who have much more than the capacity to pursue courses and to conduct simple, straightforward research. It is felt that, for the most part, the investigations and courses should be carried on in the fundamental fields of physics, mathematics, or chemistry. Although for the master's degree

certain credits can be obtained through Westinghouse courses and research work, the majority of the credits for the doctor's degree have to be obtained through the university courses.

Tables I, II, and III give some statistical data relating to the graduate program and the results obtained. Table I gives the number of degrees granted during successive years. Table II indicates that a total of 354 students have participated in this work and 59 or only about $^1/_6$ of that number have obtained degrees. Some pertinent conclusions may be drawn on the basis of these figures:

1. Requirements for the degrees are high, which means that, in addition to the necessary analytical ability, a great amount of energy and perseverance is needed.

2. Distracting influences are encountered due to increasing professional and family responsibilities.

3. Depression readjustments and low financial resources have prevented some from completing the work.

4. Under normal conditions, many students are transferred to distant branches of the company, and although the university has arranged reciprocal relations with other graduate schools, the resultant progress is slower.

Table III shows that in addition to the fact that approximately 50 per cent of the graduates remain with the company, about 25 per cent are called into teaching or some phase of educational work.

Table I—Degrees Awarded

Year	M. S.	Ph.D.
1927	1	
1928	1	
1929	8	1
1930	9	
1931	14	
1932	12	1
1933	11	1
Total	56	3

From the standpoint of the industry, the results of this postgraduate work have been most gratifying. Although the average engineering graduate is inclined to settle down to routine work after entering industry, an entirely different spirit can be noted among those taking part in this postgraduate work. During the various courses their interest in analytical work is maintained, and the necessity for taking the initiative in their thesis work develops a definite self-confidence in their ability to do original and advanced analytical work. As a consequence, all of their later engineering work is influenced along similar lines. It is noted also that of the various papers presented by the company engineers before the different professional societies, a large percentage is supplied by engineers who either are on the Westinghouse teaching staff or who have completed successfully their work for the master's or doctor's degree in this coöperative course.

Table II—Total Earned Credits

	No. of Individuals	
Less than 6 credits	106	
6–10 credits	53	
11–14 credits	38	
15–23 credits	80	
Less than 24 credits		277
Exactly 24 credits	23	
More than 24 credits	54	
Number with sufficient credit for degree		77
Total participants		354
Degrees granted		59
Credit requirement complete for master's degree		18

Table III—Present Location of Those Who Have Received Degrees

Westinghouse Elec. and Mfg. Co.	30
Teaching and educational work	15
Other work	14
Total	59

With reference to the university, this coöperative program is found to be of benefit in so far as it has a highly stimulating influence upon the faculty members connected with the work. It has made possible courses that would not have been possible without such a plan; in some cases this coöperation has led to certain mathematical courses prepared jointly by a member of the university staff and one of the industrial staff, with the result that the application of mathematics to practical engineering problems has been presented more effectively to the students.

Appendix I—Descriptions of Courses

The following course descriptions have been taken from the last edition of the "Graduate School Bulletin" of the University of Pittsburgh; they illustrate the advanced nature of the technical content of the various Westinghouse courses and the credits allowed.

EE 151W. Electrical Theory and Engineering Practice, I; 2 credits. A study of theory of operation and standards of practice in design, manufacture, and application of electrical equipment, generators, motors and their control, thermionic tubes, oscillographs, voltage regulators, relays, and transformers. *Hellmund and Dudley.*

EE 152W. Electrical Theory and Engineering Practice, II; 2 credits. A second course similar in character to *EE 151W*, but embracing synchronous converters, materials and processes, refrigeration, railway motors, circuit breakers, switches and fuses, lightning arresters, heating appliances, capacitors, switchboards, and rectifiers. *Hellmund and Dudley.*

EE 161W. Electrical Machine Design, I; 2 credits. Fundamental equations for the generated emf. The distribution of the magnetizing flux is determined by rigid graphical solutions. The mmf's of distributed windings by mathematical and graphical methods. The effect of pulsations and harmonics of the mmf's. Flux analysis for 2-dimensional fields. Calculation of saturation curves. *Laffoon and Calvert.*

EE 162W. Electrical Machine Design, II; 2 credits. A quantitative analysis of the theory of commutation for both direct and alternating current machines. Detailed treatment of commutation as a switching problem, secondary phenomena affecting commutation, etc. *Hellmund, Baker, and Labberton.*

EE 163W. Electrical Machine Design, III; 2 credits. A study of the constants of alternating current machines which determine the transient and continuous operating characteristics. Development of formulas for calculating constants. The special problems of synchronous machine design. *Dudley, Shutt, and Kilgore.*

EE 164W. Electrical Machine Design, IV; 2 credits. Consideration of the fundamental laws of magnetism and of the magnetic and electrical properties of core materials, with their adaptations to electrical apparatus. *Spooner.*

EE 165W. Electrical Apparatus Design; 2 credits. The fundamentals of design of magnets and transformers. Initial magnetizing transients. Methods of determining reactance, regulation, and short-circuit forces. Three-winding transformers. Mercury arc rectifiers. *Peters.*

EE 166W. Circuit Interruption; 2 credits. Fundamental studies in circuit interruption by an arc. Effects of resistances, inductances, and capacities; calculation of arc energies, switching surges; etc. *Hellmund and Ludwig.*

EE 171W. Electrical Insulation; 2 credits. *Hill.*

EE 172W. Laboratory Technique; 2 credits. *Miner and Tenney.*

EE 181W. Symmetrical Components, I; 2 credits. The application of the principle of symmetrical components to the calculation of currents and voltages in transmission systems when subjected to unbalanced loads and short circuits. The problems used serve to investigate the sequence constants of lines. *Lewis.*

EE 182W. Symmetrical Components, II; 2 credits. A course following *EE 181W*, in which the special method of calculating the performance of machinery when subject to balanced load is developed. The method is applied to transformers, generators, and induction motors.

EE 183W. Slow Transients; 2 credits. Transients in simple circuits of constant resistance, inductance, and capacity leading to the solution of the generalized static network, eddy currents in solid cores, and transients in polyphase machines. *Wagner.*

EE 191W, 192W. Selected Electrical Phenomena; 2 credits. Conduction in gases, kinetic theory of gases, electrons and ions, ionization by collision, sparking potentials, glow discharge, mobilities of ions, thermal ionization, arc discharge, applications to switches and lightning arresters, electronic tubes, etc. *Hoard.*

EE 193W. Conduction in Gases; 2 credits. The course proceeds to the basis of the theory of ionization, a study of ionizing agents, kinetics of ions, mobility, diffusion, recombination, space charges, Langmuir's theory of currents to an electrode, sparkover phenomena Townsend's theory, Paschen's law, and Townsend's law of similitude, glow discharge, and corona. Electric arc theories of cathode, anode, and positive column, stability and extinction of arc are developed. Applications to lightning arresters, circuit breakers, switches and fuses. *Slepian.*

ME 161W. Theory of Elasticity; 2 credits. The elements of vector analysis are considered as an introduction to the analysis of stress and strain and to tensor analysis. Mohr's representation of a tensor; the general equations of the theory of elasticity; St. Venant's theory of the bending and torsion of beams; mathematical theory of flat plates; concentration of stress and of loads; curved shells; etc. *Nadai.*

ME 162W. Applied Elasticity; 2 credits. The application of strength of materials and of the theory of elasticity in calculating stresses and deflections in machine parts, bending, and torsion of thin bars, torsion of shafts, stresses in circular rings, rotating discs and cylinders, the buckling of beams, the bending of flat plates, stress concentration, etc. *Nadai.*

ME 163W. Technical Dynamics; 2 credits. The aspects of statics, kinematics, and dynamics, important to the designer, followed by a discussion of vibration problems in simple mechanical systems. An introduction to advanced dynamics, with applications to balancing of rotating bodies, balancing of reciprocating engines, torsional vibrations, and critical speeds in rotating machinery. *Stone and Soderberg.*

ME 171W. Mechanical Design of Electrical Machinery, I; 2 credits. The application of strength of materials and of applied elasticity in the design and calculation of machine members and parts

ME 172W. Mechanical Design of Electrical Machinery, II; 2 credits. A study of the flow of fluids, the performance of fans, heat flow in solids, heat transfer from solids to fluids, and the storage of heat as applied to the heating and cooling of machines. Derivation of formulas for temperature distribution, heat transfer, and transient heating and cooling curves for special cases. A second portion of the course develops the fundamentals of lubrication in the light of recent discoveries. The hydrodynamical theory of viscous oil films. Conditions of semifluid lubrication. Bearing constructions employed in present-day engineering. Antifriction bearings. *Penney.*

ME 173W. Mechanical Design of Electrical Machinery, III; 2 credits. The principles of the arts appealing to the eye are related to the problems of the industrial designer, through an analytical comparison of industrial products with notable design examples in architecture, furniture, ceramics, and the decorative arts. Supplemented by class work in pencil and clay. *Dohner.*

ME 181W. Electro-Mechanics; 2 credits. The principle of the storage of energy in electric circuits and the theorem of constant linkages are used to derive the fundamental equations for forces between electric circuits. Forces between bus bars, forces in opening switches, pull of magnets, unbalanced radial pull on armatures, normal and transient torque in rotating machines, vibrations produced by alternating or pulsating currents, the effect of unbalanced pull on the vibration of rotating parts, etc. *Ludwig.*

ME 182W. Testing of Materials; 2 credits. Static and dynamic tests of available materials to meet modern service conditions. Application of strength theories in the use of test data for design purposes. Factors involved in the assignment of allowable working stresses. *McVetty.*

IE 161W, 162W. Distribution Engineering; 2 credits. The organization, training, and direction of a technical staff in marketing. Development of potential markets for producers' and consumers' goods of a technical nature. *Lester.*

Met 161W. Physical Metallurgy; 2 credits. Crystal structure of metals and alloys and its relation to physical and mechanical properties. Application of X rays to industry. Interpretation and use of equilibrium diagrams in relation to the heat treatment of alloys. General types of alloys; solid solution, eutectiferous alloys, intermetallic compounds. Effect of plastic deformation and temperature upon physical and mechanical properties of alloys. General theories of hardening of metals and alloys. Alloys used in engineering practice, ferrous and nonferrous. Diseases of metals and alloys. Corrosion and its prevention. *Hensel.*

197W, 198W. Research; various credits. *Staff (resident or nonresident).*

297W, 298W. Seminar; various credits. A discussion of reports on current research in mechanics, mechanical engineering, electrical engineering, physics, mathematics, and metallurgy. *Staff.*

301W, 302W. Thesis; various credits. *Staff.*

Appendix II—Completed Theses

The following list of thesis subjects, together with the name of the candidate, illustrates the wide variety and scope of material covered in the thesis research.

Stresses and Reactions in Expansion Pipe Bands, A. M. Wahl.

Arc Characteristics in an Oil Circuit Breaker, R. C. Van Sickle.

Forced Vibrations With Coulomb Damping, J. P. Den Hartog.

Some Considerations of Air Flow in a Salient Pole Alternator, S. Beckwith.

The Effect of Third Harmonic Heating on 6-Phase Synchronous Converter, I. deVilliers.

A Mathematical Analysis of a Fiction Drive Manufactured by Krupp, M. B. Hogan.

Two Winding A-C Generators for Large Power Systems, L. A. Kilgore.

Eddy Current Losses in the Armature Conductors of D-C Machines and Their Effect on Commutation, H. C. Myers.

Short-Circuit Torque in Synchronous Machines Without Damper Windings, G. W. Penney.

An Investigation of the Fundamental Critical Speeds of Multiple Shafts, J. J. Ryan.

Effect of Phase-to-Ground Fault on Symmetry of Transmission Lines, S. P. Sashoff.

Forces on Turbine Generator Stator Windings During Short Circuits, J. F. Calvert.

Vacuum Tube Voltmeter Design, R. W. Carlisle.

A Study of Improving the Method of Calculating the Reactance Voltage in Distribution Transformers, J. R. Gaston.

The Natural Frequency of Lateral Vibration in the Frames of Electrical Machines, H. E. Hall.

Weight Transfer in Electric Locomotives Caused by the Equalization of Locomotive and the Draw Bar Pull, M. B. Karelitz.

Pressure Phenomena in Oil Circuit Breakers, W. M. Leeds.

The Short Time Temperature Rise of Railway Motor Armatures, D. A. Lightband.

Determination of Stresses in Discs of Conical Profiles, F. C. Rushing.

A Study of the Vibration Motion of a Loaded Flexible Shaft Having a Nonuniform Moment of Inertia During Rotation, B. A. Rose.

Circulating Currents in the Brushes of a D-C Machine, R. M. Baker.

The Characthristics of Inverse Time-Dilay Tripping Devices for Small Circuit Breakers, M. W. Brainard.

A Tracharle Presentation of Fundamental Principles of Velocity, Acceleration, and Inertia Forces of Machines, P. H. Black.

Characteristics of D-C Arc Motion in Restricted Slots, F. Buck.

An Improved A-C Potentiometer, S. L. Burgwin.

Premature Engagement of Gear Teeth Caused by Tooth Deflection, A. H. Burr.

The Cathode Ray Oscillograph and Its Application to the Investigation of Transient Problems, M. B. Gainder.

An Economic Comparison of Electric Drives for Induced Draft Fans in Large Generating Stations, G. E. Garnhart.

Symmetrical Components in Systems of Symmetrical Phase Coördinates, B. K. Hovey.

An Investigation of Stresses in Sucker Rod Joints, E. N. Kemler.

The Effect of Unsymmetrical Magnetic Fields on the Generation of Ultra-Short Waves in a Magnetically Controlled Vacuum Tube, G. R. Kilgore.

Strength of Nailed Joints of Wood Through Lateral Resistance of the Nails, F. Paulsen.

A Method for Calculating the Bolt Spacing on Transformer Tanks, F. J. Reed.

The Time-Lag of the Oscillograph Vibrator Behind the Applied Force, V. S. Thomander.

The Design and Characteristics of a Current Transformer With Alternating Current Superposed on Direct Current, J. G. Hieber.

A Unique Equipment for Testing Room Conditioners, R. E. Holmes.

The Electrical Characteristics of Synchronous Drive Motors, J. MacBride Kay.

The Graphical Solution of Elrctrostatic Fields, M. G. Leonard.

Some 2-Dimensional Cases of Discontinuous Distributions of Pressure, C. W. MacGregor.

The Design of a D-C Double Commutator Planer Motor, M. L. Manning.

An Analysis of the Heat Flow in the Thermal Overload Tripping Device for Small Circuit Breakers, J. W. May.

The Development of the Art of Electric Welding as Revealed by Inventions Patented in the United States, W. D. O'Connor.

Saturating Reactances in Electric Circuits, E. L. Harder.

A Study of Class *B* and Class *C* Output Tank Circuits, P. H. Osborn.

Higher Efficiency Fans for Turbine Generators, C. E. Peck.

The Distribution of Stress Due to a Single Force Acting on the Edge of a Circular Hole in an Infinite Plate, W. O. Richmond.

The Bending of Semicircular Plates and Rings With and Without Radial Slots, A. M. Wahl.

Restriking of Low Voltage Alternating Current Welding Arcs With Superposed High Frequency Discharges, F. Blackmore.

Dielectric Recovery of Turbulent A-C Arcs, T. E. Browne, Jr.

The Graduate Student Training Course for Engineers of the Westinghouse Electric and Manufacturing Company, A. M. Dudley.

The Determination of the Proper Size Elevator Motor for Express Service in Rockefeller Center, New York City, W. W. Gregory.

The Characteristics and Applications of the Copper-Oxide Photoelectric Cell, G. W. Hewitt.

Transposition of Conductors in Transformer Windings, H. H. Wagner.

Starting Performance of Salient Pole Synchronous Motors, R. D. Reed.

A Special Type of Double Deck Damper Windings for Synchronous Motors, C. C. Shutt.

Methods of Improving Starting Commutation of Single-Phase Series Railway Motors, R. E. Tobey.

The Design of Long Distance Pipe Lines for Gas, K. C. Ripley.

Air Conditioning Corrections for Subnormal Wall Temperatures, D. A. Taylor.

The General Torsion Problem, M. Stone.

An A-C Potentiometer

A rectangular coördinate potentiometer circuit is described in this paper, the chief features of which are the elimination of the usual phase shifting transformer and the slide-wire type of potentiometer resistor. Although not yet available in commercial form, this potentiometer has been in use in the laboratory for several years with good results, particularly in magnetic measurements at low and medium inductions and in measurements of the power factor of capacitors.

By
S. L. BURGWIN
ASSOCIATE A.I.E.E.

Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.

WHILE the a-c potentiometer may not be adapted as well to a particular test as a more specialized meter or bridge circuit, its chief advantage is that it can be used satisfactorily for a very wide range of measurements. Furthermore, in several particular types of tests such as the measurement of magnetic characteristics of iron cores at low and medium inductions, the a-c potentiometer is the most, if not the only, practical method of obtaining satisfactory results. However, the use of the a-c potentiometer has been restricted greatly, probably because of several practical difficulties which never have been eliminated satisfactorily in spite of the many types of a-c potentiometers that have been developed. No attempt will be made in this paper to discuss these types as a very complete summary and description of them has been published by Drysdale ("Alternating-Current Potentiometers and Their Applications," *Journal* of the Institution of Electrical Engineers, London, March, 1930).

The most satisfactory type of a-c potentiometer from the standpoint of convenience and accuracy of testing generally is conceded to be the rectangular coördinate potentiometer used in conjunction with a phase shifter. However, the various a-c potentiometers of this type that have been developed all have one or more of the following defects:

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Dec. 5, 1933. *Not published in pamphlet form.*

1. The phase shifter must be changed when the test frequency is changed. Furthermore, in many measurements where a low power factor is involved, the phase setting of the phase shifter is not sufficiently stable or the shift sufficiently continuous for satisfactory results.

2. In commercial testing the slide-wire potentiometers are not very satisfactory as they require too much attention to keep them in condition.

3. Some types require very frequent checking of the quadrature phase relation between the potentiometers.

4. Leakage and capacitance effects in the types that have the power and detector circuits directly coupled are quite troublesome in some tests.

For making core-loss and permeability measurements at low inductions on small iron cores as has been mentioned, the author found that the a-c potentiometer with all its defects provides the most satisfactory method available. For this reason an attempt has been made to eliminate some of the difficulties mentioned. The attempt has resulted in the development of a circuit that has been used in the laboratory for several years. The main features of this potentiometer are:

1. A single-phase phase shifter which is capable of approximately 150° continuous shift and which maintains a steady phase angle at any setting, provided the frequency remains constant.

2. A method of obtaining the quadrature phase relation between the potentiometers, which is capable of close adjustment and varies only with frequency.

3. The use of variable mutual inductors or variometers for the potentiometers, thus eliminating the contact troubles of the slide-wire potentiometers and at the same time isolating the detector circuits from the power circuit.

This circuit has been in use in the Westinghouse research laboratories for several years with such good results in a wide variety of tests that a portable development model has been built. While a few minor changes are still necessary on this model, tests have shown that it is as capable of accurate results as the laboratory set-up.

The laboratory set-up has been found particularly useful not only in measuring core-loss and permeability of small iron cores, but also in measuring the power factors of capacitors, 2 tests that ordinarily can be made satisfactorily only with very specialized equipment. In connection with such tests it has been found that the accuracy of the results often can be increased greatly by using a mutual inductor in place of the customary resistance shunt for measuring the current.

The A-C Potentiometer Circuit

The circuit may be divided into 4 main parts each of which will be discussed separately. These divisions, as shown in Fig. 5 in the diagram of the complete circuit, are: (1) the x and y potentiometers; (2) the phase shifter; (3) device for measuring current through the potentiometers; and (4) the null detector for indicating a balance between the potentiometer voltage and the unknown to be measured.

The x and y potentiometers as has been mentioned are 2 variable mutual inductors or variometers, calibrated to read directly in voltage. The connection required to give a quadrature relation between their secondary voltages is shown in Fig. 1, and the vector diagrams of the currents and voltages are given in Fig. 2. The mathematical relations are given in Appendix I. The secondary voltage of M_1 is, of course, in quadrature with the primary current i, while the secondary voltage of M_2 is in quadrature with i_1; but i_1 is in quadrature with i, and therefore the secondary voltage of M_2 is in phase with i and in quadrature with the secondary voltage of M_1.

Quadrature relation between i and i_1, Fig. 1, is obtained by adjusting R_3 and R_4. These values of resistance are different for each frequency and have to be changed when the frequency is changed, but for any given frequency they may be adjusted very closely. The variometers are so constructed that rotating the primary gives a continuous variation of secondary voltage from a negative maximum to a positive maximum. When operating on different frequencies it is necessary to change the value of primary current to maintain the same voltage calibration for the potentiometers.

The circuit for the phase shifter is shown in Fig. 3. Its function is to change the phase angle between the voltage E and the current i to any value over a range of at least 90° for a given value of reactance X and resistance R in the rest of the potentiometer circuit. This variation must be accomplished without changing the value of i. The vector diagrams for the voltages and currents are shown in Fig. 4 and the mathematical relations are given in Appendix

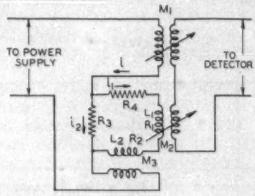


Fig. 1. Variometer circuit

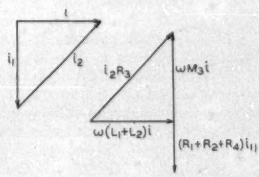


Fig. 2. Vector diagrams for variometer circuit of Fig. 1

II. The shift in phase is obtained by varying R_L, and for the conditions existing in the a-c potentiometer, covers a range of about 150° which is more than sufficient. A disadvantage of this phase shifting method is that it is not independent of frequency; and if it is to be used at more than one frequency, provision must be made for changing the value of the capacitance. The same effect

could be accomplished by changing the value of the inductance, but for this application where the rest of the circuit is inductive it is more desirable to change the capacitance and keep the inductance constant.

A current measuring device, or perhaps it should be called a voltage measuring device, is necessary to indicate when the voltage of the potentiometers is at the calibrated value. If an ammeter is used to measure the current in the primary circuit, the reading will be different for each frequency. This is a source of inconvenience and possible inaccuracy in tests where it is not necessary to know the frequency accurately. For this reason this potentiometer makes use of a fixed mutual inductor with a high resistance voltmeter connected across the secondary. Thus a voltage is measured that has the same characteristics as the voltage across the potentiometers, and consequently it should be the same for all frequencies. Practically, this is not quite true since in general, the resistance of the voltmeter will not be sufficiently high at the higher frequencies to make the effect of the reactance of the secondary winding negligible; therefore, the voltmeter must be calibrated for the readings at the various frequencies. This variation with frequency is small enough so that the calibrated voltage of the potentiometer can be obtained quite accurately although the actual frequency may deviate several per cent from the value assumed. The circuit for such a current measuring device is shown in Fig. 5 and will be discussed in detail later in this paper.

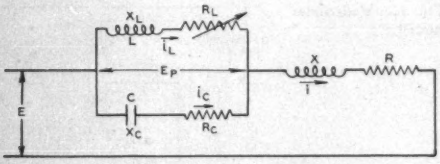


Fig. 3. Phase shifter circuit

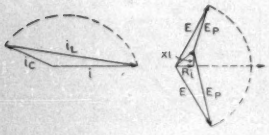


Fig. 4. Vector diagrams for phase shifter circuit of Fig. 3

For a null-current detector it is desirable to have a device that is very sensitive at the fundamental test frequency and insensitive to all other frequencies, yet it should be capable of operating at various fundamental frequencies. These 2 characteristics are contradictory and consequently both cannot be obtained without making some change in the detector when the operating frequency is changed. The most satisfactory detector for frequencies up to 300 cycles per second has been found to be the tuned vibration galvanometer of the moving coil type with interchangeable elements for the different frequencies. For frequencies above 300 cycles the low impedance telephone receiver is most satisfactory, although the higher harmonics may necessitate an additional filter circuit in some cases. These 2 detectors have the advantage of simplicity in comparison with most other detector arrangements, and at the same time are sufficiently rugged and sensitive to obtain accurate results in commercial service.

Construction of a Portable A-C Potentiometer

The complete circuit for this potentiometer is shown in Fig. 5. The instrument is designed to operate on 110 volts and is capable of operation on 9 different frequencies ranging from 25 to 1,000 cycles per second. The potentiometers have 2 ranges, from 0 to 5, and from 0 to 50 millivolts.

The potentiometer can be divided into 4 main parts as shown in Fig. 5. The construction of each of these divisions will be discussed separately and then the assembly in one instrument.

Variable Inductor Potentiometers. In the laboratory set-up, Brooks' inductors were used satisfactorily, but for a portable instrument they are too large so that 2 inductors of the variometer type were designed. To make these variometers more nearly static than the usual type, each consists actually of 2 variometers, mounted one above the other with the moving coils on the same shaft, and with the windings connected so that voltage induced by a stray field in one tends to balance out the voltage induced in the other. The windings are of Litzendraht wire supported upon micarta forms. As little metal as possible is used in the construction in order to minimize eddy currents. The maximum mutual inductance obtainable with either of these variometers is approximately 2.5 mh using the main secondary winding, and $^1/_{10}$ of that value using a smaller secondary winding.

These 2 secondary windings are wound upon the stator instead of the rotor so that any induced voltages from stray fields vary the calibration by a constant amount, and correction can be made by taking a zero balance. The primary windings are of somewhat larger Litzendraht wire as it is desirable to keep the resistance as low as possible.

The iron core mutual inductor of the phase splitting arrangement is designed with a 2 to 1 ratio of primary to secondary turns so that the mutual inductance is approximately twice the self-inductance of the secondary. As it is desirable to keep the resistance of the secondary small, it is wound next to the core. The core is of 5-mil "hipernik" (a specially heat treated alloy of iron and nickel) E-punchings, with the legs cut in such a way that an air gap may be placed in the center leg and the other 2 legs lapped. This is done to get fairly constant inductance and a good ratio of reactance to resistance without causing too much external magnetic field.

The 2 resistors included in the phase splitting arrangement are removable, as different values of

resistance are required for each frequency. Therefore, the 2 resistors for each frequency are wound noninductively upon a card, and are arranged to fit 3 binding posts provided on the control panel of the instrument.

Phase Shifter. The phase shifter circuit shown in Figs. 3 and 5, differ in that a transformer with a capacitor across its secondary is substituted in Fig. 5 for X_s and R_s as shown in Fig. 3. The 2 circuits are equivalent electrically, but the transformer circuit has a considerable advantage for this application because the equivalent capacitance in the primary circuit can be varied by changing the transformer ratio. Furthermore, for low frequencies where large capacitance is required, the size of the phase shifter can be reduced, as a large capacitance may be obtained with a small capacitor by using the proper transformer ratio. Equivalent resistances, approximately equal to the necessary values of R_s over the frequency range from 25 to 1,000 cycles per second, also can be obtained by properly designing the transformer. Such a transformer was designed and built for use with a 1-μf capacitor. The core is made of 5-mil "hipernik" E-punchings, lapped in the usual way. The induction in the core and the resistance of the windings are such as to give approximately the correct values of R_s for each frequency; 8 taps are placed in the secondary winding to give the correct equivalent capacitances for the 9 desired frequencies.

The inductance L, Fig. 3, is obtained by means of an iron core inductor, having a core similar to the one used in the phase splitting arrangement for the potentiometer variometers. The exact value of inductance is obtained by adjusting the air gap with the phase shifter in operation so that there is no change in current for a wide variation of the phase shifter rheostat. The inductance necessary for this condition is approximately 2.5 h.

The phase shifter rheostat is designed to give variations from 0 to 20,000 ohms and is capable of carrying 0.25 amp in the lower resistance ranges. This range is obtained by using 3 wire-wound rheostats in series, thus giving very fine adjustment at all resistances. The rheostats are of the circular sliding-arm type and have the following ratings: (1) 0–20 ohms, 12.5 watts; (2) 0–1,800 ohms, 150 watts; (3) 0–20,000 ohms, 150 watts. To keep the size within reasonable limits the third rheostat is constructed so that the first step is 1,800 ohms.

Current Measuring Device. As has been mentioned previously, the purpose of this device is to indicate the value of current necessary to give the calibrated voltage on the potentiometer. The device, as shown in Fig. 5, consists of an iron core mutual inductor, a thermocouple, and a microammeter. The core of the mutual inductor is made of 5-mil "hipernik" E-punchings which are stacked to give an air gap sufficient to keep the inductance practically constant for small changes in current. The value of mutual inductance is 20 mh, and the self-inductance of the secondary 6.36 mh. The thermocouple is similar to those used in Rawson "multimeters" and is capable of carrying a current of 10 ma. A Westinghouse d-c 200-μa microammeter is used to indicate the thermocouple current. The scale of the microammeter is calibrated in cycles to indicate the correct current at each frequency.

Detector. The low frequency detector, as shown in Fig. 5, is a vibration galvanometer of the type manufactured by H. Tinsley and Company, having replaceable elements tuned to the various desired frequencies. A variable rheostat is shunted across the galvanometer to give variation in sensitivity. As may be seen in Fig. 5, 2 binding posts are placed in the secondary circuit of the variable inductor

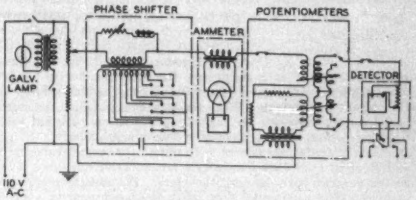


Fig. 5. Complete circuit of the a-c potentiometer described in this paper

potentiometers to which any type of detector desired, may be connected. At audio frequencies it is usually desirable to use a low impedance telephone receiver, although in some cases high impedance headphones may be preferable.

The Assembly. All component parts of this a-c potentiometer are mounted in one box which, with the cover, measures $22^1/_2$ in. long, $16^1/_2$ in. wide, and $11^1/_2$ in. deep. The total weight is approximately 55 lb.

No attempt is made to shield the potentiometer electrostatically because of the difficulty involved, and because in general either the external capacitance and leakage effects are negligible or easily can be made negligible. The component parts do not require mutual shielding since the constants of the circuit are such as to make capacitance or leakage effects inappreciable over the frequency range for which the potentiometer is designed. It is necessary, however, to eliminate mutual inductance effects between component parts and to provide a means for correcting for the effect of external magnetic fields. The first is accomplished, as has been explained previously, by special design of the inductors, both air and iron core, and also by mounting them as far apart as possible. Correction for external magnetic fields by taking a zero reading also has been explained. In addition to these precautions, it is necessary to keep all metal parts far enough from the variometers to make the eddy currents negligible. Mutual inductance between the variometers is kept low, although it would cause no error since the variometers are calibrated after being mounted in the potentiometer box.

To make the potentiometer as nearly self-contained as possible, several additional pieces of apparatus are included, as shown in Fig. 5. These are: a

110/6-volt transformer for the galvanometer lamp; a 250-ohm rheostat across the power supply to vary the current; and a selector switch in the detector circuit to permit an easy change from one unknown voltage to another.

Calibration

While it is possible to calculate and set accurately the values of resistance and inductance of the several parts of the potentiometer before assembling, it was found more practical to set these values approximately and make the final adjustments after assembling. These parts are adjusted or calibrated as follows:

Ammeter. With R_4 (Fig. 1) disconnected and the quadrature potentiometer set at a maximum, the potentiometer is balanced against a known voltage of 50 mv by varying the phase shifter and the current adjustment. When the balance is obtained the current is the correct value for the calibrating frequency. Current values for other desired frequencies may be determined similarly.

In-Phase Potentiometer Circuit. To obtain the correct values of R_3 and R_4 (Fig. 1) at each frequency a noninductive resistance is connected in series with the potentiometers. The resistance is such as to give a 50-mv potential drop when the potentiometer ammeter indicates the correct value of current for the calibrating frequency. The potentiometer is balanced against the voltage drop across this resistance by varying R_3 and R_4 with the in-phase potentiometer set at the maximum value and the quadrature potentiometer at zero. When the detector indicates a balance, R_3 and R_4 are the correct values for the calibrating frequency.

Phase-Shifter Inductor. The air gap of the phase-shifter inductor X_L (Fig. 3) is adjusted by varying the gap until the potentiometer ammeter reads the same for the zero and maximum positions of the phase-shifter rheostat.

Use of the A-C Potentiometer

Perhaps it may serve to clarify the ideas of those unfamiliar with potentiometer measurements to show how the a-c potentiometer is used in making actual tests. Furthermore, in most a-c tests, it is assumed that the voltages both known and unknown vary sinusoidally. Since this is not generally true, the validity of the assumption must be investigated. For this purpose 2 representative tests will be discussed, the measurement of the losses and permeability of an iron core, and the measurement of the power factor of a capacitor.

Measurement of Core Loss and Permeability of Iron Cores. It is assumed that in this test the power in watts and the reactive power are to be measured for given inductions in the core. The circuit most generally used, is shown in Fig. 6. (See "Some Applications of the A-C Potentiometer," by T. Spooner, *Journal* of the Optical Society of America and *Review of Scientific Instruments*, v. 12, March 1926.) Rheostat P serves to vary the current I flowing through the primary winding of the iron core S and also shunt R. The secondary winding, of N_2 turns, gives the voltage E which is reduced to the range of the a-c potentiometer by the voltage divider. The potentiometer is connected as shown, a selector switch in the potentiometer making it possible to connect the potentiometer to either the voltage divider or the current shunt. The vector diagram of Fig. 6 shows the relations of the quantities necessary to measure the watts and reactive power for any given induction in the iron.

A source of error particularly in testing iron cores is nonsinusoidal voltages. The power supply voltage is generally quite free of harmonics or can be made so. Thus the potentiometer voltage can be made nearly sinusoidal. However, even assuming a sinusoidal supply voltage, the harmonics have not been eliminated from the circuit of the sample; for if a sinusoidal voltage be impressed upon an iron core inductor, the exciting current will not be sinusoidal. Consequently, if the exciting circuit of the iron core contains impedance, neither the voltage impressed on the sample nor the exciting current will be sinusoidal. Under these conditions the results obtained by the a-c potentiometer are in error, as only the fundamentals of the voltage waves are measured. At low inductions when the harmonics are relatively small, this error can be neglected; but for higher inductions the impedance of the exciting circuit must be kept small since this allows the voltage impressed upon the sample to be more nearly sinusoidal, and the potentiometer gives more nearly correct results. To make the error negligible, it is necessary only to make the impedance of the exciting circuit sufficiently small. In the circuit of Fig. 6, this can be accomplished by making the current through resistor P large in proportion to the exciting current, and by reducing the impedance of the primary circuit; the latter may be done by replacing shunt R with a mutual inductor having only a few turns in the primary and many turns in the secondary. With such an arrangement the effect of the harmonics can be made negligible at inductions less than 12,000 gausses. It may be pointed out here that the use of such a mutual inductor also will give more accurate results than a resistance shunt for most measurements where the power factor is less than 0.70, although this has nothing to do with harmonics.

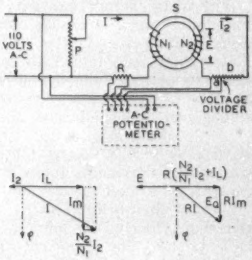


Fig. 6. Circuit for measuring core loss and permeability of iron cores, and associated vector diagrams

A general rule, derived from what has been said in the preceding paragraphs, might be stated "Correct measurements of power or any quantity involving the scalar product of 2 voltages can be made by the a-c potentiometer, only when at least one of the voltages is sinusoidal."

Measurement of the Power Factor of a Capacitor. Because of the low power factor of most capacitors,

it is rather difficult to measure their losses accurately with wattmeters or other simple means. However, it is possible to obtain very accurate results with the a-c potentiometer. The circuit that in general gives the best results is shown in Fig. 7. Rheostat P serves to adjust the current I flowing through the capacitor C the power factor of which is to be measured. Inductance L is made to form a series resonant circuit with C, to reduce harmonics in the voltage across the capacitor and to provide an easy and safe means of obtaining capacitor voltages higher than the supply voltage. The voltages to be measured by the a-c potentiometer are: (1) the voltage induced in the secondary of the mutual inductance M, which is proportional to and in quadrature with I; and (2) the voltage across resistance a of the voltage divider, which is in phase with and proportional to E.

From the vector diagram in Fig. 7 it is apparent that the ratio of the 2 components, E_p and E_q, of MI give the tangent of the angle between E and I. Therefore E_q/E_p can be taken as the power factor since the cotangent is almost equal to the cosine for angles close to 90°.

Several precautions must be observed in making measurements on capacitors with low power factors:

1. The mutual inductance M must be unaffected by stray magnetic fields and must have an exact quadrature phase relation between the primary current and the secondary voltage; this means that an astatic air core mutual inductance, free from eddy currents, must be used.

2. The voltage measured on the voltage divider must be exactly in phase with E.

3. Stray magnetic fields in the potentiometer must be eliminated or corrected by a zero balance.

Harmonics are not as serious in this case as in the previous example, since a sinusoidal supply voltage will give accurate results in capacitor measurements. Furthermore, even if the supply should contain harmonics, the series resonant circuit will reduce them to a much smaller value in the test capacitor, and if desired a series resonant circuit may be used in the power supply of the potentiometer.

Appendix I—Calculation of Phase Splitter Circuit Constants

The circuit constants of Fig. 1 may be evaluated from the geometry of the vector diagram shown in Fig. 2. However, it is just as simple to calculate them in the usual way. Referring to Fig. 1, it is desired to make i and i_1 equal in value, but with a quadrature phase relation, that is:

$$\frac{i}{i_1} = j \tag{1}$$

The network gives 2 equations:

$$i_1 + i_2 = i \tag{2}$$

$$R_2 i_2 = [R_1 + R_2 + R_4 + j\omega(L_1 + L_2)]i_1 + j\omega M_3 i \tag{3}$$

Eliminating i, i_1, and i_2 from eqs 1, 2, and 3 gives the following:

$$\omega M_3 = R_1 + R_2 + R_3 + R_4 \tag{4}$$

$$R_2 = \omega(L_1 + L_2) \tag{5}$$

Equations 4 and 5 express the relations between the circuit constants necessary to give the desired relations between i and i_1.

If an iron core inductance M_3 is used, eq 4 remains the same but eq 5 becomes

$$R_2 - r = \omega(L_1 + L_2) \tag{5a}$$

where r is an apparent resistance due to losses in the iron core.

Appendix II—Calculations of Circuit Constants for Phase Shifter

Referring to the circuit diagram Fig. 3, X and R are respectively the equivalent reactance and resistance of the entire potentiometer circuit outside of the phase shifter. It is desired in this case to make the absolute value of the current constant for all values of R_L. Thus it follows that the total impedance Z of the circuit must be a

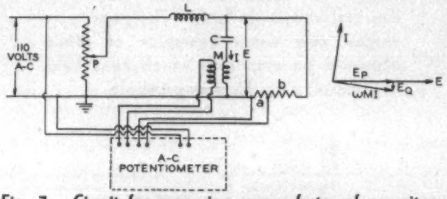


Fig. 7. Circuit for measuring power factor of capacitors, and associated vector diagram

constant, independent of R_L. To find the values of X_c, R_c, and X_L necessary to accomplish this, it is necessary to expand the equation for the absolute value of impedance of the circuit shown in Fig. 3, in powers of R_L thus:

$$AR_L^2 + BR_L + C = 0$$

where A, B, and C are functions of the circuit constants except R_L.

Since this equation must be true for all values of R_L, each of these coefficients must be equal to zero. These operations result in the following equations:

$$A = (R_c^2 + X_c^2) + 2(RR_c - XX_c) + R^2 + X^2 - Z^2 = 0 \tag{6}$$

$$B = -2R_c(Z^2 - R^2 - X^2) + 2R(R_c^2 + X_c^2) = 0 \tag{7}$$

$$C = -(R_c^2 + X_c^2 - 2X_LX_c)(Z^2 - R^2 - X^2) + 2XX_L(R_c^2 + X_c^2) = 0 \tag{8}$$

From the simultaneous eqs 6, 7, and 8 the values of R_c, X_c, and X_L may be obtained in terms of Z, X, and R.

$$X_c = \frac{(Z^2 - X^2 - R^2)(Z - X)}{R^2 + (Z - X)^2} \tag{9}$$

$$R_c = \frac{(Z^2 - X^2 - R^2)R}{R^2 + (Z - X)^2} \tag{10}$$

$$X_L = \frac{(Z^2 - X^2 - R^2)}{2Z} \tag{11}$$

The maximum possible phase shift, $\Delta\theta$, that can be obtained, is given by the following expression:

$$\Delta\theta = -\text{arc tan}\ \frac{X_L(R_c^2 + X_c^2) - X_c(R_L^2 + X_L^2)}{(R_c + R_L)^2 + (X_L - X_c)^2} + X \quad \Bigg|\ R_L = \infty$$
$$\Delta\theta = -\text{arc tan}\ \frac{R_c(R_L^2 + X_L^2) + R_L(R_c^2 + X_c^2)}{(R_c + R_L)^2 + (X_L - X_c)^2} + R \quad \Bigg|\ R_L = R_0 \tag{12}$$

If X and R are assumed negligible the expression becomes:

$$\Delta\theta = \text{arc tan}\ \frac{X_c}{R_c} + \text{arc tan}\ \frac{X_L(R_c^2 + X_c^2) - X_c(R_c^2 + X_L^2)}{R_c(R_c^2 + X_L^2) + R_c(X_L - X_c)^2}$$

Stabilized Feed-Back Amplifiers

This paper describes and explains the theory of the feed-back principle and demonstrates how stability of amplification, reduction of modulation products, and certain other advantages follow when stabilized feed-back is applied to an amplifier. The underlying principle of design by means of which "singing" is avoided also is set forth. The paper concludes with some examples of results obtained on amplifiers which have been built employing this new principle.

By
H. S. BLACK
MEMBER A.I.E.E.

Bell Telephone Laboratories, Inc., New York, N. Y.

DUE TO ADVANCES in vacuum-tube development and amplifier technique, it now is possible to secure any desired amplification of the electrical waves used in the communication field. When many amplifiers are worked in tandem, however, it becomes difficult to keep the over-all circuit efficiency constant, variations in battery potentials and currents, small when considered individually, adding up to produce serious transmission changes for the over-all circuit. Furthermore, although it has remarkably linear properties, when the modern vacuum tube amplifier is used to handle a number of carrier telephone channels, extraneous frequencies are generated which cause interference between the channels. To keep this interference within proper bounds involves serious sacrifice of effective amplifier capacity or the use of a push-pull arrangement which, while giving some increase in capacity, adds to maintenance difficulty.

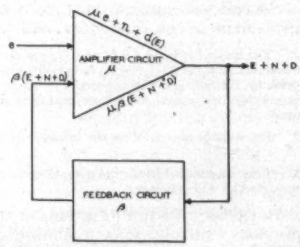
However, by building an amplifier whose gain is made deliberately, say 40 decibels higher than necessary (10,000 fold excess on energy basis) and then feeding the output back to the input in such a way as to throw away the excess gain, it has been found possible to effect extraordinary improvement in constancy of amplification and freedom from nonlinearity. By employing this feed-back principle, amplifiers have been built and used whose gain varied less than 0.01 db with a change in plate voltage from 240 to 260 volts and whose modulation products were 75 db below the signal output at full load. For an amplifier of conventional design and comparable size this change in plate voltage would have produced about 0.7 db variation while the modulation products would have been only 35 db down; in other words, 40 db reduction in modulation products was effected. (On an energy basis the reduction was 10,000 fold.)

Stabilized feed-back possesses other advantages including reduced delay and delay distortion, reduced noise disturbance from the power supply circuits and various other features best appreciated by practical designers of amplifiers.

It is far from a simple proposition to employ feed-back in this way because of the very special control required of phase shifts in the amplifier and feed-back circuits, not only throughout the useful frequency band but for a wide range of frequencies above and below this band. Unless these relations are maintained, singing will occur, usually at frequencies outside the useful range. Once having achieved a design, however, in which proper phase relations are secured, experience has demonstrated that the performance obtained is perfectly reliable.

The carrier-in-cable system dealt with in a recent Institute paper (Carrier in Cables by A. B. Clark and B. W. Kendall. A.I.E.E. TRANS., Dec. 1933, p. 1050) involves many amplifiers in tandem with many telephone channels passing through each

Fig. 1. Amplifier system with feed-back



e. signal input voltage
μ. propagation of amplifier circuit
μe. signal output voltage without feed-back
n. noise output voltage without feed-back
d(E). distortion output voltage without feed-back
β. propagation of feed-back circuit
E. signal output voltage with feed-back
N. noise output voltage with feed-back
D. distortion output voltage with feed-back

The output voltage with feed-back is E + N + D and is the sum of $\mu e + n + d(E)$, the value without feed-back plus $\mu\beta[E + N + D]$ due to feed-back.

$$E + N + D = \mu e + n + d(E) + \mu\beta[E + N + D]$$

$$[E + N + D](1 - \mu\beta) = \mu e + n + d(E)$$

$$E + N + D = \frac{\mu e}{1 - \mu\beta} + \frac{n}{1 - \mu\beta} + \frac{d(E)}{1 - \mu\beta}$$

If $|u\beta| \gg 1$, $E \doteq = \frac{e}{\beta}$. Under this condition the amplification is independent of μ but does depend upon β. Consequently the over-all characteristic will be controlled by the feed-back circuit which may include equalizers or other corrective networks.

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted March 28, 1933; released for publication December 4, 1933. *Not published in pamphlet form.*

amplifier and constitutes, therefore, an ideal field for application of this feed-back principle. A field trial of this system was made at Morristown, New Jersey, in which 70 of these amplifiers were operated in tandem. The results of this trial were highly satisfactory and demonstrated conclusively the correctness of the theory and the practicability of its commercial application.

Circuit Arrangement

In the amplifier of Fig. 1, a portion of the output is returned to the input to produce feed-back action. The upper branch, called the μ circuit, is represented as containing active elements such as an amplifier while the lower branch, called the β-circuit, is shown as a passive network. The way a voltage is modified after once traversing each circuit is denoted μ and β, respectively, and the product, $\mu\beta$, represents how a voltage is modified after making a single journey around amplifier and feed-back circuits. Both μ and β are complex quantities, functions of frequency, and in the generalized concept either or both may be greater or less in absolute value than unity: (μ is not used in the sense that it is used sometimes, namely, to denote the amplification constant of a particular tube, but as the complex ratio of the output to the input voltage of the amplifier circuit).

Fig. 2 shows an arrangement convenient for some purposes where, by using balanced bridges in the input and output circuits, interaction between the circuits that connect to the input and output is avoided. Thereby feed-back action and amplifier impedances are made independent of the properties of circuits connected to the amplifier.

General Equation

In Fig. 1, β is zero without feed-back and a signal voltage, e_0, applied to the input of the μ-circuit produces an output voltage. This is made up of

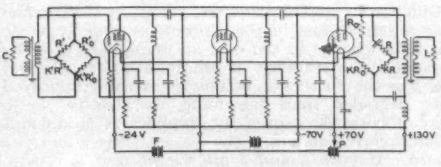


Fig. 2. Circuit of a negative feed-back amplifier

what is wanted, the amplified signal, E_0, and components that are not wanted, namely, noise and distortion designated N_0 and D_0 and assumed to be generated within the amplifier. It is further assumed that the noise is independent of the signal and the distortion of modulation a function *only of the signal output*. Using the notation of Fig. 1, the output without feed-back may be written as:

$$E_0 + N_0 + D_0 = \mu e_0 + n + d(E_0) \tag{1}$$

where zero subscripts refer to conditions without feed-back.

With feed-back, β is not zero and the input to the μ-circuit becomes $e_0 + \beta\ (E + N + D)$. The output is $E + N + D$ and is equal to $\mu[e_0 + \beta\ (E + N + D)] + n + dE$ or

$$E + N + D = \frac{\mu e_0}{1 - \mu\beta} + \frac{n}{1 - \mu\beta} + \frac{d(E)}{1 - \mu\beta} \tag{2}$$

In the output signal, noise and modulation are divided by $(1 - \mu\beta)$, and assuming $|1 - \mu\beta| > 1$, all are reduced.

Change in Gain Due to Feed-Back

From eq 2, the amplification with feed-back equals the amplification without feed-back divided by $(1 - \mu\beta)$. The effect of adding feed-back, therefore, usually is to change the gain of the amplifier and this change will be expressed as

$$G_{CF} = 20 \log_{10} \left| \frac{1}{1 - \mu\beta} \right| \tag{3}$$

where G_{CF} is *db change in gain due to feed-back*. As a quantitative measure of the effect of feed-back $\frac{1}{1 - \mu\beta}$ will be used and the feed-back referred to as *positive feed-back* or *negative feed-back* according as the absolute value of $\frac{1}{1 - \mu\beta}$ is greater or less than unity. Positive feed-back increases the gain of the amplifier; negative feed-back reduces it. The term feed-back is not limited merely to those cases where the absolute value of $\frac{1}{1 - \mu\beta}$ is other than unity.

From $\mu\beta = |\mu\beta| \underline{|\Phi}$ and (3), it may be shown that

$$10^{-\frac{G_{CF}}{10}} = 1 - 2\,|\mu\beta| \cos\Phi + |\mu\beta|^2 \tag{4}$$

which is the equation for a family of concentric circles of radius $10^{-\frac{G_{CF}}{10}}$ about the point 1, 0. Fig. 3 is a polar diagram of the vector field of $\mu\beta = |\mu\beta| \underline{|\Phi}$. Using rectangular instead of polar coördinates, Fig. 4 corresponds to Fig. 3 and may be regarded as a diagram of the field of $\mu\beta$ where the parameter is db change in gain due to feed-back. From these diagrams all of the essential properties of feed-back action can be obtained such as change in amplification, effect on linearity, change in stability due to variations in various parts of the system, reduction of noise, etc. Certain significant boundaries have been designated similarly on both figures.

For example, boundary A is the locus of zero change in gain due to feed-back. Along this parametric contour line where the absolute magnitude of amplification is not changed by feed-back action, values of $|\mu\beta|$ range from zero to 2 and the phase shift, Φ around the amplifier and feed-back circuits equal $\cos^{-1} \left| \frac{\mu\beta}{2} \right|$ and, therefore, lies between -90 deg and $+90$ deg. For all conditions inside or above this boundary, the gain with feed-back is increased; outside or below, the gain is decreased.

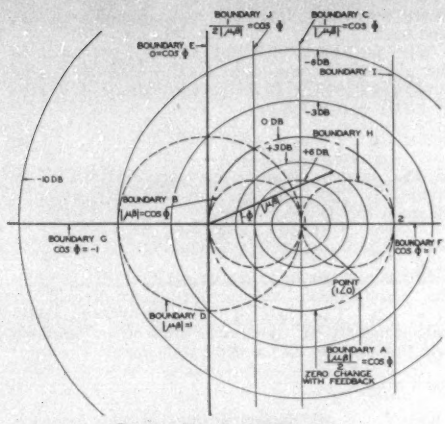


Fig. 3. The vector field of $\mu\beta$

See caption for Fig. 4

The complex quantity $\mu\beta$ represents the ratio by which the amplifier and feed-back (or more generally μ and β) modify a voltage in a single trip around the closed path

First, there is a set of boundary curves indicated by letters which give either limiting or significant values of $|\mu\beta|$ and ϕ.

Second, there is a family of curves in which db change in gain due to feed-back is the parameter.

Boundaries

A. Conditions in which gain and modulation are unaffected by feed-back.

B. Constant amplification ratio against small variations in $|\beta|$.

Constant change in gain, $\frac{1}{|1-\mu\beta|}$, against variations in $|\mu|$ and $|\beta|$. Stable phase shift through the amplifier against variation in $\Phi\beta$.

The boundary on which the stability of amplification is unaffected by feed-back.

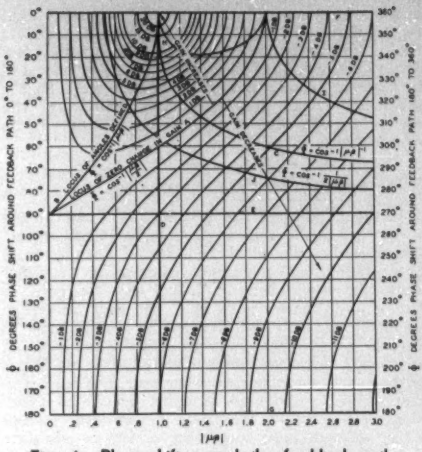


Fig. 4. Phase shift around the feed-back path plotted as a function of $|\mu\beta|$, absolute value of $\mu\beta$

C. Constant amplification ratio against small variations in $|\mu|$. Constant phase shift through amplifier against variations in $\Phi\mu$.

The absolute magnitude of the voltage fed back $\frac{|\mu\beta|}{|1-\mu\beta|}$ is constant against variations in $|\mu|$ and $|\beta|$.

D. $|\mu\beta| = 1$

E. $\Phi = 90°$. Improvement in gain stability corresponds to twice db reduction in gain.

F. G. Constant amplification ratio against variations in Φ. Constant phase shift through the amplifier against variations in $|\mu|$ and $|\beta|$.

H. Same properties as β

I. Same properties as E

J. Conditions in which $\frac{|\mu|}{|1-\mu\beta|} = \frac{-1}{|\beta|}$ the over-all gain is the exact negative inverse of the transmission through the β-circuit.

Stability

From eq 2, $\frac{\mu e_0}{1-\mu\beta}$ is the amplified signal with feed-back and $\frac{\mu}{1-\mu\beta}$, therefore, is an index of the amplification. It is of course a complex ratio. It will be designated A_F and referred to as the amplification with feed-back.

To consider the effect of feed-back upon stability of amplification, the stability will be viewed as the ratio of a change, δA_F, to A_F where δA_F is due to a change either in μ or β and the effects may be derived by assuming the variations are small.

$$A_F = \frac{\mu}{1-\mu\beta} \tag{5}$$

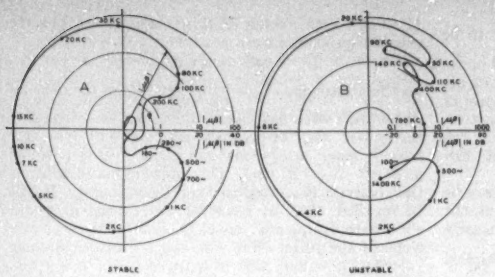
$$\left[\frac{\delta A_F}{A_F}\right]_\mu \doteq \frac{\left[\frac{\delta\mu}{\mu}\right]}{1-\mu\beta} \tag{6}$$

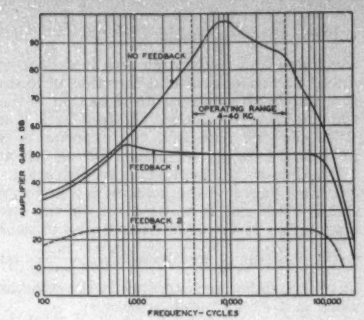
$$\left[\frac{\delta A_F}{A_F}\right]_\beta \doteq \frac{\mu\beta}{1-\mu\beta}\left[\frac{\delta\beta}{\beta}\right] \tag{7}$$

If $\mu\beta \gg 1$, it is seen that μ or the μ-circuit is stabilized by an amount corresponding to the reduction in amplification and the effect of introducing a gain or loss in the μ-circuit is to produce no material change in the over-all amplification of the system; the stability of amplification as affected by β or the β-circuit is neither appreciably improved nor degraded since increasing the loss in the β-circuit raises the gain of the amplifier by an amount almost corresponding to the loss introduced and *vice versa*. If both μ and β are varied and the variations sufficiently small, the effect is the same as if each were changed separately and the two results then combined.

In certain practical applications of amplifiers it is the change in gain or ammeter or voltmeter reading at the output that is a measure of the stability rather than the complex ratio previously treated. The conditions surrounding gain stability may be examined by considering the absolute value of A_F. This is shown as follows:

Let (db) represent the gain in decibels corresponding to A_F. Then





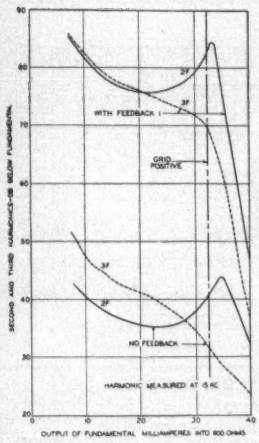


Fig. 5 (above). Measured $\mu\beta$ characteristics of 2 amplifiers

Fig. 6 (above right). Gain-frequency characteristics with and without feed-back of amplifier of Fig. 2

Fig. 7(left). Modulation characteristics with and without feed-back for the amplifier of Fig. 2

$$(db) = 20 \log_{10} |A_F|$$

$$\delta(db) \doteq 8.686 \left[\frac{\delta |A_F|}{|A_F|}\right] \tag{8}$$

To get the absolute value of the amplification:

$$\mu\beta = |\mu\beta| \angle \Phi \tag{9}$$

$$|A_F| = \frac{|\mu|}{\sqrt{1 - 2|\mu\beta| \cos\Phi + |\mu\beta|^2}} \tag{10}$$

The stability of amplification which is proportional to the gain stability is given by

$$\left[\frac{\delta |A_F|}{|A_F|}\right]_{|\mu|} \doteq \frac{1 - |\mu\beta| \cos\Phi}{|1 - \mu\beta|^2} \left[\frac{\delta |\mu|}{|\mu|}\right] \tag{11}$$

$$\left[\frac{\delta |A_F|}{|A_F|}\right]_{|\beta|} \doteq \left|\frac{\mu\beta}{1 - \mu\beta}\right| \left[\frac{\cos\Phi - |\mu\beta|}{|1 - \mu\beta|}\right] \left[\frac{\delta |\beta|}{|\beta|}\right] \tag{12}$$

$$\left[\frac{\delta |A_F|}{|A_F|}\right]_{\Phi} \doteq -\left|\frac{\mu\beta}{1 - \mu\beta}\right| \left[\frac{\sin\Phi}{|1 - \mu\beta|}\right] [\delta\Phi] \tag{13}$$

A curious fact to be noted from eq 11 is that it is possible to choose a value of $\mu\beta$ (namely, $|\mu\beta| = \sec\Phi$) so that the numerator of the right hand term vanishes. This means that the gain stability is perfect, assuming differential variations in $|\mu|$.

Referring to Figs. 3 and 4, contour C is the locus of $|\mu\beta| = \sec\Phi$ and it includes all amplifiers whose gain is unaffected by small variations in $|\mu|$. In this way it is possible even to stabilize an amplifier whose feed-back is positive, i. e., feed-back may be utilized to raise the gain of an amplifier and, at the same time, the gain stability with feed-back *need* not be degraded but on the contrary may be improved. If a similar procedure is followed with an amplifier whose feed-back is negative, the gain stability theoretically will be perfect and independent of the reductions in gain due to feed-back. Over too wide a frequency band practical difficulties will limit the improvements possible by these methods.

With negative feed-back, gain stability always is improved by an amount at least as great as corresponds to the reduction in gain and generally more; with positive feed-back, gain stability never is degraded by more than would correspond to the increase in gain and under appropriate conditions, assuming the variations are not too great is as good or much better than without feed-back. With positive feed-back, the variations in μ or β must not be permitted to become sufficiently great as to cause the amplifier to sing or give rise to instability as defined in the section devoted to the conditions for avoiding singing.

Modulation

To determine the effect of feed-back action upon modulation produced in the amplifier circuit, it is convenient to assume that the output of undistorted signal is made the same with and without feed-back and that a comparison then is made of the difference in modulation with and without feed-back. Therefore, with feed-back, the input is changed to $e = e_0 (1 - \mu\beta)$ and, referring to eq 2, the output voltage is μe_0 and the generated modulation, $d(E)$, assumes its value without feed-back, $d(E_0)$, and $\frac{d(E)}{1 - \mu\beta}$ becomes $\frac{d(E_0)}{1 - \mu\beta}$ which is $\frac{D_0}{1 - \mu\beta}$. This relationship is approximate because the voltage at the input without feed-back is free from distortion and with feed-back it is not and, hence, the assumption that the modulation is a function *only of the signal output* used in deriving eq 2 is not necessarily justified.

From the relationship $D = \frac{D_0}{1 - \mu\beta}$, it is to be concluded that modulation with feed-back will be reduced decibel for decibel as the effect of feed-back action causes an arbitrary db reduction in the gain of the amplifier; i. e., when the feed-back is negative. With positive feed-back the opposite is true, the modulation being increased by an amount corresponding to the increase in amplification.

If modulation in the β-circuit is a factor, it can be shown that usually in its effect on the output the modulation level at the output due to nonlinearity of the β-circuit is approximately $\frac{\mu\beta}{1 - \mu\beta}$ multiplied by the modulation generated in the β-circuit acting alone and without feed-back.

Additional Effects

Noise. A criterion of the worth of a reduction in noise is the reduction in signal-to-noise ratio at the output of an amplifier. Assuming that the amount of noise introduced is the same in 2 systems, for example, with and without feed-back, respectively, and that the signal outputs are the same, a comparison of the signal-to-noise ratios will be affected by the amplification between the place at which the noise enters and the output. Denoting

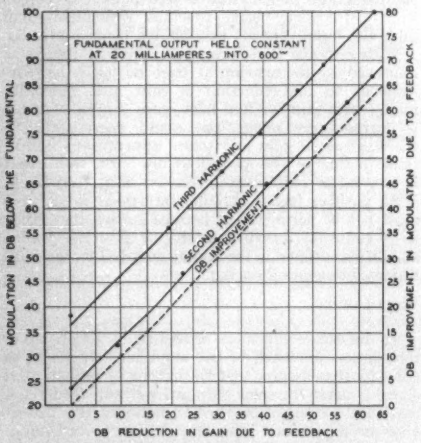


Fig. 8. Improvement of harmonics with feed-back

One example of another amplifier in which, with 60-db feed-back, harmonic currents in the output are only 1 thousandth and their energy 1 millionth of the values without feed-back

this amplification by a and a_0, respectively, it can be shown that the relation between the 2 noise ratios is $\frac{a_0}{a}(1 - \mu\beta)$. This is called the *noise index.*

If noise is introduced in the power supply circuits of the last tube, $a_0/a = 1$ and the noise index is $(1 - \mu\beta)$. As a result of this relation less expensive power supply filters are possible in the last stage.

Phase Shift, Envelope Delay, Delay Distortion. In the expression $A_F = \left[\frac{\mu}{1 - \mu\beta}\right]\underline{|\theta}$, θ is the over-all phase shift with feed-back, and it can be shown that the *phase shift through the amplifier with feed-back may be made to approach the phase shift through the β-circuit plus 180 deg.* The effect of phase shift in the β-circuit is not reduced correspondingly. It will be recalled that in reducing the change in phase shift with frequency, envelope delay, which is the slope of the phase shift with respect to the angular velocity, $\omega = 2\pi f$, also is reduced. The *delay* distortion likewise is reduced because a measure of

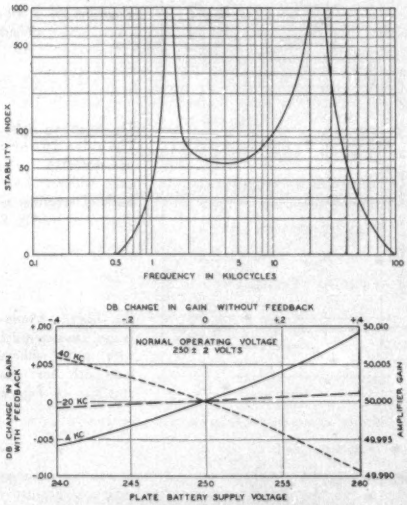


Fig. 9. Representative gain stability of a single amplifier as determined by measuring 69 feed-back amplifiers in tandem at Morristown, New Jersey

The upper figure shows the absolute value of the stability index. It can be seen that between 20 and 25 kc the improvement in stability is more than 1,000 to 1 yet the reduction in gain was less than 35 db

The lower figure shows change in gain of the feed-back amplifier with changes in the plate battery voltage and the corresponding changes in gain without feed-back. At some frequencies the change in gain is of the same sign as without feed-back and at others it is of opposite sign and it can be seen that near 23 kc the stability must be perfect

delay distortion at a particular frequency is the difference between the envelope delay at that frequency and the least envelope delay in the band.

β-Circuit Equalization. Referring to eq 2, the output voltage E approaches $-e_0/\beta$ as $1 - \mu\beta = -\mu\beta$ and equals it in absolute value if $\cos\Phi = \frac{1}{2|\mu\beta|}$

where $\mu\beta = |\mu\beta| \angle\Phi$. Under these circumstances increasing the loss in the β-circuit 1 db raises the gain of the amplifier 1 db, and *vice-versa*, thus giving any gain-frequency characteristic for which a like loss-frequency characteristic can be inserted in the β-circuit. This procedure has been termed β-circuit

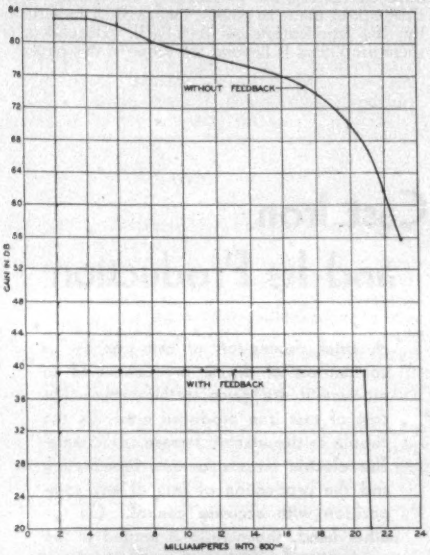


Fig. 10. Gain-load characteristic with and without feed-back for a low level amplifier designed to amplify frequencies from 3.5 to 50 kc

equalization. It possesses other advantages and properties which are beyond the scope of this paper.

Avoid Singing

Having considered the theory up to this point, experimental evidence was readily acquired to demonstrate that $\mu\beta$ might assume large values, 10 to 10,000, provided Φ was not at the same time zero. However, one noticeable feature about the field of $\mu\beta$ (Figs. 3 and 4) is that it implies that even though the phase shift is zero and the absolute value of $\mu\beta$ exceeds unity, self-oscillations or singing will not result. This may or may not be true. When first thinking about this matter it was suspected that owing to practical nonlinearity, singing would result whenever the gain around the closed loop equaled or exceeded the loss and simultaneously the phase shift was zero; i. e., $\mu\beta = |\mu\beta| + jo \geq 1$. Results of experiments, however, seemed to indicate something more was involved and these matters were described to H. Nyquist who developed a

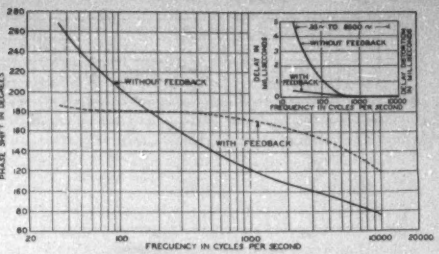


Fig. 11. Phase shift, delay, and delay distortion with and without feed-back for a single tube voice frequency amplifier

more general criterion for freedom from instability applicable to an amplifier having linear positive constants. (For a complete description of the criterion for stability and instability and exactly what is meant by enclosing the point (1, 0), reference should be made to Regeneration Theory, by H. Nyquist. *Bell System Technical Journal*, v. XI, July 1932, p. 126–47.)

To use this criterion, plot $\mu\beta$ (the modulus and argument vary with frequency) and its complex conjugate in polar coördinates for all values of frequency from 0 to $+\infty$. If the resulting loop or loops do not enclose the point (1, 0) the system will be stable, otherwise not. The envelope of the transient response of a stable amplifier always dies away exponentially with time; that of an unstable amplifier in all physically realizable cases increases with time. Characteristics *A* and *B* in Fig. 5 are results of measurements on 2 different amplifiers; the amplifier having $\mu\beta$ characteristic denoted *A* was stable, the other unstable.

The number of stages of amplification that can be used in a single amplifier is not significant except in so far as it affects the question of avoiding singing. Amplifiers with considerable negative feed-back have been tested where the number of stages ranged from 1 to 5, inclusive. In every case the feed-back path was from the output of the last tube to the input of the first tube.

Experimental Results

Figs. 6 and 7 show how the gain-frequency and modulation characteristics of the 3-stage impedance coupled amplifier of Fig. 2 are improved by negative feed-back. In Fig. 7 the improvement in harmonics is not equal exactly to the decibel reduction in gain. Fig. 8 shows measurements on a different amplifier in which harmonics are reduced as negative feed-back is increased, decibel for decibel over a 65-db range.

That the gain with frequency practically is independent of small variations in $|\mu|$ is shown by Fig. 9. This is a characteristic of the Morristown amplifier, described in the paper by Clark and Kendall referred to previously, which meets the severe requirements imposed upon a repeater amplifier

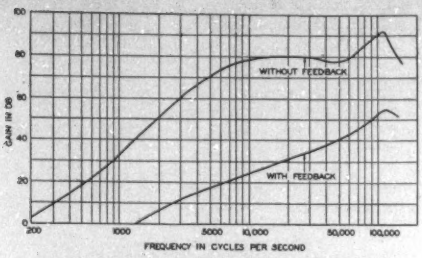


Fig. 12. Gain-frequency characteristic of an amplifier with an equalizer in the β-circuit

This was designed to have a gain frequency characteristic with feed-back of the same shape as the loss frequency characteristic of a nonloaded telephone cable

for use in cable carrier systems. Designed to amplify frequencies from 4 kc to 40 kc the maximum change in gain due to variations in plate voltage does not exceed $\frac{7}{10{,}000}$ db per volt and at 20 kc the change is only $\frac{1}{20{,}000}$ db per volt. This illustrates that for small changes in $|\mu|$, the ratio of the stability without feed-back to the stability with feed-back, called the *stability index*, approaches $\frac{|1-\mu\beta|^2}{1-|\mu\beta|\cos\Phi}$ and gain stability is improved at least as much as the gain is reduced and usually more, and is theoretically perfect if $\cos\Phi = \frac{1}{|\mu\beta|}$.

In Fig. 10 is indicated the effectiveness with which the gain of a feed-back amplifier can be made independent of variations in input amplitude practically up to the overload point of the amplifier. These measurements were made on a 3-stage amplifier designed to work from 3.3 kc to 50 kc.

As shown in Fig. 11, the negative feed-back may be used to improve phase shift and reduce delay and delay distortion. These measurements were made on an experimental 1-tube amplifier, 35–8,500 cycles, feeding back around the low side windings of the input and output transformers.

In Fig. 12 is given the gain-frequency characteristic of an amplifier with and without feed-back when in the β-circuit there is an equalizer designed to make the gain-frequency characteristic of the amplifier with feed-back of the same shape as the loss-frequency characteristic of a nonloaded telephone cable.

Conclusion

The feed-back amplifier dealt with in this paper was developed primarily with requirements in mind for a cable carrier telephone system, involving many amplifiers in tandem with many telephone channels passing through each amplifier. Most of the examples of feed-back amplifier performance naturally have been drawn from amplifiers designed for this field of operation. In this field, vacuum tube amplifiers normally possessing good characteristics with respect to stability and freedom from distortion are made to possess superlatively good characteristics by application of the feed-back principle.

However, certain types of amplifiers, in which economy has been secured by sacrificing performance characteristics, particularly as regards distortion, can be made to possess improved characteristics by the application of feed-back. Discussion of these amplifiers is beyond the scope of this paper.

Cast Iron and Its Production

A brief description of cast iron and a comparison of the 2 processes used to produce it are given in this paper. The cost of cast iron produced either by the cupola or the electric furnace is the same. The electric furnace permits superheating and the production of iron of any composition with accurate control. On the other hand, the cupola is limited to the production of high carbon iron. As a result of the success of electric melting, the field of application of cast iron has been greatly increased.

By
M. V. HEALEY
General Elec. Co., Schenectady, N. Y.

THE late Dr. Moldenke was probably the first to advance the theory that the superheating of cast iron dissolves the carbon nucleuses that are the cause of coarse graphitization and nonuniformity. In recent years the electric furnace has made possible a thorough examination of this theory, and the results indicate not only that the theory is correct, but that it has enabled the regular production of a new and reliable quality of cast iron. The data in this paper have been accumulated in the last 2 years,

Full text of a paper recommended for publication by the A.I.E.E. committee on electrochemistry and electrometallurgy, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 14, 1933; released for publication Dec. 7, 1933. *Not published in pamphlet form.*

during which time a cupola and an electric furnace have been operated in parallel and the results recorded.

The Characteristics of Cast Iron

The following brief description of cast iron is included in order to provide a common basis upon which the comparison of cupola and electric furnace melting may be judged.

Cast iron in the molten state is a solution of carbon, silicon, and manganese in iron. The proportions of these elements, disregarding impurities, are within the limits noted below:

Carbon—1.7 to 3.6 per cent
Silicon—1.6 to 3.0 per cent
Manganese—0.50 to 1.0 per cent
Iron—remainder

Other elements, particularly phosphorus and sulphur, are present as impurities.

As the temperature is lowered, the alloy passes from the state of solution to an aggregate or mixture in the solid, becoming, if cooled with sufficient slowness down to and through the critical range, a complete aggregation as exhibited by the iron-carbon constitutional diagram. This phenomenon of change from a solution to an aggregate is the basis of the consideration of the electric furnace for the manufacture of cast iron.

As cast iron cools from the solidification temperature, there is a progressive rejection of carbon from solution or combination with the iron to the free form of graphite. This rejection ceases at the gamma-alpha transformation temperature. The amount of carbon in the combined form at this point varies with the composition, particularly silicon, and with the rate of cooling. For maximum machinability, it should be zero and for maximum strength it should be the eutectoid, that is, 0.65 to 0.85 per cent. Usually more carbon is left combined than is desired, particularly at the surface of the casting, and a subsequent heat treatment is applied to reduce it to the proper amount. The retention of the major portion of the carbon in the combined form must be avoided in the original cooling. Adjustment of composition to casting size is necessary since the rate of cooling is dependent upon the section cast. The limits of composition are as noted previously.

Certain alloying elements such as nickel, molybdenum, and chromium are often used singly or in combination in cast iron for their effect on graphitization and the shape of the resultant graphite flakes. Their use necessitates an adjustment of composition in the other elements. Nickel can be used to replace the silicon in part. Its value lies in the fact that it is a graphitizer for combined carbon in excess of the eutectoid. Molybdenum has the property of "balling up" the graphite flakes, thereby increasing the strength without adding materially to the hardness. Chromium is a drastic inhibitor to graphitization. In the great majority of cases, the use of alloying elements is an unnecessary expense, as the improvements desired can be obtained by adjustment of composition and by superheating, as will be described later.

In the process of cooling, cast iron becomes a

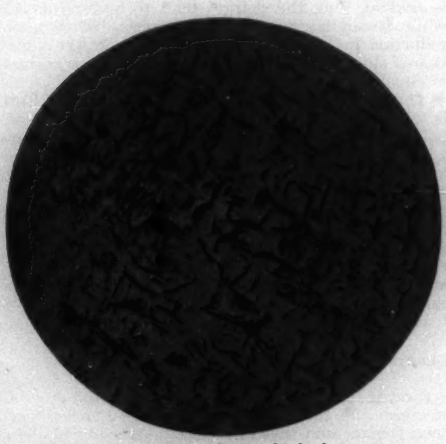


Fig. 1. Photomicrograph unetched of a specimen taken from the surface of a 2-in. wall section of cupola cast iron

Total carbon—3.16 per cent; silicon—2.13 per cent; manganese—0.62 per cent. Tensile strength—28,000 lb per square inch. Magnified slightly over 100 diameters

Fig. 2. Photomicrograph unetched of a specimen taken from the center of the same casting as in Fig. 1

Tensile strength—23,000 lb per square inch. Magnified slightly over 100 diameters

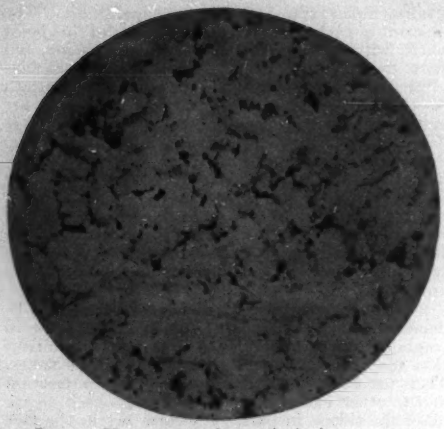


Fig. 3. Photomicrograph unetched of a specimen taken from the surface of a 2-in. wall section of cast iron which has been superheated in the electric furnace

Total carbon—3.24 per cent; silicon—2.22 per cent; manganese—0.60 per cent. Tensile strength—36,000 lb per square inch. Magnified slightly over 100 diameters

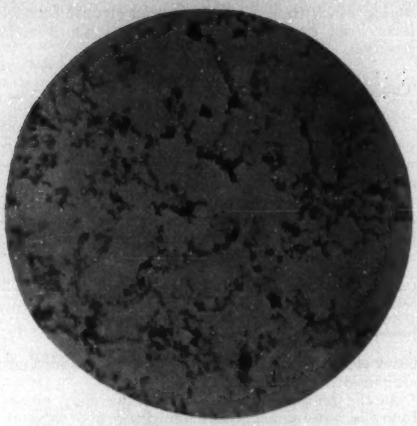


Fig. 4. Photomicrograph unetched of a specimen taken from the center of the same casting as in Fig. 3

Tensile strength—34,000 lb per square inch. Magnified slightly over 100 diameters

nonductile aggregate, consisting of a ferritic to pearlitic matrix whose continuity is interrupted by the presence of graphite flakes. Obviously, the strength and other properties are determined by the amount of graphite, by its arrangement, and by the combined carbon in the matrix. The graphite patterns of skin and center specimens of 2 irons of similar composition and section are shown in Figs. 1 to 4. The superheated iron, having the same amount of graphite as the cupola iron, is much stronger by reason of the better arrangement of its graphite. The uniformity across the section should be noted. All other factors being constant, the strength of iron varies inversely with the amount of graphite present. In Fig. 5 is shown the unetched microstructure of a low-carbon superheated iron, which has the advantage of good arrangement and low graphite content. Cast iron of maximum strength must have a eutectoid matrix and the minimum of graphite which is finely dispersed.

Cupola Melting

The cupola was the principal source of cast iron before the application of the electric furnace to cast iron melting. Cupola operation can be described briefly as a continuous process in which successive charges are melted in the presence of carbon by combustion of the carbon. The maximum temperature obtainable is approximately 1,500 deg C. The capacity varies directly with the hearth area. A 60-in. cupola can produce 20,000 lb of iron per hour. The average charge consists of 50 per cent pig iron and 50 per cent selected iron and steel scrap. The components of this charge must be sized to obtain even melting conditions. They must be of known composition, since control of composition of the product substantially ends with the selection of the charge. A change from one grade of iron to another is gradual, since the charges tend to become mixed while descending to the melting zone. While some reduction in carbon may be obtained by the addition of steel to the charge, the lower limit for carbon in cupola iron is practically 3.0 per cent.

The solution of the last traces of carbon in iron is difficult, requiring both time and temperature. Solution may be accomplished in 10 to 15 min at 1,650 deg C. A longer time is necessary at a lower temperature. As a result of the low temperature available and the intimate contact with the coke, cupola iron comes from the spout bearing undissolved carbon in suspension. The suspended particles, after solidification of the iron, act as nucleuses for the crystallization of precipitating graphite resulting in a coarse structure, particularly in the center of a casting where the rate of cooling is slow (see Figs. 1 and 2).

Electric Furnace Melting

Electric furnace melting is a batch melting process in which the cold charge is placed in a refractory lined furnace and melted by the conversion of electrical energy to heat. Two types of electric furnaces are in general use for making cast iron: the indirect-arc single-phase and the direct-arc 3-phase types. In the former, the arc is maintained between like electrodes above the charge. In the latter, the arc is maintained between the electrodes and the charge.

Cast iron of any composition from 1.7 to 3.6 per cent carbon can be produced readily and accurately, since the electric furnace simply melts what is in it. The composition of the bath can be altered as and when desired. A charge of unknown composition can be melted and held until the analysis is completed and adjustments made. The charge for melting can be of low-cost materials such as borings, turnings, punchings, and any other scrap that may be available.

A heat of cast iron in an electric furnace, when just melted, has the same characteristics as cupola iron of a like analysis. It has undissolved carbon in suspension which acts as nucleuses for coarse graphitization. If the bath is heated to approximately 1,650 deg C and held for 10 min, the suspended carbon is dissolved. This heating to obtain complete solution is known as superheating. Cast iron when so treated has no nucleuses to attract precipitating graphite. It is, therefore, fine grained and uniform throughout, as shown in Figs. 3 and 4.

Comparative Costs

The cost data shown in Table I are based upon the operation of a 3-ton 3-phase direct-arc electric furnace delivering 5 tons of metal every 3 hr. The energy, delivered to the transformer at 10,300 volts and 40 cycles, is transformed to 150 volts for melting and 100 volts for refining. The current maintained in the furnace is 6,000 amp. Charging, at the present, is done by hand. This operation takes approximately 30 min. The time consumed in melting and refining averages 2 hr. Tapping and conditioning the furnace accounts for the remaining 30 min. The cupola data were obtained from the operation of a 60-in. cupola using a 32-in. bed charge of coke and a 1 to 9 ratio of coke to metal in the charge. The blast pressure was 15 lb per square inch delivered through 8 tuyères. This cupola melted approximately 20,000 lb of metal per hour.

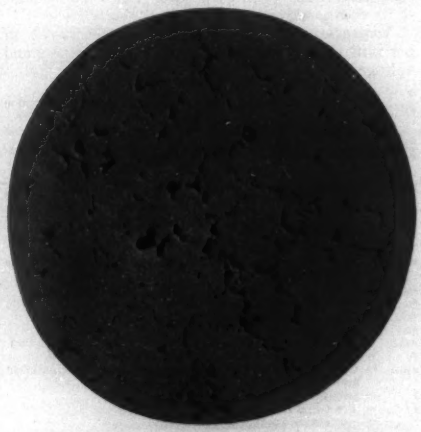


Fig. 5. Photomicrograph unetched of a specimen taken from the center of a 2-in. section of low-carbon cast iron

Total carbon—2.18 per cent; silicon—2.20 per cent; manganese—1.00 per cent. Tensile strength—62,000 lb per square inch. Magnified slightly over 100 diameters

Table I—Comparative Costs of Operation

	Cost per Net Ton	
	Electric Furnace	Cupola
Energy, 600 kwhr at 1¢ per kwhr	$ 6.00	
Labor	1.35	$ 1.20
Fuel, coke at $10 per ton		1.64
Maintenance, including refractories	1.10	0.70
Electrodes, 8 lb per ton at 10¢ per lb	0.80	
Conversion cost	$ 9.25	$ 3.54
Material for melting	7.28	12.89
Total	$16.53	$16.43

The conversion cost of the electric furnace, in this case, is higher than the conversion cost of the cupola by approximately the item for electrical energy. The lower cost of the material for melting very nearly brings the totals to the same figure. While the data contained herein are true for one locality only, they are believed to be representative of what can be expected in the ordinary manufacturing plant producing a wide variety of scrap which can be used to advantage in electric melting.

Summary

The information given in this paper may be summarized as follows:

1. Cast iron of any carbon content throughout the range from 1.7 to 3.6 per cent can be produced readily and accurately in the electric furnace. The cupola is limited to the production of irons with carbon in excess of 3.0 per cent.

2. Cast iron produced in the cupola is coarse grained and non-uniform, because it is impossible to dissolve the suspension of carbon present in the molten metal. Superheating in the electric furnace dissolves this suspension and permits the production of a fine grained uniform material.

3. The cupola is an economical unit for the production of large quantities of cast iron of the type that can be made in the cupola.

4. The control of the electric furnace is positive, and uniformity of results can be guaranteed. The control of composition of the product in the cupola ends substantially with the selection of the charge for melting.

5. There is no great disparity in cost between melting in the electric furnace and in the cupola. The higher conversion cost of the one is substantially balanced by the higher melting material cost of the other.

6. On account of the success with electric melting, cast iron specifications are being revised with a view to making cast iron really an engineering material of definite properties. This means that the day's output of the ordinary foundry is to be of a wide range of compositions with close control that is not characteristic of cupola operation. The cupola can be depended upon for the production of large quantities of a high carbon material with little flexibility within a heat. Electric melting is very flexible. The character of a bath or any part of it can be altered readily to meet the needs of a varied production.

Equivalent Reactance of Synchronous Machines

Steady state characteristics of synchronous machines of normal design are affected appreciably by changes in magnetic saturation. In this paper the effect of saturation is included in the derivation of the equations for determining steady state performance. It is shown that a saturated machine under steady state conditions, and for small changes from the original operating point, can be replaced for purposes of calculation by an unsaturated machine.

By
S. B. CRARY
ASSOCIATE A.I.E.E.

L. P. SHILDNECK
ASSOCIATE A.I.E.E.

L. A. MARCH
NONMEMBER

All of the General Electric Company, Schenectady, N. Y.

IT HAS BEEN recognized for sometime that consideration of the effect of saturation in synchronous machines is necessary to determine accurately the steady state stability characteristics of a system, and that the methods of analysis that neglect saturation lead to pessimistic results.[1,2,3,4] It is the purpose of this paper to present a method of analysis by which saturation effects may be taken into account in determining the steady state performance of a machine or system and to suggest equations for the equivalent reactances of synchronous machines in order that a rational comparison of their characteristics may be made.

Methods of analysis of system and machine steady state stability performance presented in previous papers[5,6,7,8] depend upon the linear relations existing between the currents and voltages. Saturation of the machines introduces nonlinearity. However, under steady state conditions an equivalent linear reactance may be used to represent the reactance of the machine at the particular operating condition for small changes of the initial quantities. This equivalent reactance is dependent not only upon the particular load, voltage, and power factor at which the machine is operating, but also upon the connected system. After the equivalent reactance is determined, calculations to determine the machine and system performance can be carried out in the usual manner. The following analysis shows the variation of this equivalent reactance with change in the characteristics of the system and the load on the machine. Finally, approximate formulas are developed so that a comparison of the equivalent reactances of machines can be made from the design data.

The concept of equivalent reactance is not new, as various empirical and graphical methods of adjusting the synchronous reactances of synchronous machines have been proposed. Miss Edith Clarke, in a discussion[2] in 1926, presented an empirical formula, suggested by C. A. Nickle, for the equivalent reactance of synchronous machines to be used in making stability calculations. This empirical formula is almost equivalent to the expression derived in the following analysis for the case of cylindrical-rotor or salient-pole machines when operating as synchronous condensers, but is inapplicable to the case of synchronous motors or generators operating at normal power factors. Dahl[3] and Dwight[4] also have presented methods based on charts and semiempirical methods for correcting for generator saturation. Since these empirical or semiempirical methods neglect important factors, it was thought desirable to have a more rational method available by which the equivalent reactance for a given load condition may be determined from the design data of the machine under consideration and which shows directly the factors which determine its value.

Mathematical Analysis

In the following analysis the cylindrical-rotor and salient-pole synchronous machines are considered separately, the cylindrical-rotor case first because of its comparative simplicity.

Nomenclature. All quantities are expressed in per unit on the machine normal kilovoltampere and voltage base.

$\frac{a}{b} = \frac{e_t}{k}\frac{\partial k}{\partial e_t}$ = ratio of intercept cut by tangent to load saturation curve. (Fig. 2.)

$\frac{a_1}{b_1} = \frac{e_t}{k_1}\frac{\partial k_1}{\partial e_t}$ = ratio of intercept cut by tangent to stator saturation curve

$\frac{a_2}{b_2} = \frac{e_{td}}{k_2}\frac{\partial k_2}{\partial e_{td}}$ = ratio of intercept cut by tangent to rotor load saturation curve

e_s = system voltage

$e_{(ie)}$ = voltage corresponding to equivalent field mmf

e_t = voltage corresponding to the air gap flux (behind leakage reactance)

e_{td} = direct axis component of e_t

e_{tq} = quadrature axis component of e_t

e_t = terminal voltage of machine

e_d = voltage corresponding to direct axis field mmf

$e_{d(eq)}$ = voltage corresponding to equivalent direct axis field mmf

e_q = voltage corresponding to quadrature axis field mmf

$e_{q(eq)}$ = voltage corresponding to equivalent quadrature axis field mmf

i = armature current

i_d = direct axis armature current

i_q = quadrature axis armature current

$k = 1 + \frac{\text{iron mmf}}{\text{air gap mmf}}$

$k_1 = 1 + \frac{\text{iron mmf in the stator}}{\text{air gap mmf}}$

$k_2 = 1 + \frac{\text{iron mmf in the rotor}}{\text{air gap mmf}}$

r_a = machine armature resistance

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. winter convention, New York, Jan. 23–26, 1934. Manuscript submitted Oct. 20, 1933; released for publication Nov. 29, 1933. *Not published in pamphlet form.*

1. For references see end of paper.

r_a = external resistance
x_a = external reactance
x_{eq} = equivalent reactance
x_l = leakage reactance
x_d = direct axis synchronous reactance
$x_{d(eq)}$ = equivalent direct axis synchronous reactance
x_q = quadrature axis synchronous reactance
$x_{q(eq)}$ = equivalent quadrature axis synchronous reactance
β = angle between e_d and e_l
θ = power factor angle of machine (angle between e_l and i).
ϕ = angle between e_l and i
δ = angle between e_d and e_a
δ_{eq} = angle between e_{eq} and e_a

Cylindrical-Rotor Synchronous Machine. The following assumptions are made for the case of the cylindrical-rotor synchronous machine.

1. The quadrature axis magnetic reluctance is equal to the direct axis reluctance, $x_d = x_q$. (For all symbols see foregoing nomenclature.)

2. The armature reaction mmf is proportional to a reactive voltage drop equal to $(x_d - x_l)i$.

3. The field current is maintained constant for the small changes being considered.

4. The vector difference of the armature reaction mmf and the mmf due to the field current is an mmf which is proportional to k times the voltage behind the leakage reactance drop. Where

$$k = 1 + \frac{\text{iron mmf}}{\text{air gap mmf}}$$

5. The iron mmf in the machine is a function only of the total air gap flux and the field current.

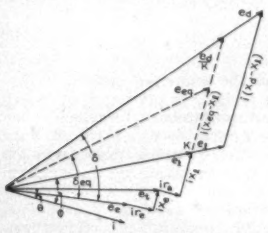


Fig. 1. Steady state vector diagram of a cylindrical-rotor synchronous generator with saturation

On the basis of these assumptions the vector diagram of Fig. 1 can be drawn. From the vector diagram the following equation can be written for the field excitation,

$$e_d = \sqrt{(ke_l)^2 + i^2(x_d - x_l)^2 + 2ke_l i(x_d - x_l)\sin\phi} \tag{1}$$

e_l, i, ϕ are variables and k is a function of the total air gap flux, e_l, and the field excitation, e_d. However, since only steady state conditions with constant field current are considered in this analysis, k is a function of only one variable, the total air gap flux e_l.

Therefore, for small changes eq 1 yields

$$\begin{aligned} 2e_d de_d = {} & [ke_l + i(x_d - x_l)\sin\phi]\left[k + e_l\frac{\partial k}{\partial e_l}\right]de_l \\ & + [i(x_d - x_l)^2 + ke_l(x_d - x_l)\sin\phi]\,di \\ & + [ke_l i(x_d - x_l)\cos\phi]\,d\phi \end{aligned} \tag{2}$$

Letting $de_d = 0$ in accordance with assumption 3 and substituting eq A-6 from Appendix A in eq 2 for $\frac{\partial k}{\partial e_l}$.

$$\begin{aligned} 0 = {} & [ke_l + i(x_d - x_l)\sin\phi]\left[1 + \frac{a}{b}\right]kde_l \\ & + [i(x_d - x_l)^2 + ke_l(x_d - x_l)\sin\phi]\,di \\ & + [ke_l i(x_d - x_l)\cos\phi]\,d\phi \end{aligned} \tag{3}$$

Where $\frac{a}{b}$ is a ratio obtained by drawing a tangent to the constant field current saturation curve at e_l. (See Fig. 2.)

Equation 3 is the differential equation governing the operating characteristics of a saturated cylindrical-rotor machine for small and gradual changes in the load conditions, with constant field excitation e_d.

If in eq. 3, $k = 1$, $\frac{a}{b} = 0$, the conditions for no saturation, and $x_d = x_{eq}$, eq 4 is obtained for an equivalent unsaturated machine.

$$\begin{aligned} 0 = {} & [e_l + i(x_{eq} - x_l)\sin\phi]\,de_l \\ & + [i(x_{eq} - x_l)^2 + e_l(x_{eq} - x_l)\sin\phi]\,di \\ & + [e_l i(x_{eq} - x_l)\cos\phi]\,d\phi \end{aligned} \tag{4}$$

Equation 4 is the differential equation governing the operating characteristics of an equivalent unsaturated machine for small and gradual changes away from the operating point, holding a constant value of field excitation, e_{eq}.

This equivalent unsaturated machine is one which has no saturation, but has the same operating characteristics as the actual saturated machine at the operating point under consideration. Such a machine responds to small changes in the load conditions just as the saturated one does: thus it can be used to replace the actual saturated machine at the particular operating conditions. The values of e_l, i, and θ are identical for both machines, but the values of reactance x_{eq} and excitation e_{eq} for the equivalent unsaturated machine generally are less than the corresponding values x_d and e_d for the actual saturated machine. (See Fig. 1.) The equivalent reactance x_{eq} is the synchronous reactance of the equivalent unsaturated machine and can be used in the usual linear equations for determining the characteristics of the saturated machine. The equivalent reactance obviously is different for each operating point of the actual or saturated machine.

The equivalent reactance x_{eq} must, therefore, be such as to satisfy the simultaneous differential eqs 3 and 4. However, eqs 3 and 4 alone cannot be solved simultaneously to obtain x_{eq} but another independent relation between de_l, di, and $d\phi$ must be obtained. For example, if the system to which the machine under consideration is connected is such that $\phi = 90°$ and $d\phi = 0$, or $\phi = 0$ and $di = 0$,

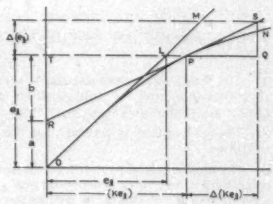


Fig. 2. Method of obtaining a/b. Load saturation curve for a cylindrical - rotor synchronous generator at constant field excitation E_d

$$x_{eq} = x_l + \frac{x_d - x_l}{k\left[1 + \frac{a}{b}\right]} \tag{5}$$

or when $\phi = 0$ and $d\phi = 0$

$$x_{eq} = x_l + \frac{x_d - x_l}{k\sqrt{1 + \frac{a}{b}}} \tag{6}$$

or if $de_l = 0$

$$x_{eq} = x_l + \frac{x_d - x_l}{k} \tag{7}$$

The condition that $\phi = 90°$ and $d\phi = 0$ is realized by a synchronous condenser. Therefore, the equivalent reactance of a cylindrical-rotor synchronous condenser is given by eq 5 and is independent of the connected system. The condition that $de_l = 0$, eq 7, is most closely realized by a machine having a small value of x_l and connected directly to an infinite bus. Equation 6 is an intermediate or average value for x_{eq}, and may be used for the approximate determination of x_{eq} for cylindrical-rotor machines, with the exception of condensers, operating over a normal power factor range and connected to a system.

If a more accurate determination of x_{eq} is required than can be obtained by the approximate formulas, eqs 3 and 4 may be solved simultaneously with another relation depending upon the connected system similar to eq B-4 presented in Appendix B. It is suggested that eq 6 be used for the determination of x_{eq} when comparing the ability of cylindrical-rotor generators or motors to remain in static equilibrium for systems whose characteristics are not definitely known.

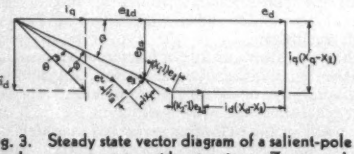


Fig. 3. Steady state vector diagram of a salient-pole synchronous generator with saturation. Zero quadrature axis field excitation

Salient-Pole Synchronous Machine. The assumptions made for the case of the salient-pole machine are:

1. The direct and quadrature axis armature reaction mmf's are proportional to reactive voltage drops equal to $i_d(x_d - x_l)$ and $i_q(x_q - x_l)$, respectively.

2. The field current is constant for the small changes under consideration.

3. The mmf required to overcome saturation can be divided into 2 components: one which is dependent only on the total flux, the other a function of the field mmf as well as the direct axis flux. The first is represented by the stator core and teeth, the second by the rotor pole piece. This assumption is made possible by the fact that there is very little saturation in the quadrature axis magnetic path in the rotor, i. e., in the pole tips. Most of the saturation in the rotor exists in the body of the pole, at and near the base, which is in the path of the direct axis flux. Under steady state conditions the second component of mmf may be considered as a function of the direct axis flux alone, with the total field mmf as a fixed parameter for a given load condition.

On the basis of these assumptions the vector diagram of Fig. 3 can be drawn. From the vector diagram the following relation can be written for the direct axis.

$$e_d = (k_1 + k_2 - 1)\, e_{1d} + (x_d - x_l)\, i_d \tag{8}$$

In a manner similar to that for the cylindrical-rotor case, eq 8 can be used to determine the equivalent direct axis reactance for a salient-pole synchronous condenser and an approximate expression obtained for the case of a generator or motor operating over the normal power factor range when connected to a system. These 2 expressions are derived in Appendix C and are as follows; for the salient-pole synchronous condenser,

$$x_{d(eq)} = x_l + \frac{x_d - x_l}{\left[k_1\left(1 + \frac{a_1}{b_1}\right) + k_2\left(1 + \frac{a_2}{b_2}\right) - 1\right]} \tag{9}$$

Equation 9 can be reduced to an expression identical to eq 5 for the cylindrical-rotor synchronous condenser as $k = k_1 + k_2 - 1$ and $k\,\frac{a}{b} = k_1\frac{a_1}{b_1} + k_2\frac{a_2}{b_2}$ since in this case $e_l = e_{1d}$. For the salient-pole motor or generator,

$$x_{d(eq)} \cong x_l + \frac{x_d - x_l}{\left[k_1\left(1 + \frac{a_1}{2b_1}\right) + k_2\left(1 + \frac{a_2}{b_2}\right) - 1\right]} \tag{10}$$

If there is no saturation in the stator teeth or core, all of the saturation being in the rotor pole piece in the path of the direct axis flux, eq 10 reduces to

$$x_{eq} = x_l + \frac{x_d - x_l}{k_2\left(1 + \frac{a_2}{b_2}\right)} \tag{11}$$

and is independent of the connected system.

In Appendix D a method is presented by which $x_{d(eq)}$ may be more accurately determined when the constants of the system to which the machine is connected are known. Complete expressions are given for $x_{d(eq)}$ and $x_{q(eq)}$ in terms of the external reactance and resistance x_e and r_e. For most practical purposes when the machine is connected through an appreciable amount of external impedance, $x_{q(eq)}$ may be considered equal to the unsaturated value x_q, as the synchronizing power coefficient $dP/d\delta$ is practically the same whether $x_{q(eq)}$ or x_q is used in its determination. It is suggested, however, as in the cylindrical rotor case, that when the characteristics of the system are not known eq 10 be used to obtain an approximate value of $x_{d(eq)}$ for salient-pole generators and motors.

Fig. 4. Vector diagram for an equivalent salient-pole synchronous machine

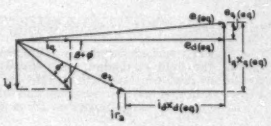


Fig. 4 shows a vector diagram of the equivalent unsaturated salient-pole machine. This machine has values of $x_{d(eq)}$ and $x_{q(eq)}$ such as to give the same response to changes at its terminals as the actual or saturated machine. Since $x_{d(eq)}$ and $x_{q(eq)}$ are

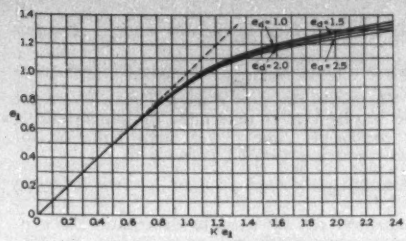


Fig. 5. With constant field excitation e_d

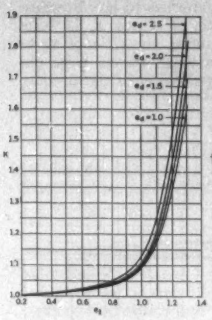


Fig. 6. Saturation factor K

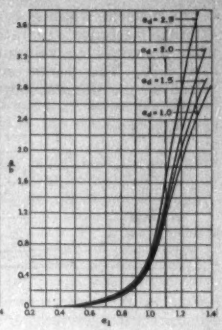


Fig. 7. Saturation factor a/b

Figs. 5, 6, and 7. Load saturation curves for cylindrical-rotor synchronous generator

different from x_d and x_q, respectively, while i, i_d, i_q, e_l, and θ are the same, $e_{d(st)}$ and $e_{q(st)}$ will be different from the e_d and e_q of the actual machine. In practically all commercial machines $e_q = 0$. Therefore, since $x_{q(st)}$ is different from x_q, and i_q is the same for both the actual and equivalent machine, the equivalent machine may have excitation $e_{q(st)}$ in the quadrature axis.

Application of Mathematical Analysis

In order to demonstrate the use of the formulas presented in the first part of this paper a numerical example will be worked out in detail for the cylindrical-rotor case.

A cylindrical-rotor synchronous generator is delivering rated kilovoltamperes at normal terminal voltage and 0.80 power factor to a system which may be represented, as far as effects at the generator terminals are concerned, by an equivalent external impedance of $0.10 + j\,0.50$ and constant voltage e_s. It is desired to determine the synchronizing power coefficient of the machine. The saturation curves for the generator for various values of e_l and e_d are shown in Fig. 5. From these curves, values of k are obtained directly as the ratio of ke_l to e_l and plotted against e_l for various values of e_d as shown in Fig. 6. From the curves in Fig. 5 tangents can be drawn, as described in Appendix A, whose intercepts on the e_l axis give the values of (a) and (b). The ratios $\frac{a}{b}$ then are plotted against e_l for various values of e_d as shown in Fig. 7. For the machine being considered, $x_d = 1.11$, $x_l = 0.11$, $r_a = 0$. From the vector diagram, Fig. 1.

$$e_l = \sqrt{(e_l \cos\theta + ir_a)^2 + (e_l \sin\theta + ix_l)^2}$$
$$= 1.07$$
$$\phi = \sin^{-1}\frac{e_l \sin\theta + ix_l}{el}$$
$$= 41.5°$$

From the curves of Fig. 5, for $e_l = 1.07$ and $e_d = 2.05$ (assumed)

$$ke_l = 1.26$$

Therefore

$$k = \frac{1.26}{1.07} = 1.18$$

Also

$$e_d = \sqrt{(ke_l)^2 + i^2(x_d - x_l)^2 + 2\,ke_l i\,(x_d - x_l)\sin\phi}$$
$$= 2.07 \text{ (checking the assumed value of 2.05)}$$

From Fig. 7, for $e_l = 1.07$ and $e_d = 2.07$, $\frac{a}{b} = 1.13$.

The quantities to be substituted in eqs 3, 4, and B-4 now are all determined and are

$x_d = 1.11$	$x_s = 0.50$	$e_l = 1.07$
$x_l = 0.11$	$k = 1.18$	$i = 1.0$
$r_a = 0.10$	$1 + \frac{a}{b} = 2.13$	$\phi = 41.5°$

Substituting these quantities in eqs 3 and B-4 there results

$$-1.839 = 4.85\frac{de_l}{di} + 0.948\frac{d\phi}{di}$$

$$0.130 = 0.591\frac{de_l}{di} - 0.418\frac{d\phi}{di}$$

Solving the above 2 equations simultaneously

$$\frac{de_l}{di} = -0.25,\ \frac{d\phi}{di} = -0.66$$

Substituting these values in eq 4

$$(x_{st} - 0.11)^2 + 0.0152\,(x_{st} - 0.11) - 0.268 = 0$$

or

$$x_{st} = 0.11 + 0.52 = 0.62$$

While eq 6 yields as an approximation

$$x_{st} = 0.11 + \frac{1.11 - 0.11}{1.18\sqrt{2.13}} = 0.69$$

Figure 8 shows the variation in x_{st} for this same turbine-generator when connected to a system through various values of external impedance $r_s + j\,x_s$. It will be noted that the system has a considerable influence on the equivalent reactance

of the machine which is connected to it. For zero external reactance, the ratio of x_{eq} to x_d is 0.75, while for very large values of x_e, the ratio of x_{eq} to x_d is 0.39. The points on these curves were obtained by the simultaneous solution of the 3 equations presented in Appendix B in a manner similar to that for the foregoing case.

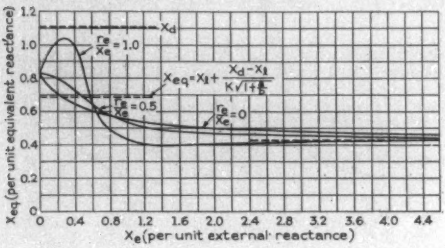


Fig. 8 (above). Equivalent reactance

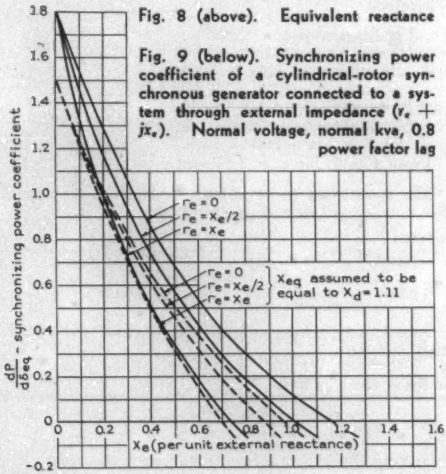


Fig. 9 (below). Synchronizing power coefficient of a cylindrical-rotor synchronous generator connected to a system through external impedance ($r_e + jx_e$). Normal voltage, normal kva, 0.8 power factor lag

The values of x_{eq} from Fig. 8 were used to calculate the values of synchronizing power coefficient,[5] $dP/d\delta_{eq}$, shown by the full lines in Fig. 9. The dotted lines show the pessimistic values of synchronizing power coefficient for the same typical large turbine generator, obtained by neglecting saturation, that is, by assuming $x_{eq} = x_d$.

In determining the synchronizing power coefficient the value of using the equivalent reactance is seen clearly. For example, the power angle equation for a saturated machine neglecting line and armature resistance is (see Fig. 1),

$$P = \frac{e_t e_s}{x_d - x_l + k\,(x_e + x_l)} \sin \delta \tag{12}$$

In this equation k is a variable and $\frac{dP}{d\delta}$ for this machine is a function of $\frac{dk}{d\delta}$, an undetermined quantity. Therefore, the power angle equation cannot be used in this form to determine the synchronizing power coefficient. The power angle equation for the equivalent unsaturated machine is

$$P = \frac{e_{eq} e_s}{x_{eq} + x_e} \sin \delta_{eq} \tag{13}$$

This equation can be used to determine the synchronizing power coefficient, as e_{eq} and x_{eq} are constants for small gradual changes from the particular load point being studied. That is,

$$\frac{dP}{d\delta} = \frac{e_{eq} e_s}{x_{eq} + x_e} \cos \delta_{eq} \tag{14}$$

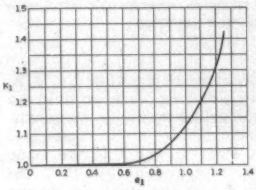


Fig. 10 (left). Saturation factors, k_1 and k_2, for large slow speed waterwheel - driven generator

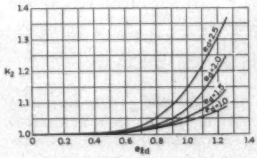
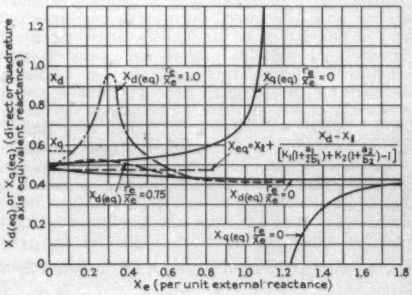


Fig. 11 (below). Equivalent reactances of this machine connected to a system through external impedance ($r_e + jx_e$). Normal voltage, normal kva, and 0.8 power factor lag



Therefore, the synchronizing power coefficient of a saturated machine can easily be written in terms of its equivalent reactance, excitation, and angle.

Fig. 10 shows the variation in k_1 and k_2 with change in e_t and e_{td}, respectively, for a large slow speed waterwheel generator. Fig. 11 shows the variation

of the direct axis equivalent reactance of this machine when connected to a system through different amounts of external impedance when the machine is operating at rated output and field excitation. As in the cylindrical-rotor machine case the variation of $x_{d(et)}$ is very large when the ratio of the external resistance to reactance approaches a value as high as unity. However, this ratio usually is considerably less than unity and the approximate equation for $x_{d(et)}$ may be used with fair accuracy in most cases.

Although $x_{q(et)}$ varies greatly it has very little effect on the synchronizing power coefficient of the machine when it is connected through a large external impedance, as is shown in Fig. 12, where the results of calculations using both $x_{d(et)}$ and $x_{q(et)}$ are compared with the results when $x_{d(et)}$ and x_q (unsaturated) are used. Fig. 12 also shows the error involved if the effect of saturation is neglected altogether when calculating the synchronizing power coefficient, $\frac{dP}{d\delta}$.

The value of the equivalent reactance cannot easily be determined by test when a machine is operated under load connected to an external system. However, a test can be made at constant power factor and field current and a check made of the value of the equivalent reactance under these conditions. For a cylindrical-rotor machine at any constant power factor angle θ (see Appendix E)

$$x_{et} = -\left(\frac{de_t}{di} + \frac{e_t}{i}\right)\frac{\sin\theta}{2} + \sqrt{\left(\frac{de_t}{di} + \frac{e_t}{i}\right)^2\left(\frac{\sin\theta}{2}\right)^2 - \frac{de_t}{di}\cdot\frac{e_t}{i}} \quad (15)$$

where $\frac{de_t}{di}$ is the rate of change of terminal voltage with armature current at constant power factor, $\cos\theta$, and constant field current, e_d. Therefore, from the coördinates and slope of the voltampere characteristic, the equivalent reactance for a cylindrical-rotor machine can be determined according to the above formula for the case of constant power factor.

For unity power factor eq 15 reduces to

$$x_{et} = \sqrt{-\frac{de_t}{di}\cdot\frac{e_t}{i}} \quad (16)$$

while for zero power factor

$$x_{et} = -\frac{de_t}{di} \quad (17)$$

The above test values of equivalent reactance for the cylindrical-rotor machine may be predetermined by calculation by means of the equations given in Appendix E.

For salient-pole machines, the zero power factor test is the only test that can be made simply to determine x_{eq}. At zero power factor

$$x_{d(et)} = -\frac{de_t}{di} \quad (18)$$

This value of equivalent reactance may be calculated by means of eq 9.

Equations 17 and 18 are identical with eq D-3 given in reference 5 for the equivalent reactance of a synchronous condenser.

Table I

Type of Machine	Voltage	Current	P.F.	x_d	Calculated Value of x_{eq}	Test Value of x_{eq}	$\frac{x_{eq}\ \text{test}}{x_d}$
Salient-Pole Water-Generator	1.0	1.0	..	0.90	0.36	0.37	0.41
Salient-Pole Condenser	1.0	1.0	..	0.92	0.71	0.70	0.36
Cylindrical-Rotor Generator	1.0	1.0	..	1.19	0.89	1.04	0.87
Cylindrical-Rotor Generator	1.0	1.0	1.0	0.74	0.57	0.63	0.85
Cylindrical-Rotor Generator	1.0	0.87	..	1.20	0.54	0.55	0.46
Cylindrical-Rotor Generator	1.0	0.66	..	1.22	0.79	0.77	0.63
Cylindrical-Rotor Generator	1.0	0.98	..	1.11	0.63	0.58	0.52
Cylindrical-Rotor Generator	1.0	1.0	..	0.77	0.45	0.40	0.52

Table I gives a comparison between the test and calculated values of the equivalent reactances for cylindrical-rotor and salient-pole machines operating at zero power factor overexcited, and at unity power factor.

Conclusions

1. Saturation of the magnetic circuit materially increases the steady state stability limits of synchronous machines. For example, for a typical relation of transmission line terminal reactances, the distance to which a given amount of power can be transmitted before the steady state stability limit is reached is about 25 per cent greater when saturation properly is allowed for, than if it is not taken into account.

2. As shown in the paper, the effects of saturation can accurately be taken into account by substituting a calculated equivalent value of reactance for the synchronous reactance. The ratio of this equivalent reactance to the synchronous reactance varies from about 0.4 for a synchronous condenser at full load and 0.6 for a generator at

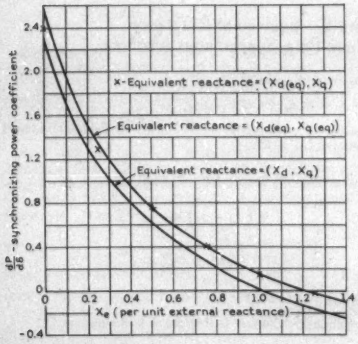


Fig. 12 (left). Synchronizing power coefficient of large slow speed water-wheel-driven generator connected to a system through external reactance. Normal voltage, normal kva, and 0.8 power factor lag

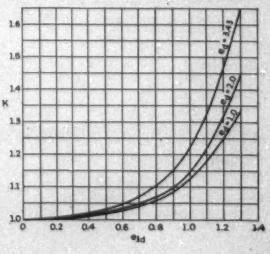


Fig. 13 (right). Saturation factor k for high speed salient-pole synchronous capacitor

full load to 0.8 or 1.0 for lightly loaded machines. A ratio of 0.8 generally has been used for motors and generators up to this time, but in the future it is planned to use the accurate values given by this theory for each particular case. For the typical relation of transmission line and terminal reactances, it is expected that this may give steady state power limits of the order of 10 per cent higher than if a factor of 0.8 had been used. Figs. 9 and 12 show the error introduced in determining the synchronizing power coefficient $\frac{dP}{d\delta}$ by neglecting saturation entirely. These machines both had a ratio of equivalent reactance to synchronous reactance of about 0.6. If a ratio of 0.8 had been used the error approximately would have been half that shown in Figs. 9 and 12.

3. The following formulas for the equivalent reactance are recommended for general use.

For either the cylindrical-rotor or salient-pole condenser,

$$x_{eq} = x_l + \frac{x_d - x_l}{k\left(1 + \frac{a}{b}\right)} \tag{19}$$

For a cylindrical-rotor motor or generator operating at ordinary motor and generator power factors,

$$x_{eq} \cong x_l + \frac{x_d - x_l}{k\sqrt{1 + \frac{a}{b}}} \tag{20}$$

For salient-pole motors and generators operating at normal power factors,

$$x_{eq} \cong x_l + \frac{x_d - x_l}{\left[k_1\left(1 + \frac{a_1}{2b_1}\right) + k_2\left(1 + \frac{a_2}{b_2}\right) - 1\right]} \tag{21}$$

In those cases where the system constants are known, a more exact determination of the equivalent reactance for motors and generators may be made by the methods described in this paper. Equation 19 for synchronous condensers is exact and independent of the connected system.

Appendix A—Determination of $\partial k/\partial e$

Figure 2 contains a saturation curve OPN showing the relation between the voltage e_l, and the mmf ke_l necessary to produce this voltage under load conditions, holding a constant value of field excitation e_d. Let P be the operating point on this load saturation curve. Then for small changes in voltage, the saturation curve may be approximated by the straight line RPS, tangent at the point P.

Then, from similar triangles PQS and PTR,

$$\frac{QS}{QP} = \frac{TR}{TP} \tag{A-1}$$

or

$$\frac{\Delta(e_l)}{\Delta(ke_l)} = \frac{b}{ke_l} \tag{A-2}$$

which gives

$$ke_l\Delta(e_l) = b\Delta(ke_l) \tag{A-3}$$

$$= bk\Delta(e_l) + be_l\Delta(k) \tag{A-4}$$

Simplifying

$$\frac{\Delta(k)}{\Delta(e_l)} = \frac{k(e_l - b)}{be_l} = \frac{ka}{e_l b} \tag{A-5}$$

Therefore

$$\frac{\partial k}{\partial e_l} = \frac{ka}{e_l b} \tag{A-6}$$

Similar expressions to eq A-6 apply for the salient-pole case, that is,

$$\frac{\partial k_1}{\partial e_l} = \frac{k_1 a_1}{e_l b_1} \tag{A-7}$$

and

$$\frac{\partial k_2}{\partial e_{ld}} = \frac{k_2 a_2}{e_{ld} b_2} \tag{A-8}$$

where

$$k_1 = 1 + \frac{\text{iron mmf in the stator}}{\text{air gap mmf}} \qquad k_2 = 1 + \frac{\text{iron mmf in the rotor}}{\text{air gap mmf}}$$

Appendix B—Determination of x_{eq} for a Cylindrical-Rotor Synchronous Machine

Equations 3 and 4 may be written as follows:

$$-\left[i(x_d - x_l)^2 + ke_l(x_d - x_l)\sin\phi\right] = \left[ke_l + i(x_d - x_l)\sin\phi\right]\left[1 + \frac{a}{b}\right]\left[k\right]\frac{de_l}{di} + \left[ke_l i(x_d - x_l)\cos\phi\right]\frac{d\phi}{di} \tag{B-1}$$

$$-\left[i(x_{eq} - x_l)^2 + e_l(x_{eq} - x_l)\sin\phi\right] = \left[e_l + i(x_{eq} - x_l)\sin\phi\right]\frac{de_l}{di} + \left[e_l i(x_{eq} - x_l)\cos\phi\right]\frac{d\phi}{di} \tag{B-2}$$

A third relation between $\frac{de_l}{di}$, $\frac{d\phi}{di}$, and x_{eq} which is dependent on the connected system is necessary in order to determine x_{eq} which may be determined with sufficient accuracy for most cases if the remaining machines of the system are considered as one equivalent synchronous machine. Any shunt impedance may be combined with the equivalent receiving system into an equivalent synchronous machine as has previously been demonstrated.[8] This results in the machine under consideration being connected directly by a series impedance $(r_a + jx_a)$ to an equivalent synchronous machine.

The expression for the voltage e_a of the equivalent system is

$$e_a = \sqrt{(e_l)^2 + i^2\left[(r_a + r_a)^2 + (x_l + x_a)^2\right] - 2ie_l\left[(x_l + x_a)\sin\phi + (r_a + r_a)\cos\phi\right]} \tag{B-3}$$

For small changes and $de_a = 0$,

$$-\left[i(r_a + r_a)^2 + i(x_l + x_a)^2 - e_l(x_l + x_a)\sin\phi - e_l(r_a + r_a)\cos\phi\right] = \left[e_l - i(x_l + x_a)\sin\phi - i(r_a + r_a)\cos\phi\right]\frac{de_l}{di} - \left[ie_l(x_l + x_a)\cos\phi - ie_l(r_a + r_a)\sin\phi\right]\frac{d\phi}{di} \tag{B-4}$$

Equations B-1, B-2, and B-4 may be solved simultaneously for any particular case in order to determine the approximate value of x_{eq}. This value of x_{eq} then can be used to determine the steady state characteristics of the machine for any particular assumed load condition.

Appendix C—Equivalent Reactance of Salient-Pole Synchronous Machine

From the vector diagram of Fig. 3,

$$e_d = (k_1 + k_2 - 1)e_{ld} + (x_d - x_l)i_d \tag{C-1}$$

k_1 is a function of e_l and k_2 is a function of $e_l d$. Therefore, for small changes equation C-1 yields,

$$de_d = \left(k_1 + k_2 - 1 + e_{ld}\frac{\partial k_2}{\partial e_l d}\right)de_{ld} + e_{ld}\frac{\partial k_1}{\partial e_l}de_l + \left(x_d - x_l\right)di_a \tag{C-2}$$

Since

$$e_{ld} = e_l\cos\beta \tag{C-3}$$

$$de_l = \sec\beta\, de_{ld} + e_l\tan\beta d\beta \tag{C-4}$$

Substituting equation C-4 and letting $de_d = 0$ in equation C-1

$$\frac{de_{1d}}{di_d} = -\frac{(x_d - x_p) + e^2_1 \sin\beta \frac{\partial k_1}{\partial e_1}\frac{d\beta}{di_d}}{\left[k_1 + k_2 - 1 + e_{1d}\frac{\partial k_2}{\partial e_{1d}} + e_1 \frac{\partial k_1}{\partial e_1}\right]} \tag{C-5}$$

Since from Appendix A

$$\frac{\partial k_1}{\partial e_1} = \frac{a_1}{b_1}\frac{k_1}{e_1} \text{ and } \frac{\partial k_2}{\partial e_{1d}} = \frac{a_2}{b_2}\frac{k_2}{e_{1d}} \tag{C-6}$$

equation C-5 becomes

$$\frac{de_{1d}}{di_d} = -\frac{(x_d - x_l) + \frac{k_1 a_1}{b_1} e_1 \sin\beta \frac{d\beta}{di_d}}{\left[k_1\left(1 + \frac{a_1}{b_1}\right) + k_2\left(1 + \frac{a_2}{b_2}\right) - 1\right]} \tag{C-7}$$

Therefore

$$x_{d(eq)} = x_l + \frac{(x_d - x_l) + \frac{k_1 a_1}{b_1} e_1 \sin\beta \frac{d\beta}{di_d}}{\left[k_1\left(1 + \frac{a_1}{b_1}\right) + k_2\left(1 + \frac{a_2}{b_2}\right) - 1\right]} \tag{C-8}$$

The second term of the numerator of eq C-8 gives the variation of the equivalent direct axis reactance with change in the connected system. However, at $\beta = 0$ or $d\beta = 0$, the conditions for a synchronous condenser,

$$x_{d(eq)} = x_l + \frac{x_d - x_l}{\left[k_1\left(1 + \frac{a_1}{b_1}\right) + k_2\left(1 + \frac{a_2}{b_2}\right) - 1\right]} \tag{C-9}$$

Equation C-9 is the equation for the equivalent direct axis reactance of a salient-pole synchronous condenser and corresponds to eq 5 derived for the cylindrical-rotor case, since

$$k = k_1 + k_2 - 1$$

and

$$k\frac{a}{b} = k_1\frac{a_1}{b_1} + k_2\frac{a_2}{b_2}$$

when $e_l = e_{1d}$.

The value of $x_{d(eq)}$ may be determined at $\beta = 90°$, also independent of the connected system by making use of the following relation.

$$e_d = e_l \cos\beta + [x_{d(eq)} - x_l]\, i_d \tag{C-10}$$

Equation C-10 for small changes and $de_d = 0$ gives,

$$e_l \sin\beta \frac{d\beta}{di_d} = [x_{d(eq)} - x_l] + \cos\beta \frac{de_l}{di_d} \tag{C-11}$$

Substituting C-11 in C-8 and solving for $x_{d(eq)}$

$$x_{d(eq)} = x_l + \frac{x_d - x_l + \frac{k_1 a_1}{b_1}\cos\beta \frac{de_l}{di_d}}{\left[k_1 + k_2\left(1 + \frac{a_2}{b_2}\right) - 1\right]} \tag{C-12}$$

Equation C-12 is an alternative expression for $x_{d(eq)}$ which for $\beta = 90°$ or $de_l = 0$ gives

$$x_{d(eq)} = x_l + \frac{x_d - x_l}{\left[k_1 + k_2\left(1 + \frac{a_2}{b_2}\right) - 1\right]} \tag{C-13}$$

Equations C-9 and C-13 indicate the range of values that are obtainable from $d\beta = 0$ to $de_l = 0$. An approximate expression for $x_{d(eq)}$ for the usual motor and generator angles and external impedance can be obtained by taking the arithmetic mean of these 2 equations. (Fig. 11.)

$$x_{d(eq)} \cong x_l + \frac{x_d - x_l}{\left[k_1\left(1 + \frac{a_1}{2b_1}\right) + k_2\left(1 + \frac{a_2}{b_2}\right) - 1\right]} \tag{C-14}$$

In Fig. 4 $e_{(eq)}$ is a voltage maintained constant in magnitude for the particular load conditions for which $x_{d(eq)}$ and $x_{q(eq)}$ were determined.

Appendix D—$x_{d(eq)}$ and $x_{q(eq)}$ for Salient-Pole Machines With External Impedance

From the vector diagram of Fig. 3 for the salient-pole machine,

$$e_d = (k_1 + k_2 - 1)\, e_{1d} + (x_d - x_l)\, i_d \tag{D-1}$$

$$e_q = -k_1 e_{1q} + (x_q - x_l)\, i_q \tag{D-2}$$

While for the external system,

$$e_{1d} - e_e \cos\delta = i_q (r_e + r_a) + i_d (x_e + x_l) \tag{D-3}$$

$$-e_{1q} + e_e \cos\delta = i_q (x_e + x_l) - i_d (r_e + r_a) \tag{D-4}$$

Also,

$$x_{d(eq)} = x_l - \frac{de_{1d}}{di_d} \tag{D-5}$$

$$x_{q(eq)} = x_l + \frac{de_{1q}}{di_q} \tag{D-6}$$

Differentiating eqs D-1, D-2, D-3, and D-4, letting de_d and $de_e = 0$ and solving for de_{1d}/di_d and de_{1q}/di_q and substituting in D-5 and D-6, the general expressions for $x_{d(eq)}$ and $x_{q(eq)}$ are obtained in terms of the external impedance $r_e + jx_e$.

$$x_{d(eq)} = x_l + \frac{\begin{array}{l} -h\,(x_d - x_l)\,[(r_a + r_e)\cos\delta - (x_l + x_e)\sin\delta] \\ +g\,(x_q - x_l)\,[(x_l + x_e)\cos\delta + (r_a + r_e)\sin\delta] \\ \quad + (x_d - x_l)\,(x_q - x_l)\sin\delta \end{array}}{(fh - g^2)\,[(x_l + x_e)\sin\delta - (r_a + r_e)\cos\delta]\,(f\sin\delta - g\cos\delta)\,(x_q - x_l)} \tag{D-7}$$

$$x^q_{(eq)} = x_l + \frac{\begin{array}{l} f\,(x_q - x_l)\,[(x_l + x_e)\cos\delta + (r_a + r_e)\sin\delta] \\ \quad + g\,(x_d - x_l)\,[(x_l + x_e)\sin\delta - (r_a + r_e)\cos\delta] \end{array}}{(fh - g^2)\,[(x_l + x_e)\cos\delta + (r_a + r_e)\sin\delta]\,(h\cos\delta - g\sin\delta)\,(x_d - x_l)} \tag{D-8}$$

Where

$$f = k_1 + k_2 - 1 + \frac{a_1}{b_1} k_1 \cos^2\beta + \frac{a_2}{b_2} k_2$$

$$g = \frac{a_1}{2b_1} k_1 \sin 2\beta$$

$$h = k_1 + \frac{a_1}{b_1} k_1 \sin^2\beta$$

Figure 11 is a plot of D-7 and D-8 for the equivalent direct and quadrature axis reactances of a salient-pole generator operating at rated kilovoltamperes and rated (0.8) power factor with varying amounts of external resistance and reactance.

Appendix E—x_{eq} for a Cylindrical-Rotor Synchronous Machine at Constant Power Factor

The differential equation, eq 3, of a saturated machine for small and gradual changes with constant field excitation may be written as follows,

$$\begin{aligned} 0 = &\left[ke_l + i\,(x_d - x_l)\sin\phi\right]\left[1 + \frac{a}{b}\right] k\frac{de_l}{di} \\ &+ [ke_l i\,(x_d - x_l)\cos\phi]\frac{d\phi}{di} \\ &+ [i\,(x_d - x_l)^2 + ke_l\,(x_d - x_l)\sin\phi] \end{aligned} \tag{E-1}$$

Using the relations,

$$e_t = \sqrt{(e_t\cos\theta)^2 + (e_t\sin\theta + ix_l)^2}$$

$$\sin\phi = \frac{e_t\sin\theta + ix_l}{e_t}$$

$$\cos\phi = \frac{e_i \cos\theta}{e_l}$$

letting $d\theta = 0$ (constant power factor) and rearranging,

$$\frac{de_i}{di} = -\frac{\left[\begin{array}{l}\frac{e_i}{i}\sin\phi\left[1 + k\left(1+\frac{a}{b}\right)\frac{x_l}{(x_d - x_l)}\right] \\ + x_l + \frac{x_d - x_l}{k} + \frac{a}{b}x_l \sin^2\phi\end{array}\right]}{\left[\begin{array}{l}\frac{e_i}{i}[\cos(\phi-\theta)]\, k\left(1+\frac{a}{b}\right)\left(\frac{1}{x_d - x_l}\right) \\ + \sin\theta + \frac{a}{b}\sin\phi\cos(\phi-\theta)\end{array}\right]} \qquad \text{(E-2)}$$

For unity power factor, eq 2E, reduces to

$$\frac{de_i}{di} = -\frac{\left[\begin{array}{l}x_l\left[1 + k\left(1+\frac{a}{b}\right)\left(\frac{x_l}{x_d - x_l}\right)\right] \\ + x_l + \frac{x_d - x_l}{k} + \frac{a}{b}x_l \frac{i^2 x_l^2}{e_l^2 + i^2 x_l^2}\end{array}\right]}{\left[\begin{array}{l}\frac{e_i}{i}k\left(1+\frac{a}{b}\right)\frac{1}{x_d - x_l} \\ + \frac{a}{b}\left(\frac{e_i i x_l}{e_l^2 + i^2 x_l^2}\right)\end{array}\right]} \qquad \text{(E-3)}$$

While for zero power factor

$$\frac{de_i}{di} = -\left[\frac{x_d - x_l}{k\left(1+\frac{a}{b}\right)}\right] \qquad \text{(E-4)}$$

Substituting $k = 1$, $\frac{a}{b} = 0$ and $xd = x_{eq}$ in eq E-2, the following expression is obtained for the equivalent unsaturated machine at constant power factor,

$$\frac{de_i}{di} = -\frac{x_{eq}\left(\frac{e_i}{i}\sin\theta + x_{eq}\right)}{\left(\frac{e_i}{i} + x_{eq}\sin\theta\right)} \qquad \text{(E-5)}$$

or

$$x_{eq} = -\left(\frac{de_i}{di} + \frac{e_i}{i}\right)\frac{\sin e\,\theta}{2} + \sqrt{\left(\frac{de_i}{di} + \frac{e_i}{i}\right)^2\left(\frac{\sin\theta}{2}\right)^2 - \frac{de_i}{di}\cdot\frac{e_i}{i}} \qquad \text{(E-6)}$$

References

1. Discussion by R. E. Doherty. A.I.E.E. Trans., v. 43, 1924, p. 83.
2. Discussion by Edith Clarke. A.I.E.E. Trans., v. 45, 1926, p. 93.
3. Electric Circuits, Theory and Applications, v. I, O. G. C. Dahl, McGraw-Hill Book Company, Inc., First Edition, 1928, Chapt. XII.
4. Adjusted Synchronous Reactance and Its Relation to Stability, H. B. Dwight. *Gen. Elec. Rev.*, Dec. 1932, p. 609.
5. Power Limits of Synchronous Machines, Edith Clarke and R. G. Lorraine. *Elec. Engg.*, v. 52, Nov. 1933, p. 780–7.
6. Steady State Stability Characteristics of Composite Systems. S. B. Crary. *Elec. Engg.*, v. 52, Nov. 1933, p. 787–92.
7. Steady State Stability in Transmission Systems, Edith Clarke. A.I.E.E. Trans., v. 45, 1926, p. 22–41.
8. Static Stability Limits and the Intermediate Condenser Station, C. F. Wagner and R. D. Evans. A.I.E.E. Trans., v. 47, 1928, p. 94–120.

Rocking Indirect Arc Electric Furnaces

By
E. L. CROSBY
MEMBER, Am. Electrochemical Soc.

President, Detroit Electric Furnace Co., Detroit, Mich.

The electric furnace of the rocking type with indirect arc has been developed to the point where it may be used not only for the melting of nonferrous metals but also in the production of castings of various types of iron and steel. Accurate control of the process is possible. Many new cast irons may thus be produced with qualities greatly superior to the cast iron which may be produced by any other means.

DURING the past 25 years the electric melting furnace has developed from the position of a very interesting experimental apparatus to that of a precise, highly dependable, thoroughly practicable device for the melting of a wide variety of metals under prescribed conditions and producing molten metal precisely conforming with both the predetermined desired chemical analysis and correct degree of temperature.

Various methods have been employed and several types of furnaces have been developed for the purpose of utilizing electric energy as a source of heat for melting metals. It is the purpose of this paper to trace the development and describe the design, operation, and utilization of the rocking indirect arc electric furnace. This furnace, first marketed in 1918, has become widely used, first in nonferrous metal melting and later in the production of castings of gray iron, malleable iron, heat treated cast iron, and alloy iron and steel.

The furnace, which is of the single-phase 2-electrode indirect-arc type, shows excellent electrical regulation and very satisfactory power-factor conditions. The metal stirring action of this furnace, together with its deoxidizing atmosphere and accurate temperature control at elevated tempera-

Full text of a paper recommended for publication by the A.I.E.E. committee on electrochemistry and electrometallurgy, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Nov. 13, 1933; released for publication Dec. 8, 1933. *Not published in pamphlet form.*

tures, afford an excellent implement for the production of the many new varieties of cast iron, heat treated iron, and alloy iron now receiving acute interest from metallurgists and design engineers. It is similarly receiving the intense interest of central stations and electrical equipment manufacturers as a builder of a substantial volume of new business in a heretofore uncultivated field for electrification.

Design

Many varying designs of stationary indirect arc furnaces were built both in this country and abroad shortly after the beginning of the twentieth century, but the difficulties encountered with electrical, mechanical, and refractory problems apparently precluded the commercial development of any of these designs to the point of general industrial utilization.

During the World War the imperative necessity of a rapid melting medium for the production of brass and bronze castings stimulated the development of the electric furnace for such purposes and it was at that time that the rocking indirect arc electric furnace was designed and developed as a commercially adaptable machine.

This furnace is of the horizontally cylindrical type with 2 electrodes, these being inserted from opposite ends at the axis of the furnace. The furnace is lined with high temperature refractories

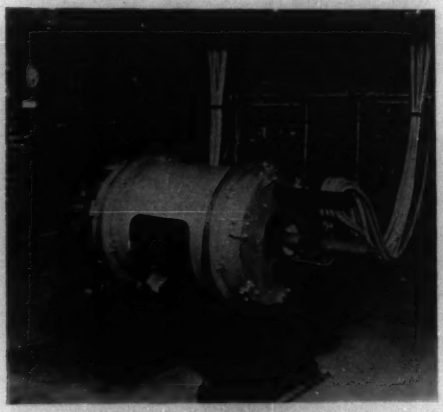


Fig. 1. A rocking indirect arc electric melting furnace. This is a 350-lb 125-kw unit with friction drive through supporting rollers

and a charging door and pouring spout are provided upon the side of the cylinder to effect easy manipulation. The furnace is carried upon a ring track which is supported by 4 rollers and the oscillating or rocking movement is imparted to the furnace cylinder either by friction drive through the rollers or, as in the larger sizes, by means of ring gears and spur gears arranged coaxially with the ring tracks and

Fig. 2. Rocking of this 3,000-lb 600-kw furnace is obtained with ring gear drive

rear rollers, respectively. The 2 types of drive are shown in the furnaces illustrated in Figs. 1 and 2.

An electric motor of requisite size is mounted upon the furnace base, this motor being controlled by a reversing switch actuated, through gears, by the furnace shell, the switch being so designed that the index or control levers upon the switch face plate correspond with the extreme positions of the pouring spout. In this way the operator may readily adjust the angle of rock or oscillation, it being only necessary to adjust the reversing switch index levers to the space or angle desired. This same switch is employed as a hand operated drum type controller while the molten metal is being poured and the switch design provides a control of the metal stream sufficiently precise to permit the accurate pouring of any amount of metal required even to the so-called "shrinking" of billets, ingots, or bars, when pouring into metallic molds.

Current is carried from suitably arranged bus bars to the water-cooled electrode clamps by means of flexible apparatus cable, this cable being covered with flame-proof insulation. The electrodes are adjustably mounted and their adjustment may be effected by either hand or automatic electrically operated control mechanism, as may be desired.

Suitable indicating meters and a special integrating kilowatthour meter are arranged for proper power input control, the rate of energy input being adjusted by controlling the distance between the 2 electrodes and thus the length of the arc. Obviously the arc is maintained at the center of the furnace and only one electrode need be adjusted during the "heat" or melting cycle, the nonoperating electrode being moved inward between heats to

compensate for its consumption, input control being effected by occasional adjustment of the opposite electrode during the heat.

A single-phase furnace transformer of special design is employed, the high voltage winding being adapted to whatever power supply service may be available and the low voltage open-circuit potential may vary between 90 and 130 volts, depending upon the furnace capacity and the metal to be melted.

Suitable voltage taps, both above and below normal, are provided in the high voltage winding, and a reactor, for arc stabilization purposes, with variable taps for changing reactance values, is built within the transformer case, being mounted above the transformer coils. The amount of reactance required varies according to the regulation of the power supply circuit and according to the metal being melted. By the latter it is meant that when melting a metal which volatilizes at a relatively low temperature, thus introducing excessive metallic vapor into the furnace atmosphere, the arc impedance is lower and the arc is less stable so that a relatively lower furnace voltage and higher reactance is necessary than when melting non-volatile metals such as iron. A typical layout plan illustrating the relative arrangement of the furnace, the transformer, and control apparatus is shown in Fig. 3.

The furnace is lined either with refractory shapes or with a monolithic rammed plastic refractory, the former usually being more satisfactory because of the technique required and difficulty often encountered in properly installing a rammed monolithic refractory material. The rapid commercial development of high temperature refractories during the past 5 years has produced a wide variety of available refractory materials, adaptable to various metallurgical operations with facility and economy previously unattainable.

Operation—
Connections and Electrical Control

It is of course desirable to install the transformer as close to the furnace as is practicable in order to avoid long low voltage conductors, and these conductors should be interlaced from the transformer terminals to a point near the furnace where they are segregated for the purpose of connecting the flexible furnace cables.

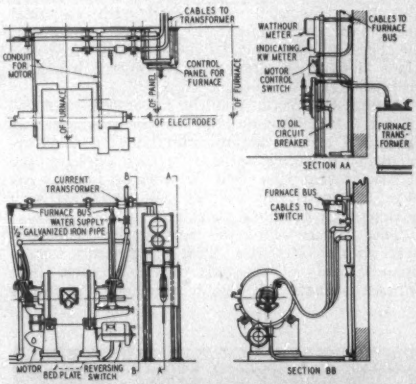


Fig. 3. Typical installation print showing relative positions of furnace, control panel, and transformer

Fig. 4. Oscillographic records of a 600-kw unit

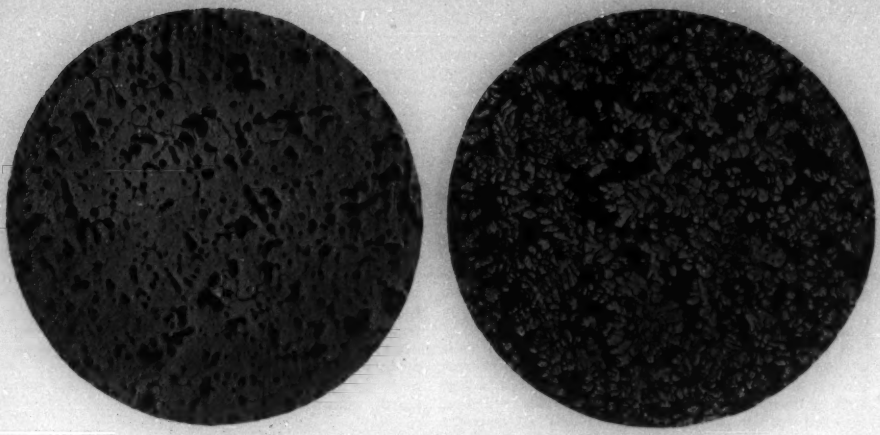


Fig. 5. Photomicrographs illustrating markedly uniform microstructure. Both etched, and magnified approximately 75 diameters

(Left). Leaded bearing liner. 78 per cent copper, 16 per cent lead
(Right). Piston packing. 60 per cent lead

The transformer voltage and reactance taps are connected for the desired energy input and arc stability. The nonoperating electrode is moved into the furnace so that its inner end projects about 2 in. beyond the center line of the furnace. The operating or controlling electrode is then moved in until contact is made and the arc established. The instantaneous rush of current occurring when striking the arc will, in a properly installed furnace, reach a value of approximately twice the transformer rated current capacity. Since the transformer is usually connected to the 20 per cent reactance tap this impedance together with that of the entire low voltage circuit, including furnace inductance and inherent arc impedance, precludes any value greater than from 2 to $2^1/_2$ times normal operating current. If it is desirable to hold the fluctuation or current surge to lower values than these, this may be very readily accomplished by inserting an additional reactor in circuit when starting a cold furnace, very simple switching equipment being provided for short-circuiting this reactor after the arc has been in operation for a few minutes.

The average power factor at the high voltage terminals of the furnace transformer, after the furnace is heated up and in regular operation, should be not less than 0.80. Many carefully installed furnaces, where close attention has been paid to arrangement of conductors, as well as to the correct adjustment of voltage and reactance taps, have shown an actual average high voltage power factor of between 0.85 and 0.90. Oscillographic records of the current and voltage on a 600-kw furnace load are shown in Fig. 4.

The electrical regulation of the indirect arc type furnace is obviously materially better than that of the direct arc type. The arc, being sustained between the 2 electrodes, does not swing or fluctuate as often or as widely as when the arc is between the electrode and the metal charge, as is the case in any direct arc furnace. In such a direct arc, the fluctuations are very frequent and very broad, either during the melting period when the arc is playing upon the rapidly varying contour of the cold scrap charge, or later when the arc is very short and plays upon the surface of boiling metal.

In the indirect arc furnace neither the physical character of the charge nor the condition of the bath has any effect upon the arc regulation, and for these reasons this type of furnace offers a much simpler problem to the electrical engineer, as well as to the furnace user, whose operating problems are sufficiently difficult without the added complications of an unnecessarily intricate electrical mechanism.

Due to the rapid metallurgical development in the iron and steel industry, the wide adoption of alloyed materials and the wide diversity of analyses resulting from this practice, the present tendency both here and abroad is toward a greater number of relatively smaller furnaces instead of toward the concentration of operation in a single unit. This movement effects a higher diversity factor and improved load factor, and consequently an improved operating efficiency with lower power costs. The indirect arc type furnace, because of its relatively simple design and construction, its flexibility and ease of operation, and its effective metallurgical performance lends itself admirably to the modern trend of the metal industry.

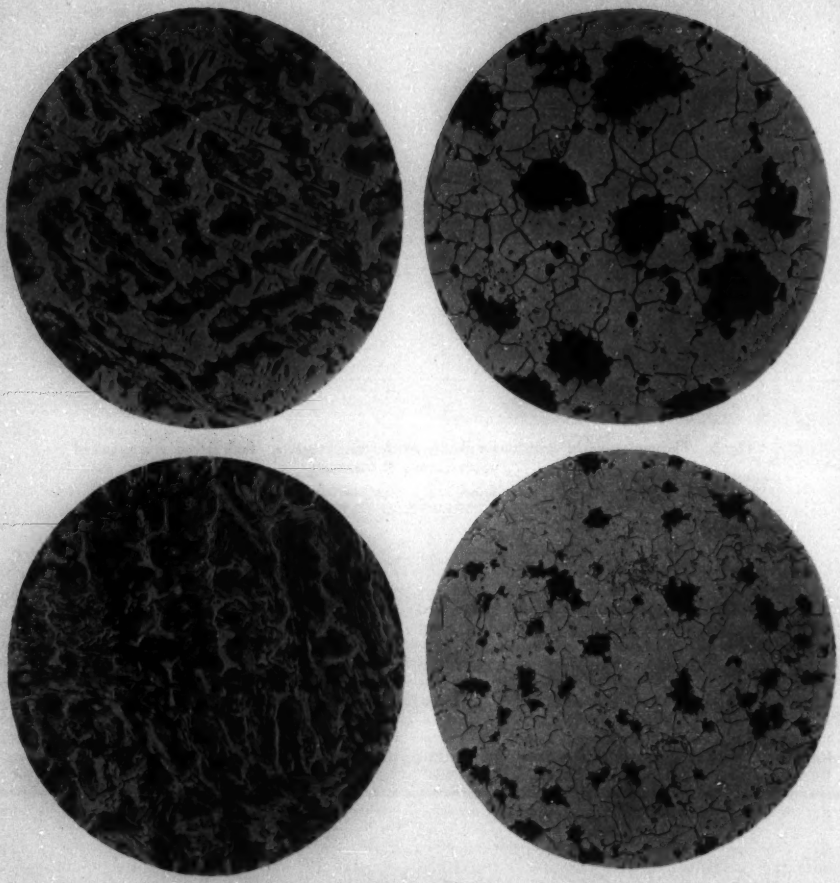


Fig. 6. Photomicrographs showing structures of air furnace iron (above) compared with iron produced in the rocking indirect arc electric melting furnace (below). All 4 photomicrographs etched, and magnified approximately 125 diameters

(Left, above). Air furnace white iron. 2.5 per cent carbon
(Right, above). The same iron annealed; approximately 140-hr cycle. Tensile strength 55,000 lb per square inch
(Left, below). White iron produced in rocking indirect arc electric melting furnace. 2.5 per cent carbon
(Right, below). Same iron annealed; 20-hr cycle. Tensile strength 62,000 lb per square inch

Deoxidizing Atmosphere

The indirect arc furnace inherently possesses a deoxidizing atmosphere, due to the prevalence of carbon monoxide gas liberated through the reaction of the incandescent electrodes and the arc itself. Such an atmosphere precludes the metallic losses ordinarily encountered in other types of melting furnaces. When melting charges containing expensive alloying elements such as chromium, nickel, vanadium, these losses in other furnaces often amount to a cost higher than the entire actual furnace melting or conversion cost. In the melting of nonferrous alloys, such as brass or bronze, the indirect arc furnace ordinarily shows a net metallic loss in the actual melting operation of only 10 to 25 per cent of the losses involved in the operation of the fuel fired furnaces which they have supplanted.

This saving of metals as well as of operating cost is of vital importance to industry and to society.

Where an oxidizing or other controlled atmospheric condition is desired, air or other gases may be very readily and easily introduced into this type of furnace under precise control, and this feature of this type of furnace has been found valuable to many users.

Temperature Control

The energy input to this furnace is integrated by an especially designed meter equipped with a 4-in. dial, so calibrated that the power used may be read to within 1 or 2 kilowatthours. The quantity of metal in the furnace being known, the rate of power input being uniform over any predetermined time, and the radiation loss being constant, molten metal temperature determinations by this method are very apt to be much more accurate than those made with ordinary precaution by any other than an experienced operator using the ordinary forms of pyrometric instruments.

In fact, many concerns requiring precision temperature control find that a charted calculation of kilowatthours input into a charge in a given period of time affords the most satisfactory form of temperature control, a pyrometer being only occasionally used for checking purposes.

Rocking Action

In the type of furnace described in this paper, undoubtedly the most outstanding characteristic is its rocking action. The principal design function of this action is to effect homogeneity of the constituents of the charge. Fifteen years of commercial usage have proved the effectiveness of this type of furnace in this respect to beyond any point of argument. In Fig. 5 is illustrated a high lead bearing mixture with which considerable segregation difficulty is ordinarily experienced. The markedly uniform microstructure will be noted.

When the charge is first placed in the furnace and the arc is established, the furnace is started rocking through an angle of about 15 deg. As melting progresses this angle is successively increased until, when the charge is completely molten, the charging door moves from metal level to metal level upon the opposite sides, or through an angle of approximately 200 deg. This full rocking action, which occurs at the rate of 2 cycles per minute, is maintained during the superheating period and is directly responsible for several highly beneficial effects.

This movement produces a thoroughly mixed homogeneous molten bath. It facilitates complete degasification of the metal and insures freedom from occluded slag particles. In melting iron this rocking action at the elevated metal temperatures employed, expedites the solution of carbon and the breaking down of carbides. It effects a diffusion of nucleuses throughout the metal as poured which affords a brief path of graphite migration when this element is precipitated either as the casting cools or in any subsequent heat treating process. In Fig. 6 is illustrated a comparison of air furnace iron and rocking electric furnace iron of identical chemical characteristics. The improvement in microstructure and physical characteristics shown is obviously the result of the rocking action at high temperature.

The automatically controlled rocking action permits the use of charges containing 100 per cent borings and turnings which, while they consist of excellent metallurgical quality, are nevertheless the cheapest form of metal on the market, being almost unsalable in many localities. These materials are thoroughly adaptable to the production of the highest types of castings when melted in this type of electric furnace. Several castings of various usage made from charges consisting entirely of borings are illustrated in Fig. 7. This is an economic advantage distinctly peculiar to this type of furnace.

This rocking action increases the melting speed since the charge is heated not only by direct and reflected radiation, but by conduction as well, the metal picking up from the refractory walls the excess heat absorbed by the refractory while it is exposed to the arc. It will be recognized immediately that this reaction must effect improved thermal efficiency since it involves the transmission of refractory heat to the metal charge instead of through the refractory to be lost to the surrounding atmosphere. This insures lower power consumption.

By this means, also, the refractory lining is kept within a relatively narrow range of temperature rise above that of the metal, and because of this lower

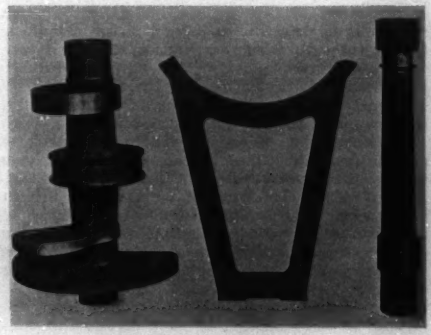


Fig. 7. Castings made from electric furnace charge consisting entirely of borings

temperature is subject to less punishment by fusion or erosion than it would be if its temperature were intensely increased by more continuous exposure to radiation from the electric arc, as would be the case in a stationary furnace. The effectiveness of this function is evidenced in the relatively low refractory cost in this furnace when compared with others doing similar work.

Contingent upon this excellent refractory per-

formance is another important matter. The freedom from excessive refractory temperatures and consequent fusion of linings is partially responsible for the remarkable control of analysis obtained when melting in this furnace. In other types of furnaces uncontrollable silicon or other chemical pick-up is regularly experienced due to the fusion of linings which introduces undesirable reaction in the metal bath. The advantage of this type of furnace in avoiding such contamination is of great commercial importance.

Since the electrode consumption of the electric arc furnace is a function of the energy consumed, granting ordinarily good mechanical structure, it also becomes apparent that the furnace which uses a lower amount of power in melting should consume a correspondingly less amount of electrodes.

Utilization

It then seems evident that the indirect arc rocking electric furnace should be an attractive melting medium in the ferrous and nonferrous fields from the standpoints of economy of operation, simplicity in performance, ease in manipulation, assurance of desired control, and quality of product. Let us for a moment study its field of use and the attendant results.

Hundreds of these furnaces are in use in this country and abroad in brass and bronze foundries of every variety. In the melting of such alloys the homogeneity and temperature control afforded by this type of furnace are of extreme importance, and the furnace has been found very effective in the elimination of segregation and of most of the troubles in foundry practice due to irregularities in pouring temperature. In bearing metals of high lead content, the stirring action of this type of furnace is of unusual value, and because of this the furnace has been the means of solution of many critical manufacturing problems in several plants.

In the melting of the various bronze mixtures used in plumbing fittings, pressure goods, and steam fittings, the close control of analysis and the assurance of dense, close grained metal is of utmost importance. The rocking action of this type of furnace, together with its freedom from oxidization and excessive local high temperatures in the molten metal, facilitates the production of a very superior casting with excellent economy.

In the production of alloy steel castings, and especially in the remelting of alloy steel scrap containing chromium, nickel, and other expensive alloys, the precise analytical control, the accurate control of temperature, and the complete recovery of alloy materials experienced in the use of the rocking indirect arc electric furnace, prove to be of extreme value to the many concerns employing them for this purpose.

Perhaps the most important application of this furnace is in its most recent adaptation to the iron foundry. During the past 3 years over 90 of these furnaces have been put to work in foundries producing gray iron castings, various types of malleable and heat treated iron, and alloy iron.

Only 5 years ago the use of cast iron in such form as an automotive crankshaft or camshaft would have been considered preposterous. Today thousands of automobiles are in service in which such shafts are made of cast iron, and the entire automotive industry is intensively studying the engineering and economic feasibility of the substitution of properly designed cast iron for scores of parts which heretofore have been produced as steel forgings or steel castings.

In the railway industry, the electrical industry, the production of automatic machinery, and scores of other important trades the many advantages of a precisely produced cast iron have been the means of not only lowering the cost of production but of simultaneously improving the product.

Five years ago ordinary cast iron was considered as a material possessing tensile strength of from 20,000 to 25,000 lb per square inch, and utterly unfit for use in any application in which dependable engineering design was involved. Today, since the adaptation of the electric furnace to the cast iron field, tons of unalloyed, unheat-treated gray iron are being produced daily, which show 45,000 to 50,000 lb per square inch tensile strength and correspondingly improved transverse strength.

A Major Metallurgical and Mechanical Engineering Change

Many concerns are regularly producing heat-treated cast iron showing from 90,000 to 110,000 lb per square inch tensile strength, with an elongation varying between 6 per cent and 2 per cent as may be desired. Such castings show a remarkable shock and fatigue resistance and possess a modulus of elasticity often above 30 million. These startling and somewhat revolutionary characteristics are acknowledged by leading engineers to be of inestimable value to industry. It is the writer's sincere conviction that this rapidly occurring development in the cast iron industry constitutes a major metallurgical and mechanical engineering change.

The highly desirable qualities and precisely controlled characteristics of these new cast irons may be enjoyed to the utmost only when produced in the closely controlled atmosphere and high temperature of the electric furnace.

In the production of such materials the rocking indirect arc electric melting furnace holds a foremost position, and its utilization for such purposes, both in the production of metal and as a source of power load of vast potentialities, is being studied intensely by the engineering and executive authorities of the largest electrical manufacturers of the country, the public utilities, and the metal working industries in general.

It is the writer's belief that before the close of the present decade there will be installed and in use in this country electric iron melting furnaces totaling over 250,000 kw capacity and using over 500,000,000 kwhr to produce approximately 100,000 tons of cast iron annually. The present rate of installation and the character of the interest shown would indicate such an estimate to be conservative.

Protecting Machines From Line Surges

Some of the more important technical problems involved in connecting rotating machines directly to overhead electric power transmission lines are discussed in this paper. Methods are developed for protecting the ground and turn insulations of the armatures of such machines which may be subjected to surge voltages. The ground insulation can be protected by lightning arresters; the turn insulation, by sloping off the incoming surge. Methods are given for determining the maximum allowable rate of rise of voltage at the machine terminals, and the apparatus needed to limit the rate of rise to that value.

By
J. F. CALVERT
ASSOCIATE A.I.E.E.

Westinghouse Electric and Mfg. Co., E. Pittsburgh, Pa.

IN connecting rotating machines directly to overhead electric power transmission lines, the possibility of surge voltages reaching the armatures of the machines introduces a serious problem. The purpose of this paper is to discuss some of the more important technical phases of that problem and to put part of the problem on a more calculable basis. The real problem has been not so much to name means of protection, but (1) to outline means that could be applied safely and economically and (2) to build up means of predetermining the protection required. In this paper, it is not intended to make *general* recommendations concerning the protection of machines of various voltages and ratings, but rather to furnish means of determining suitable protection for any *specific* machine.

Suitable methods are demonstrated for protecting the ground insulations and the turn insulations of armatures that may be subjected to surge voltages. The test waves used in this investigation were $1^1/_2 \times 40$, $^1/_2 \times 5$, and 10×20 μsec. For multiturn coil armature windings, a method is given by which the maximum allowable rate of rise of voltage at the machine terminals may be calculated in terms of the design constants of the winding; in the development of this method of calculation, electromagnetic and electrostatic coupling between turns has been considered. A method also is developed for determining the apparatus necessary to limit the rate of rise of terminal voltage to the desired value. Calculated surge impedance data based on 3 different methods of measurement are given for a 25,000-kva synchronous condenser armature winding.

From the results of this investigation the following conclusions may be reached:

1. The crest voltages of surges that may reach the machine armatures should be limited by lightning arresters at least to the crest value of the 60-cycle test voltage.[8,12]

2. On machines with the same ground insulation throughout, the ground insulation can be protected by lightning arresters regardless of the wave steepness and length for any of the usual winding connections.

3. A machine with graded insulation should be Y-connected and have a grounded neutral (preferably solidly grounded). It can be protected, so far as the ground insulation is concerned, by the proper application of lightning arresters.

4. The turn insulation can be protected by sloping off the incoming wave. The necessary value to which the rate of rise of terminal voltage must be limited can be calculated as outlined in Appendix I. The approximate rate of rise of voltage obtained when certain protective apparatus is used can be calculated as outlined in Appendix II.

5. The surge impedances of the machine when connected in various ways was determined by 3 separate methods of measurement. (See Appendix III.) Substantially the same values were found by 2 of these methods of measurement, and the third gave values of the same order of magnitude. However, these values are all much less in magnitude than those published by other authors for certain other machines. Consequently, it is believed too early to generalize concerning the surge impedances of rotating machines.

6. In all the surge studies on the synchronous condenser used in these tests, the influence of saturation was found to have a small, though measurable, effect. The electromagnetic and electrostatic coupling between phases of this machine, which is of normal design, did not produce important effects. Rotor position did not have an important influence on stator surge voltage distribution. When the rotor was completely removed from the stator, substantially the same voltage distributions in the armature windings were noted during surge tests as before the rotor was removed; but a pronounced difference in the impedance functions for various armature winding connections was observed.

How Surges Penetrate Armature Windings

There are 2 main armature insulations to be protected, the insulation to ground and the insulation

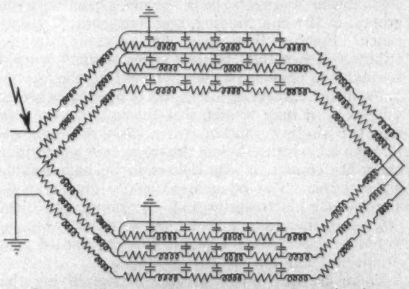


Fig. 1. Network representing approximately the circuit of a multiturn coil armature winding

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication, Nov. 17, 1933. *Not published in pamphlet form.*

8. See bibliography for all numbered references.

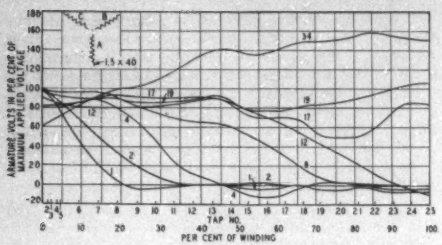


Fig. 2 (above). Y-connected, ungrounded neutral, unprotected

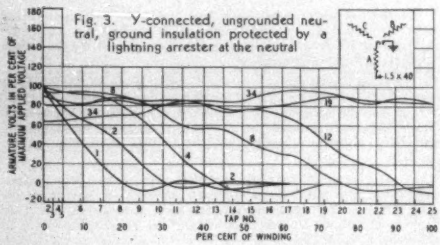


Fig. 3. Y-connected, ungrounded neutral, ground insulation protected by a lightning arrester at the neutral

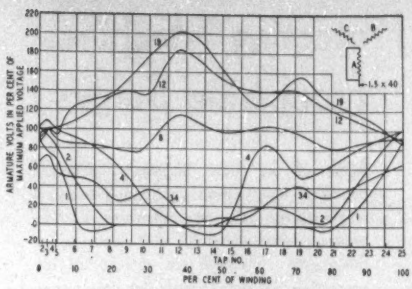


Fig. 4. Δ-connected, unprotected

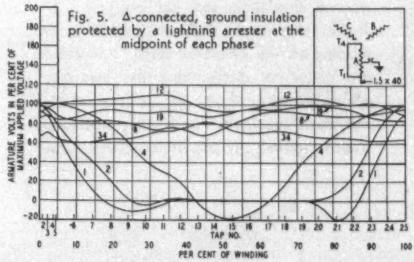


Fig. 5. Δ-connected, ground insulation protected by a lightning arrester at the midpoint of each phase

Figs. 2 to 10, inclusive. Results of surge voltage tests on a 25,000-kva synchronous condenser. The small diagrams show for each set of curves the actual test connections, point of application of surge, and dimensions of wave in microseconds. Numerical designations on the curves indicate the number of microseconds after start of applied wave

between turns. Keeping these in mind, it is desirable to obtain a mental picture of a voltage wave penetrating the armature winding of a rotating machine.

A surge may be thought of as an entering wave of charges all of one sign. The voltage wave produced by these charges may be thought of as a composite of harmonics, several of which are of frequencies higher than 10,000 cycles per second. Consequently, the generator winding should be treated more nearly in its entirety as a complicated network of inductance, resistance, and capacitance than is done in ordinary 60-cycle design or short-circuit studies. A conception of the conditions can be obtained from Fig. 1. In addition to the circuit constants shown, there is capacitance between coils, some capacitance to ground in the end winding, and some mutual inductance. Further than this, the constants are distributed rather than being a series of small lumped constants as they are shown to be in the sketch.

From the foregoing discussion of the armature as a network, it may be seen that the energy must flow into the winding somewhat as a cloud of vapor entering a labyrinth. While the surge enters primarily along the copper, it also billows in by innumerable other paths. The phenomena really present a 3-dimensional electrostatic and electromagnetic field problem rather than a circuit problem, but, as such, would be unsolvable; hence it must be treated as a circuit problem of some description.

There are at least 4 schemes of simplifying the network: (1) treating the machine as one continuous line and neglecting all coupling between turns; (2) treating the machine as an appropriate group of lumped constants; (3) extending scheme 2 by allowing the number of turns to increase without limit; and (4) considering the penetration into the first coil of a multiturn coil winding by assuming it to be similar to a group of parallel lines with one line discontinuous.

Each of these methods should be used only where checks with test data indicate its reliability within the desired range of application. In general, when the machine terminal voltage is increased suddenly and held at a constant value indefinitely, a final steady state voltage distribution is found. This voltage distribution depends on the winding connections and the magnitude of the applied steady voltage. Superposed on this is a decaying oscillating voltage starting in any case so as to produce a very large voltage drop across the terminal coils. This is true regardless of the winding connections.

One question of considerable interest is whether or not the resistance of the machine winding when confronted with a sudden change of voltage is ever likely to be an important damping factor. Numer-

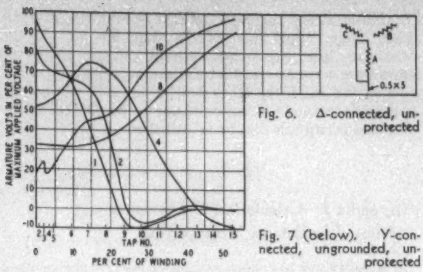
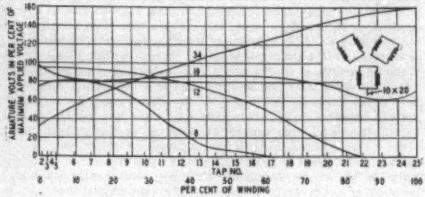


Fig. 6. Δ-connected, unprotected

Fig. 7 (below). Y-connected, ungrounded, unprotected



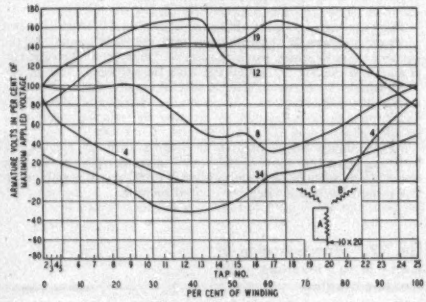


Fig. 8. Δ-connected, unprotected

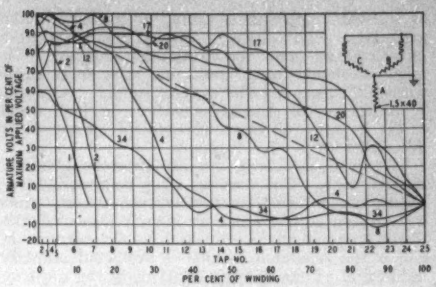


Fig. 9. Y-connected, grounded neutral, unprotected

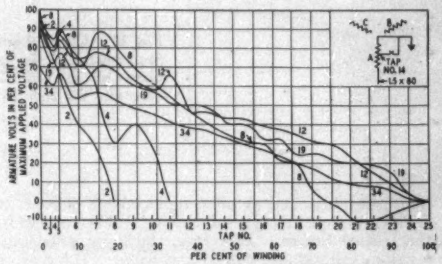


Fig. 10. Y-connected, grounded neutral, ground insulation protected by lightning arresters to permit the use of graded insulation

ous tests with surge generator and cathode ray oscillograph apparatus indicate that it will not. (See figures 2 to 10, inclusive.) From calculations using the measured impedance function (impedance *vs.* frequency) and by treating the machine as a continuous line, the same conclusion may be reached.

Since the damping action of the armature resistance cannot be counted on to prevent severe oscillations within the armature winding, other methods must be considered. In all cases, the terminal voltage must be limited at least to the crest value of the 60-cycle test voltage.[8,12] Where the terminal voltage may exceed this value, a lightning arrester at the machine terminals should be used. This is all that is required to protect the ground insulation of a normally insulated Y-connected machine with a solidly grounded neutral. (Turn insulation will be discussed later.)

Effective and economical methods for protecting the ground insulation are demonstrated in Figs. 2, 3, 4, and 5 for 3-phase machines when Y-connected with ungrounded neutral, and when Δ-connected. The applied voltage used in those cases was a $1^1/_2$ x 40-μsec wave. The numbers on each curve indicate the number of microseconds after the start of the applied wave. The data in these curves were obtained on a 25,000-kva synchronous condenser. About 1,000 cathode ray oscillograph films were taken, and these curves are simply summarized material.

It may be well to consider the effects of certain other voltages at the machine terminals, such as $^1/_2$ x 5- and 10 x 20-μsec waves. Results of tests with these waves are shown in Figs. 6, 7, and 8. If waves of both of these latter types are actual possibilities, the general necessity for protection is about the same as for the $1^1/_2$ x 40-μsec wave. Incidentally, $^1/_2$ x 5- and 10 x 20-μsec waves are of the character of those that may reach a rotating machine, even though it be connected to a transmission line through a transformer.

So far, the possibility of grading the insulation to ground has not been considered in this paper. Graded insulation may be very desirable in the design of higher voltage rotating machines, because

of the truly appreciable saving of space for active materials. The voltage to ground must be limited in accordance with the insulation strengths. The machine should be Y-connected, and it is highly desirable to ground the neutral solidly. Assuming 2 thicknesses of ground insulation on such a machine, a very effective method of protection is demonstrated in Figs. 9 and 10.

The protection of the turn insulation should be considered next. The winding using concentric turns, (one actually inside another within one slot) which was introduced in Europe for high voltage machines, should give adequate protection to the turn insulation if the ground insulation is protected properly. Because of economic considerations in the construction, assembly, and possible replacement of coils, it is unlikely that this type of winding will be favored in the United States. Therefore, the more usual rectangular coil sections will be considered. If a greater part of the energy of the incoming wave could be by-passed into the succeeding turns of the machine, adequate protection could be attained. However, there seems to be no way of accomplishing this without an undesirable complexity in the wiring connections. In previous articles[5,8,9,13] it has been shown conclusively that sloping off the incoming wave will give adequate protection to the turn insulation. General recommendations have been made.[8,13]

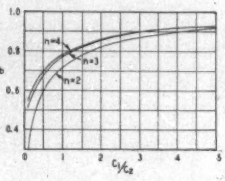


Fig. 11. Curves showing values of ξ_b in terms of C_1 and C_2 (see eqs 20 and 25)

However, for large and important machines, special consideration should be given each specific case to predetermine (1) the maximum allowable rate of rise of voltage at the machine terminals and (2) the size of the apparatus needed to limit the rate of rise to that maximum value. These 2 features are discussed in detail in Appendixes I and II, respectively, but will be described briefly now.

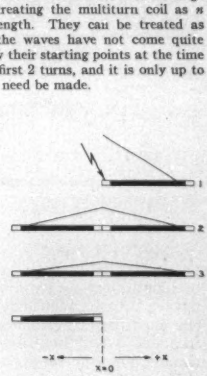
On the muliturn coil winding, the procedure outlined for determining the protection of the turn insulation is as follows: Make the calculations indicated by eq 25, with the aid of Fig. 11. Choose the appropriate factor of safety based upon the factory test voltage that has been used for the turn insulation. Determine the shortest allowable time in microseconds for the surge to reach crest value, on the assumption of a straight line voltage rise, and from this determine the maximum rate of rise of terminal voltage. Then the apparatus required to limit the rate of rise to this maximum value can be calculated according to Appendix II. If this is to be done according to the scheme in which the condenser is fed through 2,000 ft of line, the approximate surge impedance of the machine and of the overhead line must be known. Then, using the maximum rate of rise of terminal voltage just found and curves made up from eqs 35, 36, 37, and 38, the appropriate value of capacitance to be placed at the machine terminals can be established.

Appendix I—Calculation of Maximum Allowable Rate of Voltage Rise

It is desired now to develop some means of estimating the maximum voltage between turns of the first coil in a multiturn coil armature winding when a voltage having a given rate of rise is applied at the machine terminals. Tests show this maximum to occur during the first 1 or 2 μsec after the voltage is applied if the rate of rise at the terminals is steep. When the rate of rise at the machine terminals is not steep, the maximum voltage between turns may occur later, but does not seem to be of sufficient magnitude to warrant study at this time. In the former case, the maximum voltage between turns occurs when the wave has had about time to travel around one turn of the winding and come back under itself. This is based upon an assumed velocity of the main wave in the first turn equal to the average velocity of the main part of the wave in the entire machine. However, this maximum voltage between adjacent turns is considerably less than the voltage to ground on the terminal lead at this same instant. This shows an appreciable induced voltage in the other turns of the first coil while the main incoming wave is in the first turn of the first coil.

The turns may be represented as shown in Fig. 12, where the open conductors represent the end turns and the solid conductors the parts of the coils which are in the slots. The point at the right end of turn 1 in the Fig. 12 is identical with the left end of turn 2, etc. The problem is similar to that of several parallel lines. It will be shown that a satisfactory solution can be obtained for the voltage distribution in the first coil by treating the multiturn coil as n parallel no-loss lines of infinite length. They can be treated as being of infinite length because the waves have not come quite back to a point just above or below their starting points at the time of maximum voltage between the first 2 turns, and it is only up to this instant for which calculations need be made.

Fig. 12. Representation of turns in a multiturn coil armature winding



The problem of n parallel lines with one line discontinuous will be considered next. The surge will be assumed to originate at the point of discontinuity on line 1, at which point $x = 0$. The form of the general equations to be used at any given value of x is

$$\begin{aligned} V_1' &= K_{11}\, q_1' + K_{12}\, q_2' + \ldots + K_{1n}\, q_n' \\ V_2' &= K_{21}\, q_1' + K_{22}\, q_2' + \ldots + K_{2n}\, q_n' \\ &\cdot \quad \cdot \quad \cdot \\ &\cdot \quad \cdot \quad \cdot \\ &\cdot \quad \cdot \quad \cdot \\ V_n' &= K_{n1}\, q_1' + K_{n2}\, q_2' + \ldots + K_{nn}\, q_n' \end{aligned} \tag{1}$$

where the V's designate voltage, the K's coefficients of potential, and the q's charges per unit length of conductor. The subscripts indicate the numbers of the lines, and the primes indicate relations existing to the right of the point where $x = 0$. Similar equations can be established to express the relations existing to the left of the point where $x = 0$; double primes will be used in those equations.

On any line m,

$$-\frac{\partial i_m'}{\partial x} = \frac{\partial q_m'}{\partial t}$$

where t indicates time in seconds. Similarly,

$$-\frac{\partial i_m''}{\partial x} = \frac{\partial q_m''}{\partial t}$$

This leads to a set of differential equations:

$$\left.\begin{aligned}
-\frac{\partial V_1'}{\partial t} &= K_{11}\frac{\partial i_1'}{\partial x} + K_{12}\frac{\partial i_2'}{\partial x} + \ldots + K_{1n}\frac{\partial i_n'}{\partial x}\\
-\frac{\partial V_2'}{\partial t} &= K_{21}\frac{\partial i_1'}{\partial x} + K_{22}\frac{\partial i_2'}{\partial x} + \ldots + K_{2n}\frac{\partial i_n'}{\partial x}\\
&\vdots\\
-\frac{\partial V_n'}{\partial t} &= K_{n1}\frac{\partial i_1'}{\partial x} + K_{n2}\frac{\partial i_2'}{\partial x} + \ldots + K_{nn}\frac{\partial i_n'}{\partial x}
\end{aligned}\right\} \quad (2)$$

where the i's designate currents. Also, a set of relations may be set up for the voltage gradients:

$$\left.\begin{aligned}
-\frac{\partial V_1'}{\partial x} &= L_1\frac{\partial i_1'}{\partial t} + M_{12}\frac{\partial i_2'}{\partial t} + \ldots + M_{1n}\frac{\partial i_n'}{\partial t}\\
-\frac{\partial V_2'}{\partial x} &= M_{21}\frac{\partial i_1'}{\partial t} + L_{22}\frac{\partial i_2'}{\partial t} + \ldots + M_{2n}\frac{\partial i_n'}{t}\\
&\vdots\\
-\frac{\partial V_n'}{\partial x} &= M_{n1}\frac{\partial i_1'}{\partial t} + M_{n2}\frac{\partial i_2'}{\partial t} + \ldots + L_{nn}\frac{\partial i_n'}{\partial t}
\end{aligned}\right\} \quad (3)$$

where the L's and M's designate self and mutual inductances, respectively.

Solutions for the voltages and currents from these equations will be of the form

$$\left.\begin{aligned}
V'_m &= A_m f(x + \nu t) + B_m g(x - \nu t)\\
i'_m &= D_m f(x + \nu t) + G_m g(x - \nu t)
\end{aligned}\right\} \quad (4)$$

where A_m, B_m, D_m, G_m, and ν are constants.

The boundary conditions to be satisfied are

$$\left.\begin{aligned}
&q_1' \neq 0, \quad q_1'' = 0 = i_1''\\
&\text{Also, when } m \neq 1, \text{ then for } x = 0\\
&V'_m = V''_m \quad i_m' = i_m'' \quad i_m' = \nu q_m'\\
&\qquad\qquad\quad i_m'' = -\nu q_m'' \quad q_m'' = -q_m''
\end{aligned}\right\} \quad (5)$$

From eq 1 it may be noted that

$$\left.\begin{aligned}
V_1' &= K_{11}\, q_1' + K_{12}\, q_2' + \ldots + K_{2m}\, q_m' + \ldots + K_{2n}\, q_n'\\
V_2'' &= \qquad\qquad K_{22}\, q_2'' + \ldots + K_{2m}\, q_m'' + \ldots + K_{2n}\, q_n''\\
&\vdots\\
V_n' &= K_{n1}\, q_1' + K_{n2}\, q_2' + \ldots + K_{nm}\, q_m' + \ldots + K_{nn}\, q_n'\\
V_n'' &= \qquad\qquad + K_{n2}\, q_2'' + \ldots + K_{nm}\, q_m'' + \ldots + K_{nn}\, q_n''
\end{aligned}\right\} \quad (6)$$

It may be observed that the boundary conditions are satisfied if $q_m'' = -q_m'$ and $V_m'' = V_m'$ not only for $x = 0$, but also for all symmetrical values of x; it will be assumed now that this is true, and also that the final solutions for current and voltage must be unique. It remains to be shown that, on the basis of these assumptions, solutions can be found of the form shown in eq 4. All the constants in the final solution will be determined because the boundary conditions have been satisfied by the assumptions just made.

Equations 6 occur in pairs (except for $m = 1$); consequently, $(n - 1)$ simultaneous algebraic equations in the q's can be formed and all values of q_m' or q_m'' found in terms of q_1'. Thus,

$$q_2' = \rho_2\, q_1', \quad q_m' = \rho_m\, q_1' \quad \text{etc.} \quad (7)$$

where

$$\rho m = \frac{\begin{vmatrix}
K_{22} \ldots K_2 (m-1) \frac{K_{12}}{2} K_2 (m+1) \ldots K_{2n}\\
K_{32} \ldots K_3 (m-1) \frac{K_{13}}{2} K_3 (m+1) \ldots K_{3n}\\
\vdots \qquad \vdots \qquad \vdots \qquad \vdots\\
K_{n2} \ldots K_n (m-1) \frac{K_{1n}}{2} K_n (m+1) \ldots K_{nn}
\end{vmatrix}}{\begin{vmatrix}
K_{22} & K_{23} \ldots K_{2n}\\
K_{32} & K_{33} \ldots K_{3n}\\
\vdots & \vdots\\
K_{n2} & K_{n3} \ldots K_{nn}
\end{vmatrix}} \quad (8)$$

Then,

$$\left.\begin{aligned}
&V_1' = (K_{11} + \rho_2 K_{12} + \rho_3 K_{13} + \ldots + \rho_n K_{1n})q_1' = \sigma_1\, q_1'\\
&\text{where}\\
&\sigma_1 = (K_{11} + \rho_2 K_{12} + \ldots + \rho_n K_{1n})
\end{aligned}\right\} \quad (9)$$

Thus,

$$-\frac{\partial V_1'}{\partial t} = \sigma_1 \frac{\partial i_1'}{\partial x} \quad (10)$$

Similarly, since $i_m = \nu q'_m$, then

$$\left.\begin{aligned}
&-\frac{\partial V_1'}{\partial x} = \lambda_1 \frac{\partial i_1'}{\partial t}\\
&\text{where}\\
&\lambda_1 = (L_1 + \rho_2 M_{1^2} + \ldots + \rho_n M_{1n})
\end{aligned}\right\} \quad (11)$$

Then,

$$\frac{\partial^2 V_1'}{\partial t^2} = \frac{\sigma_1}{\lambda_1}\frac{\partial^2 V_1'}{\partial x^2} \quad (12)$$

From which

$$V_1' = A_1 f(x + \nu t) + B_1 g(x - \nu t), \text{ where } \nu = \sqrt{\sigma_1/\lambda_1} \quad (13)$$

$$q_1' = \frac{V_1'}{\sigma_1}; \text{ and } i_1' = \frac{\nu}{\sigma_1} V_1'; \quad V_m' = \frac{\sigma_m}{\sigma_1} V_1'; \; i_m' = \rho_m i_1' \quad (14)$$

From the foregoing, any value of current and voltage can be established, but the relations are still very clumsy for engineering use, because ρ_m, σ_m, etc., require too much time to calculate. The problem must be simplified further.

In doing this, first consider the case of n parallel lines all continuous with a surge originating on line 1 at a point $x = 0$. Then general relations and boundary conditions can be written in a manner similar to that just outlined. If it be assumed that all charges and currents are zero on lines other than that on which the surge originates, a solution may easily be found that fits all boundary conditions. The voltages on all lines are linked in a simple electrostatic field problem where charges exist only on line 1.

If the system with one line discontinuous can be expressed in terms of the case with all lines continuous and some capacitance coupling constants, the problem is simplified readily. (In passing, it may be mentioned that by superposing these 2 solutions, almost any desired boundary conditions can be satisfied.) The 2 cases that have been discussed are shown in Figs. 13B and 13A, respectively. It may be noticed that in Fig. 13B an additional line has been inserted to the left in the No. 1 position. If all lines could be assumed negligibly small, and the usual assumptions concerning

circuit constants are considered, it is seen that the presence of line 1 to the left, when not electrically joined to anything at point $x = 0$, has no effect on the electrostatic field.

Now, if the surge in Fig. 13B were applied on the left-hand part of line 1 and this superposed on Fig. 13B, all charges on lines other than No. 1 would cancel, and all voltages on lines other than No. 1 would be doubled. The charge on all parts of line 1 would be the

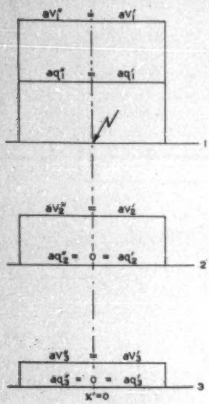


Fig. 13A

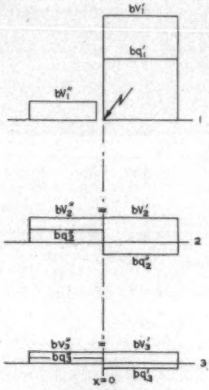


Fig. 13B

same, out as far as the waves had traveled from point $x = 0$. The voltage on lines 1, right or left, would be ${}_bV_1' + {}_bV_1''$.

The problem now is to find the relation that will give ${}_bV_1'/{}_bV_2'$ in terms of ${}_aV_1'/{}_aV_2'$ and any simple arrangement of capacitances, because from the foregoing it is apparent that ${}_aV_1'/{}_aV_n'$ is much easier to establish than ${}_bV_1'/{}_bV_n'$ by straight arithmetical calculation. This relation can be established as follows:

$$\text{Let } {}_aV_1' = {}_bV_1' + {}_bV_1''; \text{ then } {}_aV_2' = 2\,{}_bV_2' \tag{15}$$

$$\text{Let } \xi_a = \frac{{}_aV_1' - {}_aV_2'}{{}_aV_1'} = 1 - \frac{2\,{}_bV_2'}{{}_bV_1' + {}_bV_1''} \tag{16}$$

$$\text{or } -\frac{{}_bV_1'}{{}_bV_2'} - \frac{{}_bV_1''}{{}_bV_2'} = \frac{2}{\xi_a - 1} \tag{17}$$

Now, ${}_bV_1''$ can be obtained in terms of ${}_bV_2'$ as follows: By Fig. 14A, C_1 and C_2 are defined, and it can be written that

$$ {}_bV_1'' = \frac{C_2}{C_1 + C_2}\,{}_bV_2''; \quad \text{then } {}_bV_2' = {}_bV_2'' \tag{18}$$

and

$$-\frac{{}_bV_1'}{{}_bV_2'} = \frac{2}{\xi_a - 1} + \frac{1}{C_1/C_2 + 1} \tag{19}$$

and

$$\xi_b = 1 - \frac{{}_bV_2'}{{}_bV_1'} = 1 - \frac{1}{\dfrac{2}{1 - \xi_a} - \dfrac{1}{\dfrac{C_1}{C_2} + 1}} \tag{20}$$

The value of ξ_a can be expressed readily in terms of C_1/C_2 and the number of lines, n, since it simply involves the relative voltages at points connected by the chain of capacitances as shown in Fig. 14A when a charge is placed only on the first conductor (at the top of the chain). This makes it possible to plot ξ_b as a function of C_1/C_2 for various numbers of conductors n. This will be made use of later.

Numerical calculations have shown that the capacitances between the end turns are not negligible quantities. The capacitance to ground in the end windings is relatively small and the inductance is small, so the end winding probably should be considered as joining the conductor of one slot to another by a small capacitance coupling, and as furnishing lumped capacitances of considerable size between adjacent turns within each coil side. However, even this sort of an approximation results in very involved calculations. Reasonable results can be obtained by assuming the capacitance between turns in the end windings to be distributed uniformly in the slots, and by assuming the end turns to perform the duty merely of conducting links between slot conductors.

A further approximation is involved in the treatment of the slot problem, which is as follows: In reality, the electric wave is retarded greatly so that it is no longer possible to assume that the electrostatic and electromagnetic fields lie in planes strictly perpendicular to the conductor. However, the insulation thickness relative to the length of the slot is very small, and the distortional effect on the wave in going around one turn, due to the reduced velocity and changed constants, is probably small. An idea of the accuracy of this method of calculation can be obtained from Fig. 15.

It is customary to test the turn insulation before coils are assembled in the machine, by impressing a voltage E_T at high frequency across each armature coil. The voltage per turn under this condition will be equated to that experienced on a surge with a given

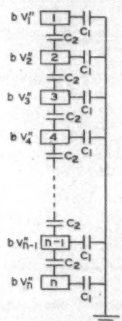


Fig. 14A

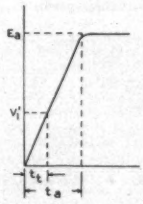


Fig. 14B

rate of rise at the machine terminals. Factors of safety can be taken on this at the discretion of the designer.

Refer to Fig. 16; then by the arrester setting,

$$E_a = \xi_b \sqrt{2}\; E_g \tag{21}$$

where E_a = arrester voltage, E_g = line-to-ground voltage of the machine, and ξ_b is a constant defined by eq 21. From Fig. 14B,

$$V_1' = \frac{t_t}{t_a} E_a, \text{ and } (\xi_b)\, V_1' = \frac{t_t}{t_a}\, \xi_b\, E_a \tag{22}$$

where t_t = time in seconds for the wave to travel around one turn; t_a = time in seconds for the wave to reach crest value E_a, on the assumption of a straight line rise in voltage. This will be equated to the crest voltage on the high frequency test as follows:

$$\frac{t_t}{t_a}\, \xi_b\, \xi_0 \sqrt{2}\; E_a = \frac{E_T}{n} \sqrt{2}\,, \text{ giving } t_a = n\, t_t\, \xi_b\, \xi_0 \frac{E_g}{E_T} \tag{23}$$

where n = number of turns per coil. Assuming the wave velocity in the slot as 10,000 miles per second, and that in the end winding as 125,000 miles per second,[8]

$$t_t = \left[\frac{2 \times lc}{12 \times 5{,}280 \times 10{,}000} + \frac{(MT) - 2\,lc}{(12 \times 5{,}280 \times 125{,}000)}\right] \tag{24}$$

where lc = core length of machine and MT = coil mean turn length, both in inches. The ξ_b is calculated as shown in eq 20 and

$$i_s = n\, i_b\, i_a \frac{E_g}{E_T} \frac{1}{63.36} \left[\frac{2\,lc}{10} + \frac{(MT) - 2\,lc}{125} \right] 10^{-4} \tag{25}$$

(Note that i_b is plotted in curve form, as shown in Fig. 11.)

Appendix II—Calculation of Protective Apparatus Required

The rate of rise of the voltage at the machine terminals may be limited by a capacitor at the terminals fed through a given length of line, as has been described in a previous article.[4] This scheme is indicated in Fig. 16. An analysis to show the approximate performance of this scheme now will be given.

The machine is to be treated as a line of surge impedance, Z_2, so far as reflections at its terminals are concerned. The incoming surge, E, from the open line will be assumed to have a steep front and long duration. The wave to the right of the arrester will have practically an infinitely steep front to arrester voltage and a flat top for several microseconds thereafter. If this wave suffered no reflections, it would remain flat topped until the voltage of the tail of the incoming wave, E, dropped below the arrester voltage, E_a. However, reflections do occur at the machine, and in turn produce other reflections at the arrester, which must be considered. This requires certain assumptions concerning the arrester performance, as follows:

1. If the arrester draws current, it will be such as to limit the arrester voltage to E_a.

2. If the arrester draws no current, the voltage, e_a, across the arrester is such that $-E_a < e_a < +E_a$.

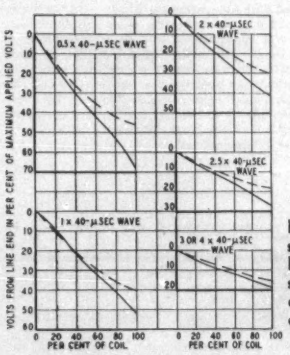


Fig. 15. Comparison between calculations and test results. Solid lines determined by tests; dotted lines by calculations

In fulfilling the first condition, voltage waves arriving at the arrester from the machine may be thought of as passing over the arrester and, simultaneously, voltage waves of equal form but opposite sign must be considered as emanating from the arrester and traveling in both directions from the arrester. The resulting current waves can be calculated readily. When condition 2 of the arrester performance is reached, it will become apparent in such a calculation. So far as conditions between the arrester and machine are concerned, and until the condition 2 for the arrester is reached, it is as though the voltage waves arriving from the machine to the arrester were completely reflected at the arrester with reversed signs. If the line surge is of a sustained large magnitude, arrester condition 1 exists long enough to permit several oscillations to occur between the machine and the arrester.

Consider then the first wave passing over the arrester. It is rectangular and flat topped; upon reaching the machine terminals, the following relations hold:

$$E_a = R_a = E_a + E_{r0} = i_2 Z_2 \tag{26}$$

where E_a = voltage across the arrester; i_2 = current entering surge impedance Z_2; E_c = the voltage across the capacitor; E_2 = voltage on Z_2 at the capacitor and E_{r0} is the reflected wave defined by eq 26.

$$i_1 = \frac{E_a - E_{r0}}{Z_1} \text{ and } i_c = c\frac{dE_2}{dt} = i_1 - i_2 \tag{27}$$

$$C\frac{dE_2}{dt} = \frac{E_a}{Z_1} - \frac{E_2}{Z_1} - \frac{E_2}{Z_2} + \frac{E_a}{Z_1} \tag{28}$$

where C = capacitance of the capacitor and Z_1 = line surge impedance. Arranging in operational form,

$$\frac{E_2}{E_a} = \frac{2}{Z_1 C}\left(\frac{1}{\frac{Z_2 + Z_1}{Z_2 Z_1 C} + p}\right)1 \tag{29}$$

where p = the differential operator $\frac{d}{dt}$, and 1 represents Heaviside's unit function. Then,

$$\frac{E_2}{E_a} = S(1 - \epsilon^{-\alpha t_1}) \tag{30}$$

where

$$S = \frac{2Z_2}{Z_2 + Z_1}, \qquad \alpha = \frac{Z_2 + Z_1}{Z_2 Z_1 C}, \qquad t_1 = t - T_1,$$

t = time in seconds after wave reaches arrester; and T_1 = time in seconds for wave to travel from arrester to machine. A part of this wave returns to the arrester, namely $[(S - 1) - S(\epsilon^{-\alpha t_1})]$ and reflects there with reverse sign. A part, $S(1 - \epsilon^{-\alpha t_1})$, enters the machine winding. The time required for the voltage wave to travel from the machine to the arrester and back, $2T_1$, is only about 4.07 μsec. The time required for a wave to reach the machine neutral and return, $2T_2$, is usually much longer on a large machine. (On the 25,000 kva synchronous condenser for which tests are

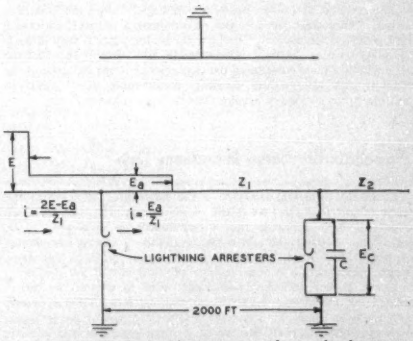


Fig. 16. Method of limiting rate of rise of voltage at machine terminals by a capacitor at the machine terminals fed through a given length of line

reported in this paper, $2T_2 \cong 38$ μsec.) Consequently, several reflections between the arrester and machine may occur before any effect from the machine neutral takes place at the machine terminals.

Hence, for $T_1 < t < 3T_1$, when $2T_2 > 2T_1$

$$\frac{E_2}{E_a} = S\,(1 - \epsilon^{-\alpha t_1}) \tag{31}$$

For $3T_1 < t < 5T_1$, when $2T_2 > 4T_1$, by the use of Heaviside's superposition theorem,

$$\frac{E_c}{E_a} = S(1 - \epsilon^{-\alpha t_1}) - (S - 1)S(1 - \epsilon^{-\alpha t_{11}})$$

$$+ \frac{d}{dt_{11}} \int^{t_{11}} S\,[1 - \epsilon^{-\alpha(t_{11} - \lambda)}] \cdot S \cdot \epsilon^{-\alpha\lambda} \cdot d\lambda \qquad (32)$$

or

$$\frac{E_c}{E_a} = S\,[1 - \epsilon^{-\alpha t_1}] - (S - 1)\,S\,[1 - \epsilon^{-\alpha t_{11}}] + \alpha\, S^2\, t_{11}\, \epsilon^{-\alpha t_{11}} \qquad (33)$$

where $t_{11} = t - 3T_1$

Similarly, E_c/E_a can be found for successive periods of time as $5T_1 < t < 7T_1$ when $2T_2 > 6T_1$, etc. These have been calculated for several periods, but require too much space to be included in this paper. Note, however, that when

$$\alpha t = 1;\quad Z_1 \geqq 250;\quad C \cong 0.10 \times 10^{-6};\quad 100 < Z_2 < 1{,}500 \qquad (34)$$

Then $t \geqq 7.14 \times 10^{-6}$, which is a far longer time than it takes for the wave to travel around one turn of any commercial machine; consequently, the values not of $\frac{E_c}{E_a}$ but of $\frac{d(E_c/E_a)}{dt}$, when the latter are largest are the things that are of greatest importance. These values of $\frac{d(E_c/E_a)}{dt}$ were determined from $\frac{E_c}{E_a}$ and are as follows:

$$\text{At } t = T_1;\ \frac{d(E_c/E_a)}{dt} = S\alpha \qquad (35)$$

$$\text{At } t = 3T_1;\ \frac{d(E_c/E_a)}{dt} = S\alpha[1 + \epsilon^{-2\alpha T_1}] \qquad (36)$$

$$\text{At } t = 5T_1;\ \frac{d(E_c/E_a)}{dt} = S\alpha[1 + (1 - 2\alpha S T_1)\, C^{-2\alpha T_1} + \epsilon^{-4\alpha T_1}] \qquad (37)$$

$$\text{At } t = 7T_1;\ \frac{d(E_c/E_a)}{dt} = S\alpha[1 + (2S^2\alpha^2 T_1^2 - 4S\alpha T_1 + 1)\, \epsilon^{-2\alpha T_1} + (1 - 4\, S\alpha T_1)\, \epsilon^{-4\alpha T_1} + \epsilon^{-6\alpha T_1}] \qquad (38)$$

The method of protection shown in Fig. 17 often has been discussed. Of course, the problem of obtaining a lumped inductance makes such a scheme one for which the performance is very difficult to predetermine without considerable test data. This scheme generally has been considered too expensive, but the writer is of the opinion that the method warrants considerably more attention, and may prove in many applications to be the most suitable.

Appendix III—Surge Impedance Data

From the foregoing analysis of the capacitance required at the terminals to limit the rate of rise of voltage on multiturn armature windings, it is apparent that surge impedance data need to be collected. Considerable data are available on surge impedances of open lines. These usually lie in the range of 250 to 600 ohms. Surge impedance is a less definite physical entity for machines; however, it is a sufficiently constant value to warrant its use in calculating conditions external to the machine. Measurements were made on the 25,000-kva synchronous condenser by two methods, each of which required the use of a surge generator and cathode ray oscillograph:

1. A surge was applied to one end of one phase, and the rise in voltage at the open-circuited opposite end was recorded. The resistance to ground at the neutral required to reduce the maximum voltage at the neutral to half that found on open circuit was determined, and this was called one measure of the surge impedance.

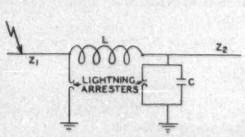


Fig. 17. Method of protection using lumped series inductance and shunt capacitance

2. The resistance equal to the surge impedance determined by the above method was left in at the neutral, and the voltage to ground and incoming current measured on surge at the machine terminal. The "surge impedance" then was determined as a function of time. Readings were taken for phase A with the rotor in and on the direct axis of phase A, and with the rotor in and on the quadrature axis of phase A (both with and without field excitation); readings also were taken with the rotor out. Waves of about 1 x 40 to 1 x 60 μsec and 10 x 40 to 10 x 60 μsec were used in each case.

These 2 test methods showed results as follows: (1) The average surge impedances measured by the different methods were of the same order of magnitude, though at some instants the second method might give values differing by 50 per cent from those determined by the first method; (2) there was no great effect of coupling between phases; (3) the surge impedance is about the same with the rotor in and on the direct axis as with the rotor in and on the quadrature axis, or with the rotor not in at all; (4) the change from 1- to 10-μsec fronts (with 40- and 60-μsec tails) on the applied surge had only a small affect on the average values of the surge impedance; (5) the values obtained on this 3-turn coil machine are much lower than those shown in certain earlier papers[8,12] on some other machines. The values obtained on the particular machine referred to in this paper were roughly as follows:

One section, phase A	365 ohms
Both sections, phase A, in parallel	190 ohms
All sections, all phases, in parallel	43 ohms

(Each phase had 2 parallels; in this tabulation, one section means one of these continuous circuits in one phase.)

The methods of measuring surge impedance by means of a surge generator and cathode ray oscillograph are somewhat cumbersome. It seems possible to obtain approximate data by the use of an oscillator and of a capacitance bridge. Suppose the machine reacts as a no-loss line. The impedance function (impedance vs. frequency) can be measured with an oscillator outfit. Its total capacitance to ground can be measured with a capacitance bridge. On the basis of these assumptions and measurements, the surge impedance can be determined. The surge impedance of both sections of phase A in parallel when found by this last method gave 145 ohms as compared with about 190 ohms found by using the data taken with the surge generator and cathode ray oscillograph. Apparently the use of the oscillator and capacitance bridge does not give accurate data, but when corrective methods are devised, it may be made to give a fairly good approximation of the surge impedance with only a small amount of work to obtain readings.

Bibliography

1. Operational Circuit Analysis (a book), V. Bush. John Wiley and Sons, New York, N. Y., 1929.

2. The Mathematical Theory of Electricity and Magnetism (a book), Sir James H. Jeans. The University Press, Cambridge, Eng., 1925.

3. Introduction to Theoretical Physics (a book), L. Page. D. Van Nostrand and Co., New York, N. Y., 1928.

4. Principles of Transmission in Telephony (a book), M. P. Weinbach The Macmillan Co., New York, N. Y., 1924.

5. Voltage Oscillations in Armature Windings Under Lightning Impulses—I, E. W. Boehne. A.I.E.E. Trans., v. 49, 1930, p. 1587–615.

6. Transient Oscillations in Mutually Coupled Windings, L. V. Bewley. A.I.E.E. Trans., v. 51, 1932, p. 299–308.

7. Traveling Waves on Transmission Circuits, L. V. Bewley. A.I.E.E. Trans., v. 50, 1931, p. 532–50.

8. Surge Protection for Rotating Machines, J. F. Calvert, A. C. Montieth, and E. Beck. *Elec. Jl.*, v. 30, 1933, p. 91.

9. Effect of Lightning Voltages on Rotating Machines and Methods of Protecting Against Them, F. D. Fielder and E. Beck. A.I.E.E. Trans., v. 49, 1930, p. 1577–86.

10. Direct Generation of Alternating Current at High Voltages, Sir Charles A. Parson, and J. Rosen. *Trans.* of the Inst. of Elec. Engrs. (British), v. 67, 1929, p. 1065.

11. Effect of Transient Voltages on Power Transformer Design—IV—Transition of Lightning Waves From One Circuit to Another Through Transformers, K. K. Palueff and J. H. Hagenguth. A.I.E.E. Trans., v. 51, 1932, p. 601–20.

12. Surge Proof Transformers, H. V. Putnam. A.I.E.E. Trans., v. 51, 1932, p. 579–600.

13. Protection of Rotating A-C Machines Against Traveling Wave Voltages Due to Lightning, W. J. Rudge, Jr., W. Weiseman, and W. W. Lewis. A.I.E.E. Trans., v. 52, 1933, p. 434–65.

Electric Power Switching

By ALFRED H. LOVELL MEMBER A.I.E.E.
University of Michigan, Ann Arbor

A SYMPOSIUM on switching power at modern large generating plants is included on the program of the Institute's forthcoming winter convention. Five papers, each describing the facilities at one such plant, are to be discussed. Three of these papers are included in this issue, the other 2 having been included in the December 1933 issue. The following article serves as an introduction to this symposium.

AT ITS MEETING in Baltimore, Md., October 12, 1932, the Institute's committee on power generation decided to prepare this symposium because it felt that the profession wanted to know of the progress and improvement which had been made in switching large amounts of energy, the trends of the latest designs, and the limitations and operating experience which the recent types of stations had shown under actual working conditions. Accordingly a plan was developed for a group of papers not so much to bring out the description of a few typical modern large switching plants as to tell the reason for their existence and to explain their particular functional performance, how far the designs attained or fell short of the objectives which had been set for them, how adequately they met the requirements of present day operation, and what their records had been for serviceability and reliability. It was hoped also that trends or changes in the switchgear, and in bus and control arrangements would be indicated. Naturally, it was realized that the economic aspect of the designs was of great importance but because of the extra labor this would have required of the authors of the papers this phase of the investigation had to be foregone. The committee felt that if several authors would each prepare a paper on the modern plant with which he was thoroughly familiar, more of the worth while design, operating features, and intimate difficulties would be covered than by any other plan. With this material available then the engineering fraternity could make its own comparisons and draw its own conclusions.

The original plan contemplated 7 papers in all, 2 of them to be on the switching at hydroelectric plants, one from the West coast and one from the East coast. Unfortunately, it was not feasible to include these at the present time so the symposium consists of 5 papers on the switching of energy at steam-electric plants. A summary of these papers follows:

Period

The switching plant designs treated in this symposium cover the period from 1922 to 1932 in the following order: Hudson Avenue 1922; Richmond 1925; Long Beach and State Line 1928, and Essex 1932. Thus there is a very uniform advance of time between the various plants described.

Size

All the stations are of large capacity, the individual ratings being as follows:

Hudson Avenue—planned for 400,000 kw; now 770,000 kw

Richmond—120,000 kw; in 1935, 285,000 kw

Long Beach No. 3—now 200,000 kw; ultimately 800,000 kw

State Line—350,000 kw;[1] ultimately 1,000,000 to 1,500,000 kw

Essex—330,000 kw[1] to 450,000 kw

1. Including units under construction.

Voltages

A wide range of voltages for generation and transmission is represented in this group of stations, the particular values in each case being associated with the special functions of the individual plant.

Hudson Avenue—27.6-kv bus and feeders

Richmond—13.8-kv for feeders, frequency converter; 66-kv to transmit bulk power

Long Beach No. 3—16.5-kv paralleled on 220-kv bus, 66-kv substations

State Line—22-kv, 33-kv, 66-kv, and 132-kv feeders

Essex—24-kv bus and feeders

Function

These 5 stations represent the principal types of switching functions in most common use today on large systems. Each design, of course, has the fundamental problem of generator control, and in addition the various duties are as follows:

Hudson Avenue—system supply, frequency conversion, and interconnections

Richmond—feeders for system and railway supply, system ties, and interconnections with other systems

Long Beach—system supply and interconnections

State Line—wholesale supply and interconnection center

Essex—feeder supply to system substations and system ties

Busses

Many varieties of bus schemes are represented: the vertical isolated phase, the star design, a double bus sectionalized with reactors, the "*H*" connection,

Full text of a paper recommended for publication by the A.I.E.E. committee on power generation, and scheduled for discussion at the A.I.E.E. winter convention Jan. 23-26, 1934. Manuscript submitted Nov. 20, 1933; released for publication Nov. 20, 1933. *Not published in pamphlet form.*

2 duplicate rings, and the latest design, which presents a simple single bus with a single circuit breaker for each individual feeder.

Both indoor and outdoor busses are represented. In the former class 2 use air insulation, while 1 uses herkolite or micarta insulation on copper tubing. One outdoor installation uses rigid hollow copper conductors with solid insulation of micarta tubes in oil filled pipes or enclosures, and the other outdoor construction is at 220 kv, air insulated. Some of the designers indicate their approval of eliminating air as insulation for the busses yet find that other insulating materials present many problems. Furthermore, while some adopt oil as a bus insulating medium all are desirous of keeping to a minimum the amount of oil which might be released and ignited in case of a fault. It is in the estimation of the relative advantages and disdavantages of the various bus constructions that the widest divergence of opinion is expressed by the authors.

Protection and Service Record

All designs have the generator or unit step-up transformer neutral grounded, several of them using a reactor in the ground lead. The later plants have made full use of isolated metal housings, thus securing predetermined paths for the fault current and definite applications for the bus fault relaying. Practically all generators and autotransformers are relayed differentially as a unit.

Various relaying systems are used in the protection of the bus sections, synchronizing bus, feeders, etc., depending upon the type of bus scheme being used and the feeder service.

In spite of the differences in age and type of station design all plants have an excellent record for continuity of service and an exemplary standard of safety for the operating personnel. The authors' frank discussions of improvements required by some of the early apparatus and related developments in switching station design should be extremely helpful to engineers engaged in this field.

Trends

Higher voltages for bussing at the generating stations, and even for generators, are becoming more evident as is indicated by these plants.

There is a marked tendency toward the greater use of metal housings for circuit breakers and busses with ground fault protection, and an increasing interest in factory built complete units.

All the writers look forward to greater simplicity in switching layouts, improvement in design details, and perhaps a further approach to the unit principle.

Switching at State Line Station

A station having several unique features, including an outdoor oil-filled metal-clad 22-kv switchgear for main generator bus is referred to in this paper. The station forms an important link in a large and intricate transmission and distribution system. This paper is part of a symposium on electric power switching at modern large steam-electric generating plants.

By
T. C. WHITE
MEMBER A.I.E.E.

Chicago Dist. Elec. Generating Corp.

ONE OF the more recent steam-electric power stations, involving some of the latest developments, is located about 14 miles from the business center of Chicago. It was built on "made" land on the shore of Lake Michigan, on the Indiana side of the Illinois-Indiana state line, hence its name, State Line station. It is the purpose of this paper to point out, following a brief picture of the station and its relation to the system, some of the problems and experiences peculiar to the electrical installation, particularly the switchgear.

The outstanding experiences at State Line with switching equipment have been incident to the use of a duplicate ring bus and outdoor oil-filled metal-clad switching equipment, using conventional oil circuit breakers. The duplicate ring bus has demonstrated its suitability for large generating units in giving an economical design, combined with great flexibility for handling unusual loading conditions. The performance of the metal-clad switching equipment has fully justified the expectation of its proponents in regard to safety and reliability and places it beyond the experimental stage. The next step, it is believed, should be the refinement of details and standardization of component parts.

Plant and System

The State Line station is owned and operated by the Chicago District Electric Generating Corporation (formerly the State Line Generating Company),

Full text of a paper recommended for publication by the A.I.E.E. committee on power generation, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 31, 1933; released for publication Nov. 25, 1933. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

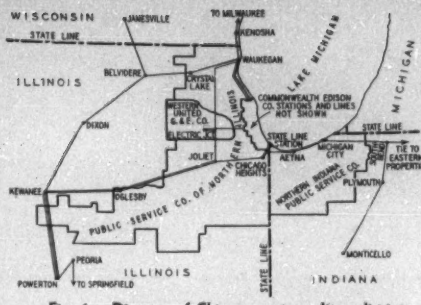


Fig. 1. Diagram of Chicago metropolitan district

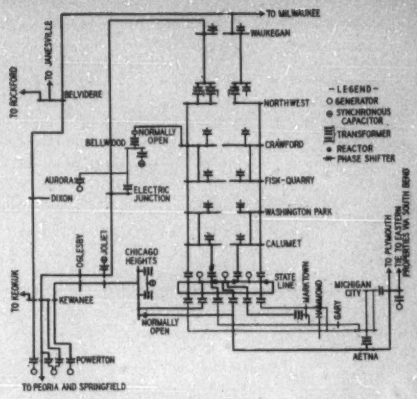


Fig. 2. Main connections of the Chicago metropolitan district's system

Two separate systems are used by the Commonwealth Edison Company for their main connections, and the supply from Powerton is brought into Chicago through 3 separate systems. For simplicity, generators and generator busses in the Commonwealth Edison Company and Public Service Company of Northern Illinois stations are not shown

which was organized to supply electrical energy on a wholesale basis to the public utilities operating in what is known as the Chicago metropolitan district.[1,2] This district may be considered roughly as the northeastern part of the State of Illinois and the northwestern part of the State of Indiana, an area of several thousand square miles, shown geographically in Fig. 1. The station serves not only as a generating plant for its customer companies, but also forms an important interconnection center for the district. The main interconnections of the system are shown in Fig. 2.

The station[4] at present has a generating capacity of 200,000-kw in a single 3-element unit, with a 150,000-kw unit under construction, and an installed feeder capacity of 520,000 kva. The system of which it forms a part has had a total peak load of approximately 1,250,000 kw, about 60 per cent of which was sold to large users, such as railways and industries. The system has at present an active generating capacity of approximately 1,700,000 kw, and has an interconnection with a group of properties to the east which has an additional capacity of approximately 2,500,000 kw. The station as originally planned was to have had an ultimate capacity of 1,000,000 kw in 5 units, but present indications are that the ultimate capacity will be about 1,500,000 kw.

The plant serves the system at present primarily as a modified base load station, normally carrying for 15 hours a day approximately full load, less a 10 per cent reserve, but varying its output over a range of about 8 per cent for regulation of the connecting tie line between the properties of the Chicago metropolitan district and the properties to the east. During the remaining 9 hours of the day, when the system has a light load, the plant output is varied over a wide range with the system load. The eastern properties regulate frequency and the companies in the Chicago metropolitan district regulate the flow of energy over the interconnection.

The station also performs an important secondary function made necessary by its position in the transmission network. It serves as an energy interchanging point, and incidentally controls as far as possible the flow of current into the various parts of the system.

The use of the plant for energy interchange, as well as generation, imposes unusual duties on the bus and switchgear and intensifies the problems of load concentrations and short circuits. It also made necessary the development of an extensive relay scheme to eliminate undue interruptions to service.

A concise description of the 22-kv generators and metal clad switchgear at State Line station has been given in a previous paper.[5] The initial main generating unit consists of 3 60-cycle 22-kv single-winding generators on 3 shafts driven by 1 high pressure and 2 low pressure elements of a triple cross-compound unit. The generator driven by the high pressure element is of 76,000-kw rating, while those driven by the low pressure elements are each 62,000 kw. In addition, each low pressure turbine drives a 4,000-kw 2,300-volt house generator. This unit can be operated if desired either with one low pressure element only, 2 low pressure elements only, or with the high pressure and one low pressure element only, thus giving necessary flexibility.

The voltage used for generation and distribution to the 10 main feeder transformer banks and the 2 station auxiliary transformers is 22 kv. Power is provided for station auxiliaries at 2,300 volts, and for small loads, at 440 volts. The transmission voltages and feeder transformer data are given in Table I. All feeder transformers are equipped for ratio adjusting and the 100,000-kva bank in addition is supplied with phase angle control[9] for load regulation. Both voltage and load regulation are accomplished by remote control and under load. The transformers connect directly to their lines on

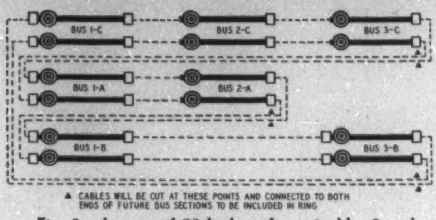


Fig. 3. Layout of 22-kv bus after units No. 2 and No. 3 are installed

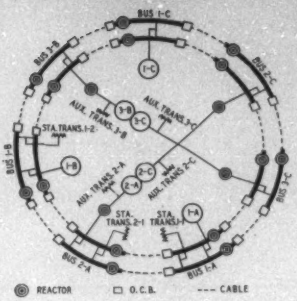


Fig. 4. Electrical conception of 22-kv bus with Units No. 1, No. 2, and No. 3 in service

the high voltage side through disconnecting switches, no high voltage busses or oil circuit breakers being used.

Table I—Data on Feeders

Three feeders of	20,000-kva capacity each at	33 kv[1]	
Three feeders of	60,000-kva capacity each at	66 kv	
One feeder of	60,000-kva capacity at	66 kv[2]	
Two feeders of	60,000-kva capacity each at	132 kv	
One feeder of	100,000-kva capacity at	66 kv[3]	

All transformers are delta connected on the 22-kv side and Y-connected on the feeder side

1. Three-phase transformers; all others are banks of 3 single-phase transformers
2. Nitrogen filled type transformers; all others use conservators
3. Equipped with a separate phase shifter

22-Kv Bus Scheme

A sectionalized duplicate ring bus scheme was adopted as the most desirable for meeting all requirements.[5] Current limiting reactors shunted when desirable by remotely controlled oil circuit breakers, are inserted in each section between generators, and tie switches are provided between sections. In Fig. 3 is given an idea of the physical layout of the bus system, providing for the 3 generators of unit No. 1 and the double windings of units No. 2 and No. 3, and shows the method of expanding the bus as the station grows. In Fig. 4 is given diagrammatically an electrical conception of the ring bus showing the arrangement of the 7 generating elements comprising the first 3 units. A one line diagram of the main electrical connections in the first section is shown in Fig. 5.

Feeders to customer companies have been laid out in such a way that in the event of the loss of a generator or bus, the entire feed to any particular part of the system will not be lost, and also, so that feeders which normally carry incoming power are connected to different sections of the bus.

Construction and Arrangement of Outdoor Metal Clad Switch Gear

The main 22-kv switchgear, including the busses, connections, and breakers, is of a compact, outdoor, metal-clad oil-filled type.[5] A plan of the present switch yard is given in Fig. 6, showing all the equipment now installed and the locations of equipment to be installed when unit No. 2 is placed in service. The 3 rows of metal clad gear in the first section each consist of 7 bays forming a bus section structure. The second section area of the yard contains 2 rows of gear, each containing 5 bays. There are also 2 isolated bays. Each bay accommodates 2 oil circuit breakers, 1 connecting to each of the 2 busses, "main" and "reserve."

The buses and switching equipment for 350,000 kw of generator capacity and 520,000 kva of feeder capacity, with one spare circuit, are accommodated in a switch yard of approximately 85,000 sq ft area. In this area are all the transformers and reactors with their spares, and all necessary track, with space reserved for future equipment.

In Figs. 7 and 8 are shown typical elevations of one bay each of the first and second section switchgear. A photograph of the first section part of the switch yard is reproduced in Fig. 9.

The oil circuit breakers are of the 3-tank type, arranged for disconnection from the bus by lowering. The 22-kv connections are made to the metal clad bus by means of male and female type contacts with spring retained fingers. The control connections are made in a similar manner. Current ratings are either 2,000 or 3,000 amp, depending upon the service. The interrupting capacity is 2,000,000 kva for breakers in the first section of the station, and 2,500,000 kva for those in the second section. These were the largest interrupting capacities available at the time of manufacture. Breakers in the same section are all interchangeable. All control voltages are 250 volts direct current supplied from a 760 amp-hr storage battery floating on a motor-generator set.

Potential transformers are open delta connected, the 2 transformers being enclosed in a single oil filled tank but separated by steel barriers. Fuses and current limiting resistors are provided in the tanks, and fuses may be removed or replaced while in service, without lowering the potential transformers.

Both the oil circuit breakers and the potential transformers are handled by means of motor operated elevators which roll on transfer trucks. The elevators may be run under any structure, and any breaker or potential transformer raised into the connected position, lowered to the disconnected position for protection or repairs, or removed to any other location. Hooks are provided in the structure whereby a breaker may be left in the disconnected position. While in this position, the tanks may be lowered on the elevators for internal inspection, and

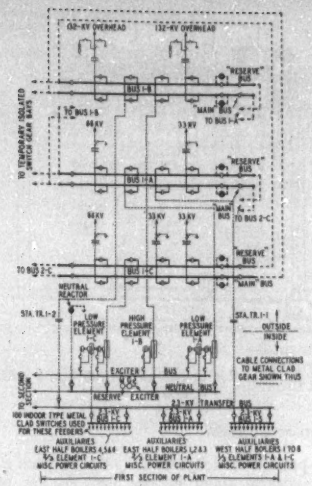


Fig. 5. One-line diagram of main electrical connections in first section

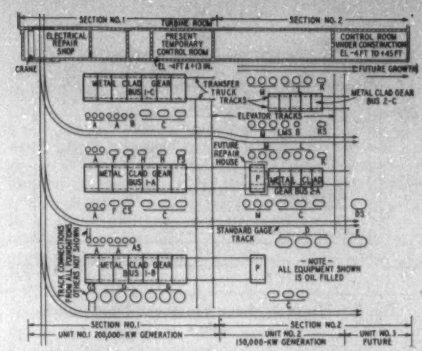


Fig. 6. Plan of switch yard for units No. 1 and No. 2

LEGEND

A. Bus reactors
AS. Spare bus reactor
B. Neutral reactor
C. 66-kv transformer bank, 60,000 kva
CS. Spare 66-kv transformer
D. 66-kv transformer bank, 100,000 kva
DS. Spare 66-kv transformer
E. 66-kv phase shifter, 100,000 kva
F. 33-kv transformer bank
FS. Spare 33-kv transformer
G. 132-kv transformer bank
GS. Spare 132-kv transformer
H. Station auxiliary transformer
K. Unit auxiliary transformer
KS. Spare unit auxiliary transformer
L. Generator reactors
M. Bus reactors
LMS. Spare reactor
P. Temporary isolated switchgear bay

practically all maintenance may be done without removing the breaker from its bay. Mechanical and electrical safety interlocks are provided, which prevent the lowering of tanks while the breaker is in the connected position, the raising or lowering of a breaker into or from the connected position while closed, or the closing of a breaker except while in the completely connected or disconnected position. Automatically operated shutters are provided which close off the bushings on the bus when a breaker is disconnected, thus providing safety against accidental contact, and reducing to a minimum the entrance of dirt.

While the second section switchgear is similar in fundamental construction to that of the first section, it is of later design. Rigid hollow copper conductors with solid insulation consisting of micarta tubes are used in the later design in place of insulated flexible cable,[5] and occasional micarta spacers are used instead of a varnished cambric spiral rope to maintain the bus concentrically within the enclosure. Modification of arrangements to facilitate shipment resulted in a higher but narrower and shorter structure. (Compare Figs. 7 and 8.)

Metal clad construction at this station is extended to the high voltage side of all outgoing feeder equipment except for the high voltage side of the 2 132-kv overhead lines. The transformer high voltage bushing is enclosed in an oil filled metal box bolted on to the transformer, and the outgoing cable enters this box through a pothead and connects to the center point of a double-throw externally-operated knife switch, permitting the cable to be either connected to the transformer, completely isolated, or connected to a test bushing mounted on the box. Observation windows and lighting arrangements are provided on the later transformers so that the position of the oil immersed switch blades may be observed directly. These switches are not designed to be operated with the line under load.

Main Generator Neutral Equipment

The neutral switching equipment is also metal clad, but of the indoor type, and is similar to the 2,300-volt auxiliary power equipment described below, but has a petrolatum compound around the bus. The generator neutral reactor of 8-ohms 1,588-amp capacity, is located outdoors in the switch yard.

Switch Yard Power Cables

Connections such as those between switch gear and transformers, and bus-ties between bus sections, are made by means of lead covered cables. This, in addition to the outgoing feeders, results in a concentration of power cables which introduced problems from the standpoint of adequate heat dissipa-

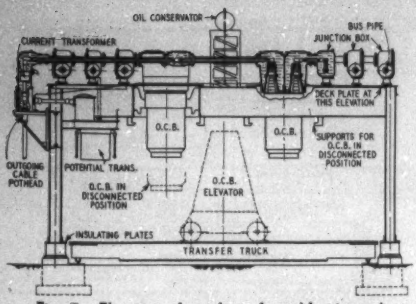


Fig. 7. Elevation of one bay of unit No. 1 switchgear

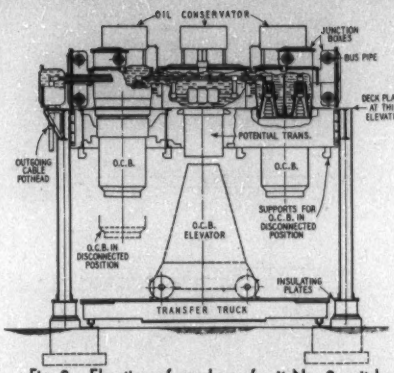


Fig. 8. Elevation of one bay of unit No. 2 switchgear

tion. In this case, however, it was possible to install the cables under the water table.

Relay Protection

The relay protective scheme for the bus has been planned to combine a high degree of selectivity with completeness, every portion of the bus having automatic protection. In some cases this has resulted in an overlapping of protection, but a fault anywhere in the bus or its connections will not result in the loss of more than one generator or of enough feeder capacity to affect any one part of the system seriously.

Protection of the switchgear and bus including its reactors and tie cables is by means of a coördinated arrangement of ground fault relays, reactor differential relays, and bus tie cable differential relays, selectivity being obtained without time delay.

Generators of unit No. 1 are protected by means of conventional differential relays, opening armature, neutral, and field breakers, and shutting down generator ventilating fans. Unit No. 2 generator will be protected by a modified arrangement due to the use of a double winding in the generator and unit auxiliary transformers directly connected to the generator leads.

All transformers are protected by differential relays backed up by the line relays. On all circuits, except generators, overload relays are used, and on transformer banks operated with neutral grounded at the station, ground relays are also provided. On some circuits directional impedance relays are used in order to afford proper selectivity with the rest of the system. On the circuits feeding into Chicago (a distance of about 2 miles) pilot wire relays are used. The lack of switching on the high voltage side presents a problem in obtaining complete transformer protection, as complete clearing of the transformers in case of failure depends upon relays at the far end of the line, except on lines on which pilot wire relays are used. It is felt, however, that the cost of oil circuit breakers on the high voltage side cannot be justified, and no serious need for them has developed at State Line up to the present time.

Switching Control

The present switchgear is controlled from a temporary control room in the first section of the building. The control equipment and instruments are mounted on steel switchboards.

The permanent control center is being constructed in the far end of the second section of the building adjacent to the switch yard, and it will be extended into the third section to take care of the ultimate plant. It has 3 main floors, a terminal room floor, a main control room, and a balcony.

The main control room will have a flat top benchboard in the center, upon which all of the control switches will be mounted. Vertical panels on one side of the room will have mounted upon them the instruments and gauges for the generators and important station equipment. On the other side of the room a similar vertical board will be used for feeder instruments. Likewise, on the balcony over the main control room, vertical panels will contain relays and miscellaneous meters for the generators and feeders. The boards for the new control center will be of ebony asbestos, and will be completely wired in the factory.

A chief operator located at a desk on the balcony will be able to supervise all control room activities, coördinating these with the boiler room and turbine room operations, and the requirements of the interconnected companies. Directly below the main control room is located the terminal room where all control and instrument wires will pass through terminal boards.

Some of the features being incorporated in the permanent control room are: The use of anti-vibration floors upon which are mounted the instrument and control panels, double windows in the turbine room wall, artificial ventilating system, and indirect lighting.

The cables used throughout the station for control and instrument circuits are all lead and armor covered, and are carried in groups through trenches, 8-in. metal ducts, and on metal shelving.

Auxiliary Switching

The 2,300-volt auxiliary power switching equipment is also metal clad, and is compactly arranged in switch rooms centrally located. The switches are remotely controlled. Bare conductors in air filled enclosures are used, without phase isolation, the system operating with ungrounded neutral. Breakers are of the vertical lift type. Motors are of the line start type, eliminating all starting equipment. In the lower part of Fig. 5, the general layout of the 2,300-volt auxiliary bus is shown.

Continuity of service is obtained by distributing the feeds to essential auxiliaries between the 3 busses, supplied from separate sources, and also by employing automatic switching of any bus to a standby transformer should a bus voltage fail. All of the essential auxiliaries consist of 2 or more units, so that a shutdown of any one auxiliary motor will not necessarily shut down a boiler or generating unit. Sections of the bus are located in separate rooms. Bus ground detectors are provided but no automatic protection is employed for the busses.

Fire Hazards and Protective Features

The concentration of equipment and the large amounts of oil present have made the question of fire hazard a very important one. Several effective precautions have been taken to avoid or minimize the effects of fire. The use of instantaneous type relays, comparatively high speed switching, and the limitation of ground fault currents, tend to reduce the chance of fire starting. Portable fire extinguishing equipment suitable for oil fires, and for use on live electrical equipment is provided at convenient locations to take care of small fires, and this is supplemented by foam generators and a large and reliable water supply system with conveniently located hydrants and hose equipment. The entire switch yard is covered with approximately 18 in. of coarse gravel, which has been proved by extensive tests to be effective in rapidly draining away oil and rendering it harmless as a fire hazard.

Ramps and curbs also have been provided for the indoor low voltage switch rooms. An organized routine has been developed for fighting fires. So far there have been no oil or electrical fires at this station.

Operating Experience

The 22-kv switchgear for the first section at State Line station was installed in 1928 by a local contractor, under the supervision of the operating company's construction department, and placed in service, a few bays at a time, between November 1928 and April 1929. One-half of the second section switchgear was placed in service in June 1933. Construction on the remainder has not yet been completed.

The electrical installation throughout the station is characterized by almost complete metal-clad construction, and this is undoubtedly responsible to a great extent for the high degree of safety and reliability with which the station has operated to date.

In common with most of the later plants, practically all of the station auxiliaries are electrically driven and controlled, which makes it necessary for large numbers of nonelectrical, as well as electrical, men to work close to complicated electrical equipment operating at voltages ordinarily considered hazardous. This situation, in addition to the regular higher voltage hazards, has made it necessary to give safety to personnel considerable thought, and it has been possible to operate and maintain the station to date without major or minor electrical accidents.

The reliability of the metal clad bus has been exceptionally good; no outages due to insulation failure or flashover have occurred. Breaker mechanisms and control wiring in the switch yard have caused some difficulties without, however, resulting in interruptions to service. In one case, however, a transformer was damaged due to an oil circuit breaker failing to open automatically with a short circuit on the line. This occurred during the first few months of service, and before the breaker mechanism remodeling had been completed by the manufacturer. The difficulties have been due almost entirely to outdoor exposure, and the problems of moisture and atmospheric impurities affecting control wiring, terminal blocks, and moving metal parts of breaker mechanisms were quite serious in the early period of operation, but have been practically solved by minor changes in design by the use of more suitable materials where necessary and more adequate protection of vital equipment from the elements. In some cases, where convenient, heaters have been installed to guard more completely against the effects of moisture condensation.

Immediately after installation, oil leaks developed

Fig. 9. First section part of switch yard

In the lower left-hand corner can be seen 1 of the oil storage tank cars, 2 of the movable elevators supporting 2 oil circuit breakers, and elevator cross-over tracks used for rolling elevators to other structures or on to car for moving into repair shop

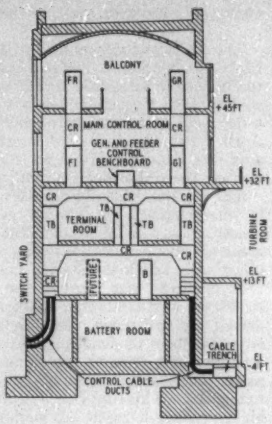


Fig. 10. Cross section of permanent electrical control center

LEGEND

FR. Feeder relays and miscellaneous meters

GR. Generator and station relays and miscellaneous meters

FI. Principal feeder indicating instruments

GI. Principal generator and station indicating instruments

CR. Cable racks, metal enclosed

TB. Terminal boards

B. Battery and d-c control panels

in many places due to porous metal castings; these were corrected by piening over the metal and subsequently on later equipment, by the use of a heavy oil-resisting varnish on the inside of the castings. Other oil leaks developed at the gasketed joints from time to time, especially with seasonal changes in temperature, causing expansion and contraction of the bus structure; such leaks have been effectively corrected to date by occasionally tightening up on the bolts. Tests are being conducted at the station, to determine whether there are more suitable or more easily applied materials than cork or vellumoid for this purpose. In a few cases it has been necessary to replace parts to correct leaks, but in no case has there been any serious leaks.

While no trouble has yet been encountered with either oil circuit breaker or potential transformer bushing flashovers in service, static discharges have been noted on bushings during periods of heavy fog when the bushings were not absolutely clean. Therefore, a program of thorough periodic cleaning and inspection of both male and female bushings during the late fall and early spring has been followed. During the summer overhauling of the breakers, bushings are again cleaned and also tested. These inspections have uncovered a few cases of small cracks and compound leaks.

Recently the use of the power-factor method of testing the male bushings and other breaker insulation to detect hidden weaknesses has been used with encouraging results, and it is thought that by combining this method with other means, it may be possible to eliminate completely all bushings having slight defects before trouble develops.

The performance of the oil circuit breakers has been very satisfactory, and under no condition has any breaker shown signs of distress after opening a fault current.

All breakers, mechanisms, and wiring of the outdoor gear are thoroughly overhauled once each summer and this has been found to be sufficient, except for occasional inspections after breakers have opened fault currents, at which time any necessary contact work or filtering is done.

A maintenance program, such as outlined above, can be efficiently followed at this station, as it is possible to do all necessary outdoor work during favorable weather conditions and use the maintenance men, who normally do switch yard work, on indoor work during adverse weather conditions. As the station grows, this may be difficult because of the increased amount of switch yard work, and it may be desirable at some future time partly to enclose, with thin removable siding, the sides of the oil circuit breaker structure below the deck plate. This arrangement might also be desirable in cases where traveling oil switch crews, which cannot be employed efficiently during inclement weather on inside work, are used for oil circuit breaker overhauling.

Other work which must be scheduled for the same months devoted to switchgear overhauling includes, in addition to the usual testing, filtering, and adjustment of oil levels in outdoor equipment, the overhauling of transformer tap changer mechanisms and contacts.

Due to close clearances and relatively small oil volumes, with a large number of points where moisture in the oil may collect, the moisture content of the oil has been closely watched on the first section equipment. It has been found that what little moisture has collected at the regular sampling points has been readily removed at the time the sample was taken, but some difficulty has been experienced in removing moisture from the long bus enclosures where the bus is supported by spiral varnished-cambric rope. This has been overcome in later designs by using, for bus supports, discs with slots in the periphery to permit free horizontal movement of oil and escape of air.

The method of handling oil may be of interest; a central oil storage system with permanent piping and pumps is not used, all equipment being portable. Three oil tank cars equipped with steam heating coils, 2 of which have a single 10,000-gal compartment and one having 2 5,000-gal compartments, are used both as storage tanks for spare oil and as a temporary means of handling oil during repairs and inspection of equipment. Filter presses and a centrifuge equipment with necessary pumps and numerous lengths of flexible metal hose equipped with fittings and valves are carried in an enclosed car.

Certain oil levels throughout the switch yard and all pressures on cable end bells are closely watched and recorded by the operators. The pressures have caused some difficulty because of considerable variation with load and outdoor temperature changes, and an attempt is now being made to reduce necessary pressure adjustment work by connecting several of the pressure reservoirs together into common headers. A few leaks which developed in the lead sheathing because of lamination of the lead were discovered before moisture was able to get into the cable by close watching of these pressures.

The use of 2 ring busses has resulted in sufficient flexibility to meet all maintenance requirements, as well as every condition of loading imposed on the

station, both as a generating and distributing center. It was primarily the intention to use normally one bus at a time with the other held as a standby, but it has been necessary for the past 2 years to use both busses or portions of both busses to meet loading conditions.

A limited control over power distribution to the various lines is being accomplished by the use of 2 busses with proper switching of generators and feeders on to the busses with reference to the bus tie reactors, and this together with the use of the transformer ratio adjusters has provided control of the ampere loading of the different lines where necessary, due to maximum capacities being approached. The phase angle control provided on the 100,000-kva bank has been very effective in load division control.

In the event that some unusual load distribution causes overloading of a section of bus, the use of the corresponding section of the reserve bus in parallel is resorted to. Bus tie ammeters recently installed, assist the operator in analyzing, at a glance, loading conditions in the bus. Portable metering equipment consisting of an ammeter with a split core current transformer which may be slipped around any bus enclosure is also available if needed for detailed loading checks.

The question of voltage surges in the metal clad equipment has been given some study, and surges of values up to approximately 4 times the normal crest voltage to ground were recorded recently during a short test period. No troubles due to surges have been encountered.

Some fairly successful preliminary tests have been made to determine the feasibility of detecting, by means of a sensitive radio receiving set, discharges shielded by metal; should this method be developed to a reliable state, it would greatly assist in locating and correcting substandard equipment before a dangerous condition developed.

The possibility of trouble from poor contact in the disconnecting devices between breakers and structure has been watched for, but no serious trouble has so far developed at this station.

It has been pointed out that the use of metal clad gear makes for very safe normal operation, but it should also be noted that great care is necessary in opening up enclosures for inspection or repair, since it is impossible to test conductors at the point where an enclosing cover is to be removed. Extension contacts are provided which fit over the oil circuit breaker bushings while in the disconnecting position to make connections to the bus or to ground the bus if work is to be done.

Experience and tests point out the desirability of certain refinements in switch yards of the type used at State Line. The use of gravel covering the switch yard under and around the oil filled equipment as previously explained under "Fire Hazards" increases the difficulty of walking around the yard to make inspections or work on the equipment; concrete walks therefore should be provided, taking care that all such walks and also manhole covers which must be left exposed are given sufficient pitch to drain rapidly off into the gravel any burning oil which might run on to them. Plenty of permanently installed lighting equipment, as well as facilities for additional temporary lighting, also should be provided.

Due to the special design of this equipment, it has not yet been standardized to the point where it can be manufactured on a quantity basis and this means that in case of trouble which might possibly wreck a portion of the bus structure, considerable time would be required for replacement if it were necessary to await manufacture of new parts. In order to guard against such an interruption, considerable investment in spare parts for this gear has been necessary.

Spare transformers are not connected and no serious inconvenience has been encountered so far, although 2 transformer failures have occurred since the station was put in operation. When interchanging transformers, however, it is not necessary to remove potheads from the cables.

The use of a triple cross-compound unit, even though provision is made to operate the low pressure elements on boiler pressure steam by means of separate throttle valves and governors, would, in the event of a sudden loss of load or shutting down of the high pressure element, result in a momentary loss of load in the low pressure element generators, were it not for an automatic load relay which automatically admits high pressure steam to the low pressure elements, if the electrical output of the high pressure element falls below a predetermined value. Tests have shown that this device, assisted at the beginning by the stored steam, practically prevents loss of load in excess of that carried by the high pressure element.

There have been no instability difficulties to date between the plant and system. Governor action and voltage control have been satisfactory. Tirrill voltage regulators and a self-excitation system are now used, but pilot exciters will be used on units No. 2 and No. 3, and may be added later to unit No. 1.

Trends and Suggested Improvements

The popularity of compact outdoor oil-filled metal-clad switching equipment has steadily increased in the Chicago district, and much experience in the design and operation has been obtained.

The Public Service Company of Northern Illinois[3] has done considerable pioneering in the use of equipment of this type and is now employing it outdoors at 33 kv in 6 different locations, and at 132 kv at the Waukegan station.[7] The Northern Indiana Public Service Company is using this type of switchgear at 33 kv in its Marktown substation, and the Superpower Company of Illinois (Powerton station) is using it for the station 22-kv generator bus.

Recent developments of outdoor metal-clad gear have tended toward the use of more compact factory assembled units which may be shipped completely filled with oil. Manufacturers are now also offering gear with stationary breakers which use oil immersed knife switches or movable connectors for isolation of the breaker, instead of providing for isolation by vertical movement of the entire breaker. However, experience with the movable breaker scheme has been satisfactory at State Line and would seem to be simpler when disconnection is required only for

work on the breaker. If, however, frequent disconnection is necessary to provide an additional visual break in a circuit for work beyond the breaker, facilities should be provided for doing this without the necessity of using a portable elevator.

It would be desirable in the case of an installation such as that at State Line, to provide individual motor-operated raising and lowering devices on at least the generator circuits, and this will possibly be done when the cost of such devices has been reduced to the point where they can be economically justified. This or some other means would also be desirable in the case of the 2,300-volt oil circuit breakers.

On outdoor switchgear, the deck plates under the busses (see Figs. 7 and 8) should be extended the full width of the structure, made absolutely water tight, and given a definite slope. This will prevent the formation of ice on the equipment under the deck plates and, in case of fire, drain any oil off into the gravel. If this were done and siding applied as previously mentioned, certain work which is now normally postponed during periods of bad weather, could be performed without inconvenience at any time.

The large number of gasketed joints used in oil-filled metal-clad gear and the inconvenience of replacement make it very desirable to simplify, as far as practical, such joints, and develop a gasket material of more lasting qualities and easy application than those available at present.

The use of silver-to-silver contacts for disconnecting switches and brazing or welding of all possible joints within the gear are desirable developments.

The use of indoor metal-clad gear, especially at voltages around 2,300 volts, is becoming well established, being used exclusively at the State Line, Powerton, and Michigan City plants. The Public Service Company of Northern Illinois is using considerable indoor metal-clad equipment, ranging up to 18 kv. The apparent trend in the case of indoor equipment, up to 15 kv, is to use tape or molded insulation with air, instead of oil or compound, resulting in simplicity and greater safety from fire. It should be noted that on indoor construction complete tightness of the enclosures is not usually provided, and there is some possibility of the entrance of foreign matter or hot gases and metallic vapors from a nearby fault. These are possibilities entirely avoided by the complete tightness of the oil-filled or compound-filled type of gear.

The thoughts on switchgear embodied in the foregoing, are largely the result of a close association with engineers connected with Sargent and Lundy, Inc., with the equipment manufacturers' engineers, and with associates in the construction and operating departments. The assistance of C. T. Hesselmeyer in the preparation of the paper and the helpful suggestions of other members of the electrical division are also acknowledged and greatly appreciated.

References

Chicago District System

1. System Connections and Interconnections—Chicago District, by G. M. Armbrust and T. G. LeClair. A.I.E.E. Trans., v. 49, 1930, p. 582–96.
2. Combined Reliability and Economy in Operation of Large Electric Systems—Chicago District, by L. L. Perry and F. V. Smith. A.I.E.E. Trans., v. 51, 1932, p. 879–88.

American Metal Clad Switchgear Practice

3. Metal Clad Switchgear, by J. L. Hecht. *Elec. Wld.*, v. 93, March 30, 1929, p. 634–6.
4. "State Line"—A Departure from the Conventional. *Elec. Wld.*, Nov. 2, 1929, p. 871–4.
5. Metal Clad Switchgear at State Line Station, by A. M. Rossman. A.I.E.E. Trans., v. 49, 1930, p. 397–400.
6. Outdoor Switchgear of High Capacity, by H. H. Rugg. *Elec. Jl.*, v. 29, June 1932, p. 290–1.
7. Electrical Design Features of Waukegan Station, by E. C. Williams. A.I.E.E. Trans., v. 51, Sept. 1932, p. 644–51.
8. Metal Clad Gear Offers Plant Economy, by M. H. Hobbs. *Elec. Jl.*, Feb. 1933, p. 60–5.
9. 100,000 Kva Three-Phase Regulating Transformer for Phase Angle Control. *Gen. Elec. Rev.*, v. 36, Sept. 1933, p. 398–9.

European Practice

10. European Switchgear Practice, by W. R. Farley. *Elec. Jl.*, Aug. 1930, p. 455–8.
11. Design of Electrical Plant, Control Gear and Connections for Protection Against Shock, Fire, and Faults, by H. W. Clothier. *I.E.E. Jl.*, May 1925, p. 425–46.
12. Metal Clad Switchgear, Automatic Protection, and Remote Control, by H. W. Clothier. *I.E.E. Jl.*, Aug. 1932, p. 285–330.

Switching at Richmond Station

The essential features of the switching facilities at 13 kv and 66 kv at the Richmond generating station of the Philadelphia Electric Company are described in this paper. Operating experiences with such facilities are outlined and certain desirable improvements in future design are indicated. This paper is part of a symposium on electric power switching at modern large steam-electric plants.

By
RAYMOND BAILEY
MEMBER A.I.E.E.

F. R. FORD
MEMBER A.I.E.E.

Both of the Phila. Elec. Co., Phila., Pa.

RICHMOND station of the Philadelphia Electric Company was placed in service in 1925, and is located in the city of Philadelphia, Pa. Switching at Richmond station is at 13.8 kv and 66 kv; a switch house structure of the vertical phase isolated design is used for 13.8 kv, and an outdoor

Full text of a paper recommended for publication by the A.I.E.E. committee on power generation, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 25, 1933; released for publication Nov. 27, 1933. *Not published in pamphlet form.*

1. For a more complete description of Richmond station itself than is given in this paper see the *Electrical World* for May 1, 1926, p. 907–26.

substation of the flat type with the bus insulators supported on steel pedestals is used for 66 kv.

The operating experiences outlined in this paper indicate that, since completion of certain modifications to the circuit breakers, the last of which were made about 2 years ago, switching facilities at Richmond Station which are adequate, reliable, easy to operate, and safe, have been obtained. The use of the straight double bus scheme is believed to contribute much to these results. It is questioned, however, whether the present type of isolated phase construction is the most desirable for 13.8-kv switching. It is also suggested that in the future circuit breakers may be applied which have lower interrupting ratings relative to the circuit breaker duties than generally used today. Features to be considered in future oil circuit breaker development also are discussed.

General

Richmond station[1] has sufficient land for considerable expansion and will very likely develop into a station of quite large capacity. Generation in the station is at 13.8 kv with transmission at this voltage to distribution substations and large industrial customers, and with transformation to 66 kv for transmission of bulk power to other parts of the system.

While Richmond station is not designed primarily as a base load plant, the economy of this station is such that it is operated at a very high load factor. With contemplated increases in the capacity of this station, its economy relative to that of other stations of the system possibly will be such that it will continue to operate as a base load plant for many years.

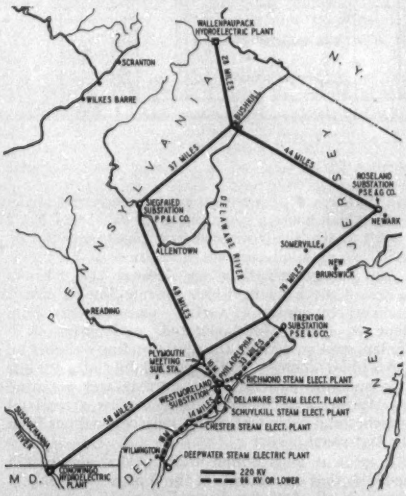


Fig. 1. Map of the system to which the Richmond generating station is connected

The present capacity of Richmond station is 120,000 kw in 2 generating units, comprising the initial installation; one of these units was placed in service in November 1925, and the other in January 1926. In addition to the 2 60,000-kw generators now in operation, a 165,000-kw generator is being installed which it is expected will be placed in service in 1935. The present total generating capacity of the Philadelphia Electric Company's system is about 900,000 kw.

Interconnections exist between the system of the Philadelphia Electric Company and the systems of the Pennsylvania Power & Light Company and Public Service Company of New Jersey; these interconnections at 220 kv constitute the so-called Pennsylvania-New Jersey interconnection. There is also an interconnection with the Public Service Company at 66 kv between Richmond station and Trenton, N. J. A moderate capacity interconnection exists with the Atlantic City (N. J.) Electric Company through the Deepwater generating station. There are also several light capacity interconnections with other companies in the surrounding territory. The relation of Richmond station to the rest of the system is shown by Fig. 1.

Features of Electrical Installation

The lines (all underground) in the Richmond station include 23 outgoing 6,000-kva 13.8-kv lines to distribution substations and substations in industrial plants, 2 43,000-kva 13.8-kv lines to the adjacent frequency converter substation for the supply of single-phase energy for railroad electrification, 3 12,000-kva 13.8-kv tie lines to Delaware generating station, and 2 60,000-kva lines to 13.8/66-kv bus tie transformer banks in the adjacent 66-kv substation. The 6,000-kva 13.8-kv lines are of no greater importance than those supplied from various other transmission centers on the system.

The ultimate capacity in generators, transformer banks, lines, etc., is not at all definite, and for this reason and the fact that such information is not essential in a review such as is given in this paper, figures on probable ultimate capacity are not given.

The 66-kv substation includes, in addition to the transformer banks, 4 lines which are part of the transmission system used for bulk power.

In Fig. 2 is given the essential electrical connec-

Table I—Oil Circuit Breaker Ratings and Duties

	O.C.B. Rated Current (Amp)	Maximum Load Current (Amp)	O.C.B. Interrupting Capacity (Kva)	Calculated Maximum Interrupting Duty (Kva)
13.8-Kv				
Generators				
60,000 kw	3,000	2,955	1,500,000	870,000
165,000 kw	5,000	4,630	1,500,000	1,160,000
Outgoing lines	600	263	780,000	280,000
Delaware tie lines	1,200	526	780,000	440,000
Frequency conv. substation lines	3,000	1,530	780,000	530,000
Bus tie trans. banks	3,000	2,510	1,500,000	1,250,000
66-Kv				
Transformer banks	800	557	1,500,000	800,000
Lines	800	440	1,500,000	800,000

tions of the generating station and of the step-up substation. It will be noted that the present 2 generators as well as the generator now being installed connect to the double 13.8-kv busses and that the 2 bus tie transformer banks provide connections between these busses and the double 66-kv busses. Some of the future generators will be connected through individual transformer banks directly to the higher voltage busses, depending upon system capacity requirements relative to the 13.8-kv distribution at Richmond.

The ratings of the old circuit breakers, both as to normal current capacity and interrupting rating in relation to the actual requirements, are given in Table I, the short-circuit duties being upon the basis of an assumed ultimate condition.

It is the practice to provide a liberal amount of insulation on all switching facilities, particularly the bus and that portion of the connections which would not be isolated automatically in the event of failure. To this end the equipment in the 13.8-kv switch house has a nominal voltage rating of 25 kv. In the 66-kv outdoor substation the bus insulators and disconnecting switches are rated 110 kv, and the oil circuit breakers 73 kv.

The generator neutrals are grounded through a 4-ohm resistor so that with ground faults occurring in the switch house or on a cable the current is limited to a relatively low value. Thus the 13.8-kv circuit breaker duty is very moderate in the majority of operations.

It is expected that circuit breakers installed in the future on 13.8-kv outgoing lines, for which the calculated interrupting duty is 280,000 kva, will be considerably lower in interrupting rating than those now in use.

Switch House Structure

The 13.8-kv switch house structure, which is of the vertical phase isolated design, is shown in cross section in Fig. 3. The first, second, and third floors are similar, each floor containing the concrete structures which house a given phase for No. 1 and No. 2 busses, with the corresponding phase selector oil switches, main oil switches, and line reactors.

On the ground floor are located the solenoid operated mechanisms which operate the oil circuit breakers by means of vertical pipes running from floor to floor. Hand-operated mechanisms in a similar manner control the disconnecting switches on the 3 phase-floors. On the ground floor also are line disconnecting switches, line current and potential transformers, cable potheads, generator ground oil switches and cable test busses with connections from the test room below.

A central longitudinal wall divides the switch house so that on one side of the 3 phase-floors No. 1 bus with all of its breakers, disconnecting switches and reactors are separated from bus No. 2 on the

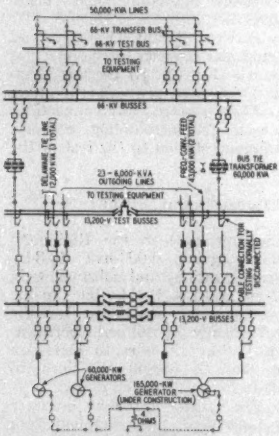


Fig. 2 (above). Single-line wiring diagram of Richmond station

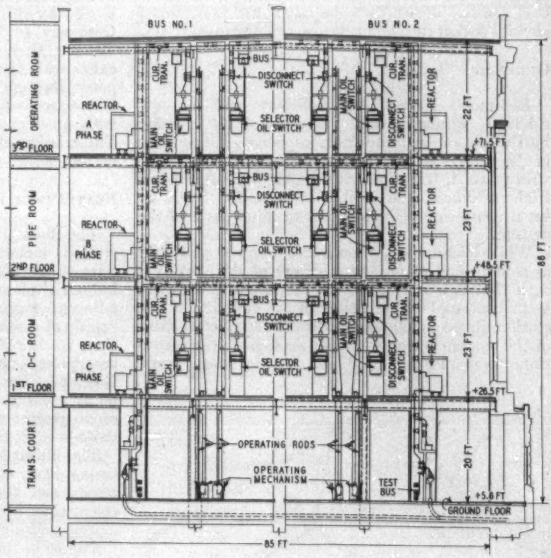


Fig. 3 (right). Cross section of Richmond switch house ("H"-pair line section)

other side with all of its corresponding equipment. A central corridor on each floor, at right angles to the above mentioned wall, divides the switch house into 2 parts, with approximately equal capacities and loads on each.

The 13.8-kv busses are sectionalized by means of reactors and the associated oil circuit breakers trip automatically in case of fault on a bus section. The 13.8-kv lines are arranged in pairs using the "H" connection with the main oil circuit breakers on each line automatically operated for faults, and with the selector breakers also provided with relays for tripping in case the main breaker does not function properly.

The electrical connections employed are such as to guard against errors which might result in personal injury, interruption to service, or damage to equipment. In the switch house, mechanical interlocks are provided to insure correct operation of disconnecting switches in relation to their associated oil circuit breakers. Compartment doors must be unlocked with a key released only when the proper disconnecting switches are open. Bus section grounding switches cannot be closed until a test has been made to insure that the bus is deënergized.

All generator and line sections in the switch house are plainly designated on the compartment doors and by suitable targets on exposed equipment such as the operating mechanisms of the oil circuit breakers and disconnecting switches.

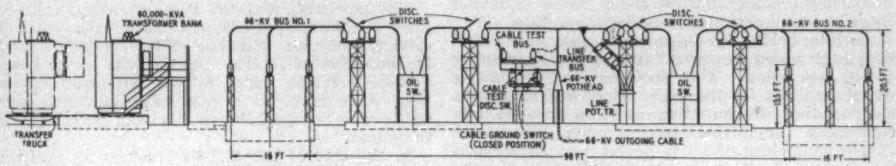


Fig. 4. Cross section of Richmond step-up substation

to give operating simplicity while at the same time providing ample flexibility and reliability. The simple and symmetrical electrical connections permit of a simplified physical arrangement with a 7-ft wide section through the switch house for each generator, and a 5-ft section for each transformer bank, frequency converter feeder, and line pair. This scheme of connections also makes possible an arrangement of control switches, instruments, etc., that is not likely to confuse the operator, a factor which is very important.

Various features have been incorporated in the switch house design to minimize the extent of the trouble which might result from a fault current. Barriers have been installed between floors in the vertical copper runs on the various circuits and smoke caps have been provided at the tops of the barrier bushings. Smoke barrier plates also are provided around the operating rods of the breakers and disconnecting switches where they pass through openings in the floor. In the case of the potential transformers where taps are involved from 2 phase-floors, smoke barriers are applied to the bushings where they pass through the compartment side walls. Additional features include the fireproofing of generator neutral cable in all places where it runs exposed through the basement, the installation of barriers in the basement ceiling where connections are carried through from the test set to the test bus, and also barriers in the ceiling of the oil filter room in the openings through which the test set leads are carried up into the test bus compartments.

While the principal reliance against errors in switching or blocking is placed on the selection and training of the operating personnel, rather extensive use has been made of interlocking facilities

Certain control interlocks are provided to minimize the possibility of operating errors. Closing circuits of oil circuit breakers on generators and important tie lines are interlocked through the synchronizing receptacles. Closing circuits of the circuit breakers on major apparatus are interlocked through the hand reset auxiliary relays associated with the differential relays to prevent inadvertently reënergizing faulty equipment.

Testing of the switch house equipment and outgoing cables is facilitated through the provision of an induction voltage regulator-transformer set which will supply up to 30,000 volts. This set connects to a tets bus, which in turn can be used to energize the various circuits through disconnecting switches or in some cases, portable jumpers.

66-Kv Substation

The 66-kv substation is of the flat type with the bus insulators supported on steel pedestals as indicated in Fig. 4. All lines entering or leaving the substation are underground. The electrical arrangement involves duplicate busses with connections to each through an oil circuit breaker for all transformers and lines. The simplicity of the electrical connections permits a relatively simple physical arrangement.

The 66-kv busses are widely spaced to prevent any possibility of trouble on one affecting the other. As indicated by the cross section of the substation, the individual groups of selector equipment connecting to their respective busses are well spaced to insure maximum reliability. The conductors of each bus are on 8-ft centers, and the conductors of the circuits are on 6-ft centers. With the flat type

of bus there are no structural parts above the busses, and a minimum of conductors crossing the busses on the individual circuits thus insuring a maximum degree of safety against bus short circuits from mechanical causes.

To provide for the contingency of a simultaneous conductor failure in each of the 2 parallel 66-kv lines to a substation, a transfer bus is installed so that one of the unfaulted conductors in one line can be connected in place of the faulted conductor in the other line, thus forming a complete circuit for emergency operation. The connections between the conductors in the lines and the single conductor transfer bus can be made by means of temporary jumpers when required.

Provision is made for the installation of bus sectionalizing reactors and oil circuit breakers should these be found desirable at some future date.

An interlocking arrangement through the use of keys is provided to prevent improper disconnecting switch operation. This includes the grounding switch facilities for the lines and busses, as well as the isolating disconnecting switches for the line equipment. A further precautionary feature includes padlocking the trip levers and mechanism housings of the 66-kv breakers. The keys for the individual locks are kept in the operating room. All of the equipment in the switch yard is clearly designated by prominent targets.

Testing of the 66-kv substation end of the outgoing cables is provided by means of a 300-kv kenetron (2-electrode hot-cathode vacuum tube) set which connects to a test bus. The various circuits may be connected to the test bus through disconnecting switches.

Experience With Breaker and Other Equipment

At the time of installation of the isolated phase breakers and disconnecting switches some difficulty was experienced in getting proper alignment of parts and operation. Operating rods were weak mechanically, supports for toggles required bracing, balancing springs had to be installed to balance the weight of the rods, and other modifications were involved. However, it is probable that these troubles were such as might be expected with equipment located on different floors and tied together mechanically. The experience indicates that the parts for isolated phase equipment should be very carefully designed to minimize trouble.

Shortly after the station was placed in operation a fault occurred involving the failure of 4 of the individual oil switch phases and a considerable amount of other equipment. The trouble was due to a short circuit occurring on an outgoing 13.8-kv line which the breaker failed to open successfully and in the surging which followed another circuit broke down on a different phase giving the equivalent of a phase-to-phase short-circuit. As a result of this trouble, the breakers were modified by the manufacturers; also, some of the features previously mentioned in this paper were incorporated in the switch house design, particularly to prevent smoke from passing between floors.

There has been a considerable amount of trouble experienced with both the 13.8-kv and 66-kv oil circuit breakers during the period from the original installation to the present. A summary indicating the nature of the difficulties is given in Table II.

Table II—Classification of Troubles With 13.8-Kv and 66-Kv Oil Circuit Breakers

	13.8 Kv		66 Kv	
	Electrical	Mechanical	Electrical	Mechanical
Total	10	10	20	8
Design	8	2	19	7
Construction or defective material	2	8	1	1
Occurring during clearing of fault	5	0	15	5

The experience with the 13.8-kv breakers is based upon a total of approximately 560 breaker-years of service, and that with the 66-kv breakers on 80 breaker-years of service. In the case of the lower voltage breakers, most of the automatic operations have involved a relatively light duty due to the cable failures being mostly from one conductor to ground.

In the case of the 13.8-kv breakers, in addition to the serious trouble previously mentioned, there has been a certain amount of unfavorable experience while interrupting fault currents, principally excessive contact burning and carbonization of oil. There has also been the usual experience with mechanical features requiring readjustment or replacement from time to time.

Serious troubles have also been experienced with the breakers in the 66-kv substation. In one case a breaker bushing flashover resulted in damage to a considerable amount of adjacent equipment and interruption to one 66-kv bus.

In another case, in attempting to clear a line fault, a tank was blown off the breaker with a resulting oil fire which destroyed considerable equipment. This also resulted in a short circuit of one 66-kv bus.

After several cases of contact burning, oil carbonizing, and oil being thrown from the breaker, the breakers were rebuilt to improve their interrupting characteristics. Shortly after, one of the rebuilt breakers failed, resulting in a bushing being cracked, contacts pitted, oil carbonized, and general distress of the breaker. As a result of this experience, minor changes were made to the contact system and no difficulties of this nature have developed since.

In addition to the experience with the oil circuit breaker equipment there have been other scattered cases of trouble, such as the failure of a reactor in the switch house and undesirable expansion of the bus bars requiring the installation of expansion joints.

While the design was based upon accepted standards at the time of the original installation, evidence of high temperatures in the present 60,000-kw generator lead runs indicated the desirability of providing for movement of the copper to relieve the strain on the insulator supports. Leaf copper expansion joints suitably spaced with a fixed insulator between, together with springs under the bolts of

the existing clamps have been installed to permit ample movement with temperature variation.

In connection with the installation of the 165,000-kw generator, most of the main bus conductor is being changed from a laminated to a copper channel construction to provide for the greater current. Channel construction also is being used for the connection from the new unit to the bus. The design includes provision for expansion in the copper members resulting from temperature variation both in the conductors and in the supporting structure. Expansion joints of leaf copper are provided at intervals with one fixed support between joints. The remaining supports are of the sliding type which permits the complete conductor assembly to move appreciably in either direction.

The installation of the large generator will necessitate modification to the switch house ventilation. The switch house is ventilated by a gravity system, utilizing for exhaust ducts the unused portion of vertical conductor compartments beyond the point where the conductor leaves the compartment at each isolated phase floor. With the increased generating capacity, a mechanical system will be required to dissipate the additional heat losses. The new system will consist of fans, one each in the up-river and down-river sections of each floor. Each blower will supply air to a distributing duct from which the incoming cold air will exhaust through discharge openings located near the floor line in the several equipment aisleways. The heated air will pass up through vertical compartments and dissipate through openings in the roof. Small fans will be installed, if experience shows them to be necessary, to circulate air through the main bus and new generator lead enclosures.

Conclusions

The experience with the Richmond switching facilities during the past 2 years, with the breakers modified to their present arrangement, indicates that an adequate and safe installation has been attained. Operation has been of a nature to give continuity of service and there have been no undesirable outages of individual circuits for which the switching facilities were responsible.

Ease of operation has been realized to a most satisfying degree, due primarily to the simplified arrangements provided for both the 13.8-kv and 66-kv layouts. It is believed that the straight double bus scheme with selector oil circuit breakers inherently gives maximum operating simplicity with maximum provision for reliability of service, and that the cost involved with such a layout is moderate for an important transmission and distribution center in a large metropolitan system.

At the time when Richmond Station was designed, experience throughout the country indicated that an isolated phase switch house would be most suitable for the purpose to be accomplished. Widespread experience obtained since the construction of Richmond station with switching facilities of various types is such, in the opinion of the authors, that there is some question as to whether the present type of isolated phase construction would be used in providing 13.8-kv switching facilities in excess of that which can be accommodated in the present switch house. It is rather difficult, and perhaps of little purpose, to predict what type of switching facilities will be provided in the future for Richmond or a similar installation. It is possible, however, that such facilities would be of the outdoor type. Of the various disadvantages of outdoor switching equipment, it is believed that the most serious is the possible damage from flying material in the event of failure of some piece of equipment. It seems that in many cases when equipment fails pieces of porcelain, oil, etc., may travel considerable distance; in fact, one case is known where relatively large pieces of porcelain traveled a horizontal distance of over 200 ft in an outdoor substation.

It is important that the development of switching facilities be such as to permit such installations being made at a lower investment cost than has been possible in the past. In the opinion of the authors standardization of oil circuit breakers, on which considerable work already has been done, should do much to accomplish this end. Just what other ways will be found to assist in bringing about a reduction in cost of oil circuit breakers is difficult to suggest. It may be that savings will be accomplished in the future in the application of circuit breakers by selecting breakers that will have an interrupting rating much lower compared to the calculated fault current than would be used according to the general practice today. To take full advantage of this suggestion apparently would require a complete knowledge of the magnitude of actual fault currents compared to the calculated values generally used for selecting oil circuit breakers. It would also be desirable to design the switchgear so that in the event of its failure to interrupt fault current, possibilities of serious damage would be eliminated. This apparently requires the use of circuit breakers that do not contain an inflammable fluid.

Considerable improvement has been made in the last few years in the technique relating to interruption of fault current, which has been largely responsible for the decreased time required to interrupt fault currents.

It is believed that the following features would be desirable to be kept in mind as further improvements in oil circuit breaker development:

1. Breakers should be capable of interrupting fault currents of any magnitude within their rating a number of times without requiring inspection or maintenance.

2. As mentioned above, it is highly desirable that the hazard from the use of inflammable fluid be eliminated.

3. It is believed that the bushings of oil circuit breakers should be improved in design and construction so as to better the performance of the oil circuit breaker as an interrupting device, and also to minimize the hazard due to flying pieces of porcelain in the event the bushing is disrupted at time of failure.

4. It should be possible to improve the oil circuit breaker as a mechanical device, so that there wil be fewer adjustments and replacements required to keep it in satisfactory operating condition.

5. It would also be helpful if circuit breakers could be arranged so that the contact parts could be inspected and replaced with greater facility than is possible with the larger equipment at the present time.

Switching at the Connors Creek Plant

A description of the switching facilities at Essex station, adjacent to the Connors Creek generating plant of The Detroit (Mich.) Edison Company, is given this paper, which is part of a symposium on electric power switching at modern large steam-electric generating plants. Essex station, which has been in operation less than 2 years, has had an unusually good service record.

By
A. P. FUGILL
MEMBER A.I.E.E.

The Detroit Edison Co., Detroit, Mich.

ESSEX, the switching station for the Connors Creek generating plant, is The Detroit Edison Company's most modern station. It was constructed in anticipation of the rehabilitation of the generating plant because the old switching station was inadequate for the increased generating capacity contemplated. The general system diagram of Fig. 1 shows the relation of Connors Creek to the rest of the system serving Detroit and vicinity, the installed generating capacity at each of the 4 steam generating plants, and the interconnections between them. By the fall of 1934, the Connors Creek plant will consist of 2 modern 30,000-kw turbine-generators, 2 45,000-kw units and 1 20,000-kw unit. The latter 3 are part of the original installation and will be replaced eventually by new machines. The expected future plant will consist of 2 30,000-kw and 3 90,000-kw units, although a total of 5 of the larger machines could be installed if conditions warrant.

When the design of Essex station was first considered, certain fundamental features were recognized as being highly desirable. These features may be outlined as follows:

1. The interrupting duty on the circuit breakers, with the ultimate generating capacity, should be kept within the rating of present-day circuit breakers by some scheme which would not interfere with the effective interchange of power between this station and the system.

2. All equipment in the station, particularly the circuit breakers, should contain a minimum of oil or compound. Experience had indicated that much of the serious damage in indoor switch houses was due to oil fires, and that oil circuit breakers were the most likely offenders.

3. All faults, including those directly on the bus, should be cleared rapidly and positively. Instantaneous relaying for feeder faults had been in use for many years but, until recently, no simple yet positive method was available for clearing bus faults promptly.

4. Bus fault currents should be kept to a predetermined, adequate path and not allowed to roam at will throughout the building. Two or 3 previous disagreeable experiences had shown that fault currents in the reinforcing rods could do considerable damage to the concrete at the most unexpected places.

5. The building construction should be entirely divorced from the electrical installation. Since 2 classes of workmen were required for these functions, it was felt that time and money could be saved if each class could complete its work without interference from the other group.

The detailed description of the Essex station given in this paper indicates that the fundamental design features mentioned above as being desirable have all been incorporated in the station as designed and built. The important features may be summarized as follows:

1. The connection diagram chosen provides fault current limitation without handicapping power interchange between the station and the system.

2. Possible damage from oil fires is reduced to a minimum by the use of *H*-breakers or deion breakers, air cooled reactors, and air insulated busses, and by the sectionalization of breakers in small rooms.

3. Rapid, positive clearing of bus faults is secured by enclosing all electrical equipment in isolated metal housings and by the associated bus fault relaying.

4. The bus fault current is kept to a predetermined path by the use of isolated metal housings and a low impedance ground network of copper and building steel.

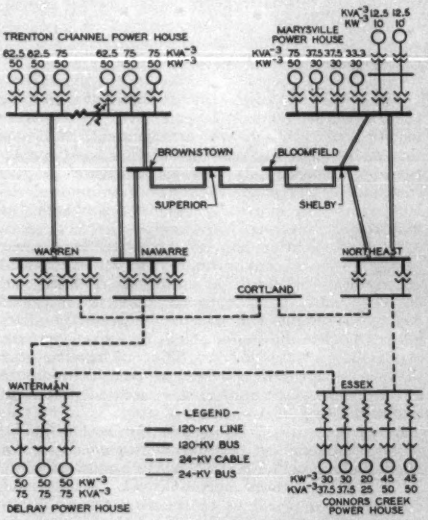


Fig. 1. General system diagram of The Detroit Edison Company

Full text of a paper recommended for publication by the A.I.E.E. committee on power generation, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 23, 1933. *Not published in pamphlet form.*

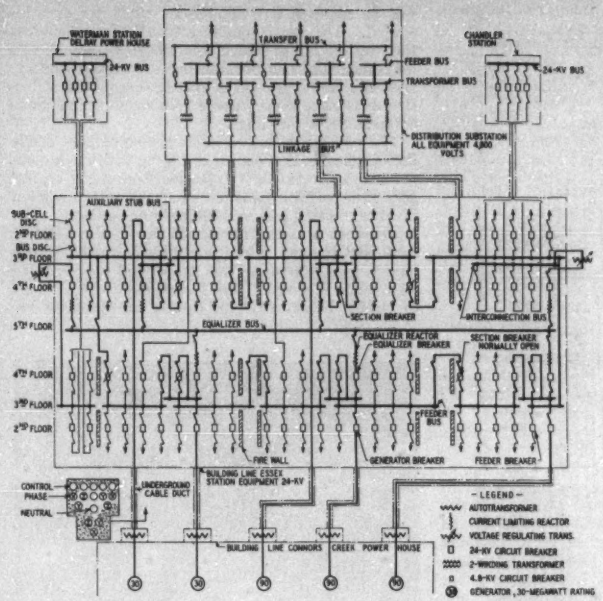


Fig. 2. Connection diagram of Essex switching station with typical distribution substation

5. Metal housings and armored control cable permit the building construction and electrical installation to be distinct and separate operations.

Connection Diagram

The connection diagram for this station was chosen to coördinate with the type of distribution substation it was to serve. As indicated by Fig. 2, the typical substation is radially supplied, but the load busses are interconnected through reactors so that one supply feeder or more can be lost without any interruption to service. Inasmuch as only one feeder to the substation is supplied from each bus section at the switching station, the loss of a section of bus at Essex is of no more importance to the distribution substation than a transformer failure or a cable breakdown. Since, then, there is no necessity for double bus or double breaker, the connection diagram for the switching station combines the star-connected reactor or synchronizing bus scheme of fault current limitation with a simple, single bus and single breaker arrangement for individual feeders, but provides section breakers to obtain flexibility in the grouping of bus sections. Normally, bus sections are so combined that each generator supplies the load directly with as little interchange over the synchronizing or equalizer bus as is feasible.

This connection for reactors was preferred to a ring bus with intermediate reactors, to 2-winding generators, or to 3-winding transformers, because the system ties are equally available to all load in the station and, conversely, all generators are equally available to the system and to each other. Furthermore, the outage of a feeder bus does not cause the loss of any system ties.

Feeder reactors were discarded for the present because it was more economical to use a breaker of sufficient interrupting capacity than a smaller breaker and reactor. Furthermore, they are not necessary from the standpoint of reducing voltage disturbance on the bus because the fault is cleared so quickly. The design is such, however, that all feeders can be equipped with reactors if it should be necessary in the future.

The connection diagram of Fig. 2 shows that each generator, its autotransformer, and its 24-kv underground cables are considered as a unit and switched only at the switching station. Since multiple single-conductor cables are used, it is desirable to insure the proper division of current

Fig. 3. External view of Essex station

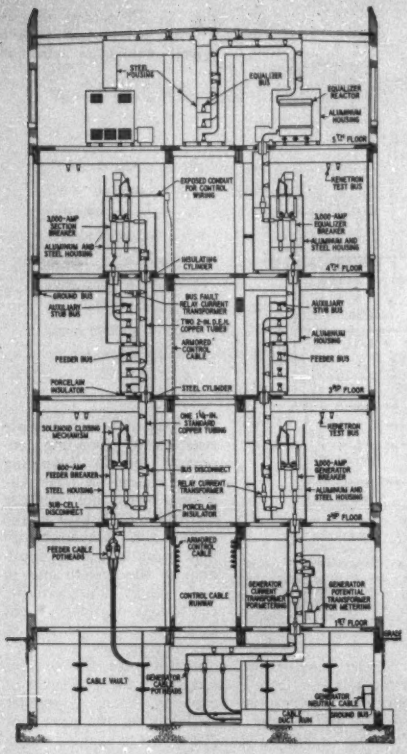


Fig. 4. Composite cross section drawing of Essex station

among the cables of each phase. To accomplish this, the special, equilateral-triangle configuration of cables shown by the duct cross section on Fig. 2 was adopted. In addition, the neutral of the generator was grounded at the switch house through the neutral cable in the center of the triangle. This connection forces the fault current supplied over the phase cables by each generator to return by approximately the same path so as to reduce the voltage induced by these currents in the control cables and their sheaths. The control cables for each generator are carried in ducts directly above the main cable ducts but at no point are they exposed to the main cables.

Physical Arrangement

An outside view of the Essex switching station is shown in Fig. 3. The present building with its 68 feeder positions is adequate for a generating plant of 330,000 kw, but an extension to the right end will be required if 5 90,000-kw units are ever installed. The small building in the foreground is the control house which contains the switchboard for control and relay equipment, the control battery, and the kenotron cable testing equipment. Enclosed passageways provide convenient connections between the 2 buildings.

The physical arrangement of the equipment inside the building is best shown in Fig. 4, which is a composite cross section of the station, showing a typical generator position, equalizer breaker position, section breaker position and second-floor line position. The fourth-floor line position is not essentially different from that shown. The feeder busses, auxiliary stub busses, and interconnection busses are on the third floor while the second and fourth floors are devoted to circuit breakers. This double breaker-floor arrangement permits direct connections between breakers and busses and reduces the length of bus per breaker position. The symmetrical arrangement of equipment in horizontal cross section permits the location of breakers on outside walls of the building where large windows provide ample relief in case of serious explosion. The location of the equalizer bus and reactors on the fifth floor follows naturally from the breaker and bus arrangement. The fifth-floor equipment shown in the cross section drawing is not installed at present but will be as soon as the first 90,000-kw generator goes into service at the power house. The first floor is used, at present, only for the generator instrument transformers, feeder cable potheads, and the control cable runway. There is space, however, for the future installation

Fig. 5. Typical circuit breaker room on the outside building wall

of feeder reactors on the first and third floors, should they ever be required.

Two photographs of equipment housings are included to show the construction and method of insulating them from the building. A view of a typical breaker room on the outside wall of the building, Fig. 5, shows the breaker cells with the subcell disconnecting switch compartments underneath. The housings are mounted on porcelain insulators, the black insulating material shown being used to prevent smoke or gas from the breaker room traveling to other parts of the station and not for mechanical support. A view of the bus floor in one of the outer aisles, Fig. 6, shows the housings for feeder busses at the floor elevation and the housings for stub busses and aisle crossovers above them. The pothead housings for the feeder cables from the fourth-floor breakers are shown along the wall.

Fig. 6. Bus floor in the aisle on the outside building wall

Circuit Breaker Equipment

Pursuant to the policy of using equipment with a minimum of oil in the station, the design was laid out for the General Electric type *FH-209-C* circuit breaker which has only a small amount of oil in the pots. Before the station had been completed, however, the Westinghouse deion breaker with no oil entered the field, so a few of these breakers were purchased for a trial installation. In Fig. 7 is shown one of these deion breakers and the sub-cell disconnecting switches installed in the metal cell.

All breakers have an interrupting capacity of at least 40,000 amp, although the station design limits the calculated fault current any breaker will be required to interrupt to 35,000 amp or less. All feeder breakers are rated at 600 amp, and generator, equalizer, and section breakers are rated at 3,000 amp. Although operated on a 24-kv system, all insulation to ground, not only on these breakers but on all other electrical equipment in the station has a minimum flashover guarantee of 95 kv.

Since even the *H*-breaker contains sufficient oil to cause considerable smoke in case of an oil fire, the breaker floors are divided by fire walls into 7 breaker rooms per floor. In case of breaker trouble which fills a room with smoke so that the operator cannot make the inspection necessary before putting equipment back into service, only 9 breakers or less are involved. Furthermore, these breaker rooms are closed off from the center aisle where the disconnecting switches between the breaker and the bus are located, so that the operator could always pull these disconnecting switches even if he cannot get into the breaker room which is in trouble.

Metal Housings

One of the major features of this station is the use of metal housings for all electrical equipment. Each phase of the equipment is entirely metal enclosed by substituting metal for the conventional masonry construction in cells and bus walls. The complete housings rest on porcelain insulators to provide positive insulation from the building. In addition, they are grouped in units, each unit being definitely insulated from the others. Each bus section and its breakers form one unit, each auxiliary stub bus and generator breaker form another, the equalizer bus and reactors, a third, and each section breaker and equalizer breaker form a unit by itself. Thus, a fault in the station up to and including the feeder breakers must be a line-to-

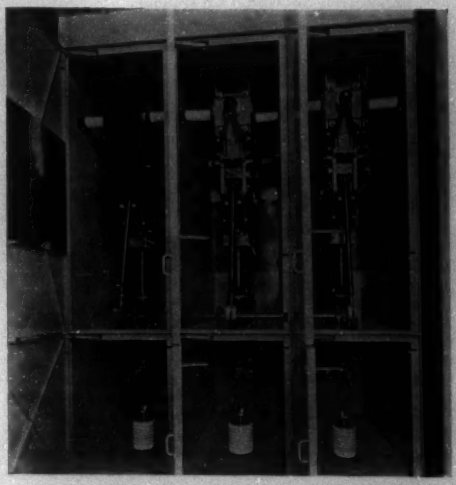


Fig. 7. Deion circuit breaker and sub-cell disconnecting switches in a metal housing

ground fault and the fault current can flow only to the isolated housing of the faulted equipment. It is a simple matter, then, to ground each unit of housing through a current transformer and provide relays to trip the proper breakers whenever current flows through this transformer.

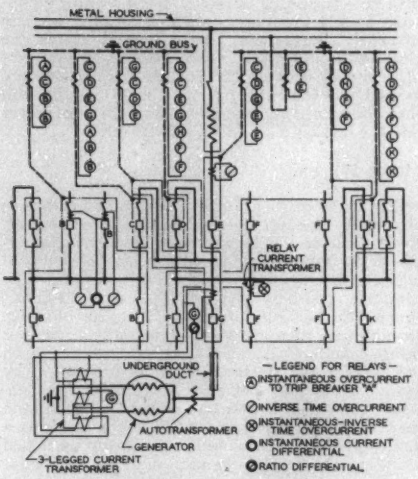


Fig. 8. Schematic diagram of protective relaying for typical bus sections

In this station, both steel and aluminum are used, depending upon the current capacity of the enclosed equipment. All 600-amp equipment uses steel entirely and, in general, 3,000-amp equipment uses aluminum. There is considerable steel, however, in the 3,000-amp breaker cells, and some steel bracing in the bus enclosures. Although the equalizer bus is designed for the same current as the other busses, its housing will probably be steel because of the low load factor. Each equalizer reactor will probably be enclosed in an aluminum cylinder with openings for self ventilation.

Several advantages can be claimed for metal housings in comparison with the conventional masonry type. They are lighter in weight but probably would not be as seriously damaged by an explosion or oil fire. Since they are built on jigs to precise dimensions, the joints are tighter and the clearances around doors and removable panels are smaller than is usually obtained with masonry construction, so that there is less chance of conducting gas entering the housing from an external source. They provide a means of keeping the current for a bus fault to a definite path away from the reinforcing rods in the concrete. Still more important, they are constructed as a unit in the shop so that erection in the station is a comparatively simple matter and does not interfere with the purely building operations. And, most important of all, they permit the fast, positive clearing of a bus fault by the use of simple overcurrent relays. Despite these advantages, the cost is slightly less than the conventional masonry type of construction.

Fault Protection

The relay protection for Essex station is outlined schematically in Fig. 8, which shows clearly the method of bus fault protection used with the isolated metal housings. Since each unit of housing is grounded at one point only, any fault current flowing to ground must pass through the current transformer in the ground connection. As many instantaneous

Fig. 9. Control cable room located immediately under the switchboard

plunger-type overcurrent relays as there are breakers to be tripped to clear a fault are connected in series to the secondary of this transformer. By using a separate relay for each breaker instead of a multicontact relay, accidental closing of the contacts of one relay will trip only one breaker. It is felt that this scheme of bus fault protection is so simple and positive, and the protective relays so rugged, that correct operation is practically assured. In another station, where this scheme is employed, one bus fault has occurred and the bus fault relaying performed perfectly.

In Fig. 8 also is shown differential protection which is used on some of the larger machines at other stations and which probably will be used on the 90,000-kw units at this station. The winding on the middle leg of the 3-legged current transformer shown in the neutral end of the parallel-circuit generator winding provides sensitive protection on the generator itself. Normally, with equal currents in the 2 halves of the winding, no flux passes through the center leg of the core. If the currents are unbalanced, due to a fault in one half of the winding, some flux will pass through the middle leg and cause current to flow in the relay connected to the winding on that leg. Since the setting on the relay can be set

low without danger of false operation, the protection for generator faults is very sensitive. Inasmuch as this scheme offers no protection for faults outside the generator, additional overall differential protection, including the transformer, underground cables, and generator breaker at the switch house, is provided by balancing the windings on the outer legs of the 3-legged current transformer against a current transformer on the generator breaker. Two sets of relays are used for this protection, each set tripping both the generator breaker and field breaker. Ratio differential relays, set as low as the transformer will permit, are depended upon for first-line protection

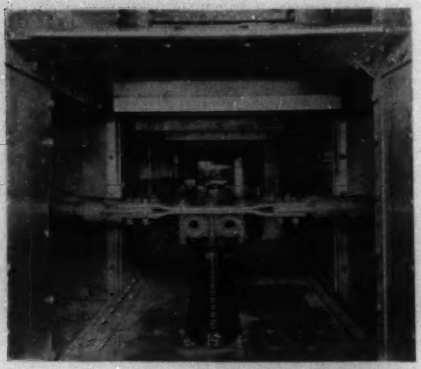


Fig. 10. One phase of bus with 2 3,000-amp taps

but are backed up by the more rugged but less sensitive, instantaneous, plunger-type relays which are set high to prevent tripping due to slightly dissimilar current transformer characteristics.

Partly as back-up protection for the bus fault relaying, but mostly to clear the affected bus from the rest of the station in case a feeder breaker fails to open but does not cause a line-to-ground fault, the equalizer breakers are provided with time-delay overcurrent relay protection. It is possible to get selective action by the proper choice of the current setting on the relays, because the current through the equalizer breaker on the affected bus is divided approximately equally among the other equalizer breakers. For a fault on the equalizer bus, all equalizer breakers will trip if the bus fault relaying fails to operate.

The radial feeders have combination instantaneous time-delay relays to give instantaneous tripping for cable faults and time-delay for faults beyond the transformer in the distribution substation. The parallel circuits, which are mostly the system interconnection cables, have current differential relays to give instantaneous tripping when 2 lines are in service and overcurrent relays with inverse-time-limit characteristics for protection when only one line is in service.

Armored Control Cable

Another feature which simplified building construction considerably was the use of armored cable for control wiring instead of the conventional conduit buried in the walls and floors. With buried conduit, not only does the installation have to be coördinated with the building construction in an effort to avoid delays, but frequently, floors, particularly in the control room, have to be made thicker than necessary merely to accommodate the conduit. Since it is usually impossible to judge future needs accurately, extra conduit is installed just to be sure that there will be sufficient for the future. Even so, any change in plans causes considerable difficulty in revamping or extending the control system

The use of armored control cable removes these difficulties. As employed at Essex, the method is comparatively simple. The control wiring from each breaker mechanism, relay transformer, and instrument transformer is carried in exposed conduit to a connection box on the nearest building column in the center aisle. By the use of a special construction at the floor joints, a duct the length of the column is provided between the fireproofing and the steel. The armored lead-covered control cables are carried in the duct from the connection box on the upper floor to the control cable runway on the

Fig. 11. Partial view of control room

first floor. This runway extends the length of the building and is connected to cross runways into the control house to provide access to the space under the switchboard. The cables are supported by clamp hangers in the columns and on racks in the horizontal runs. The routing is indicated in the cross-section diagram of Fig. 4 but a better conception of the installation can be obtained from Fig. 9, which shows the control cable room underneath the switchboard.

Type of Bus

At the time this station was designed, there was considerable published information on the current rating of various types of busses in open air but little was available as to bus ratings when totally enclosed. Hence, tests were made to determine the rating of different types of flat-bar or round-tube bus when enclosed in a housing like that at Essex. It was found that, for the type of bus considered, a non-magnetic metal housing reduced the bus rating to about 75 per cent of that in open air while a magnetic housing reduced it still further to about 65 per cent.

On the basis of these tests, the bus of 2 double, extra-heavy copper tubes in parallel, used in this station, will carry 2,700 amp at 35 deg C rise above the ambient of the housing. A third tube can be added to increase the bus rating to 3,200 amp if it becomes necessary. Tubing was used instead of flat bar because it could be adapted more readily to a bus design which would stand the rather large mechanical stresses occasioned by the heavy fault currents at this station. One phase of the bus with 2 3,000-amp taps is shown in Fig. 10.

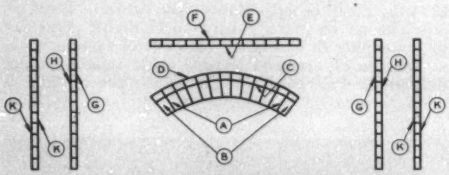


Fig. 12. Schematic floor plan of switchboard showing location of equipment

A. Generator controls, equalizer breaker controls, section breaker controls,
B. Interconnection breaker controls
C. Indicating meters
D. Bus fault relays
E. Bus fault relays, generator differential relays, recording meters
F. Bus fault relays
G. Feeder breaker controls
H. Bus fault relays
K. Feeder relays

With the equipment housing isolated from the building and grounded only through one connection to the ground bus, it is essential that this connection and the ground bus itself have a low impedance to ground or at least to the building steel in order to prevent excessive voltage on the housings. Hence, the connection from the housing was made as short as possible and a network of copper tubes and bars used for the ground bus. In addition, this bus was solidly connected to the building steel at frequent intervals so that it is impossible for much voltage to exist between the building steel and the ground bus. This arrangement takes advantage of the building steel, which is really a very low impedance network to ground, but still does not depend upon it entirely.

Steel Switchboards

The switchboard, as shown in the partial view of the control room in Fig. 11, is made up of cabinet-type steel panels, a benchboard for the generator controls, and a number of vertical boards for the feeder controls and relay equipment. The boards were all built and equipped in the shops of the company. They are totally enclosed with a hinged panel at the rear to provide access to the wiring and equipment terminals in a conventional manner. A schematic floor plan showing the arrangement of the panels and the location of the equipment on them is given in Fig. 12.

Service Record

It is felt that the design of this station is such that any faults which can occur will be promptly and positively cleared. It would take a series of simultaneous failures in several pieces of equipment to cause loss of service to any important load, and such a series of coincidences is not likely to occur. To be sure, this particular station has operated less than 2 years but to date no trouble has been experienced. Furthermore, there are 4 other 24-kv switching stations on the system, incorporating most of the essential features of Essex station, which have been in operation for a total of 17 station years. The only case of a bus fault which has occurred is that mentioned previously and the protective equipment operated properly so that no interruption to load resulted. All faults on feeders out of these stations also have been properly cleared.

Trends in Design

Since the design of Essex station was based upon experience in the operation of such stations over a period of years, the developments in the art of switching in this company are incorporated in its design and exemplified by the features found in that station. To date, its operation and the operation of similar stations have not brought to light any situations which would cause a major change in design. As far as can be ascertained at the moment, if a new station, with the same function, were to be erected in the near future, it would be a virtual duplicate of this one in all its essential aspects. It is merely necessary to add, then, that the trend in the design of switching stations for modern generating plants as far as The Detroit Edison Company is concerned is most clearly indicated by referring to the foregoing description of Essex station.

Impulse Generator Circuit Formulas

With impulse voltage testing of electrical equipment becoming more widely used, it seems highly desirable to be able to calculate the circuit constants required to produce the desired test waves and to calculate the waves that any given circuit constants will give. In this paper the solution of the more commonly used impulse generator circuits is developed and summarized. Waves calculated by these formulas check closely the waves actually recorded by the cathode ray oscillograph.

By
J. L. THOMASON
ASSOCIATE A.I.E.E.

General Elec. Co., Pittsfield, Mass.

IMPULSE TESTING now has expanded from an experimental into a commercial field, and it is desirable that there be available a reliable and ready means of calculating the discharge or test waves of impulse generators to facilitate testing in this broadening field. Insulator time-lag characteristics usually are obtained for 0.5x5- and 1.5x40-μsec (defined later) waves, whereas to develop fully the internal oscillations in transformers long waves with steep fronts may be necessary; or to study the possibility of cumulative oscillations, the applied voltage should be oscillatory and of the same frequency as that of the apparatus tested. It is thus evident that to produce these specific waves and to make sure they are recorded on cathode ray oscillograms, it is necessary, if cut and try methods are to be avoided, to be able to calculate the circuit constants required to produce these waves and to calculate the test waves that these circuit constants give. In several articles[1,2,3,4] written at various times, the solutions for particular problems or particular circuits of the impulse generator have been shown. However, the rigorous solutions of many useful circuits probably never have been developed; hence in this paper the solutions of the more commonly used impulse generator circuits are developed and summarized.

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Sept. 28, 1933; released for publication Dec. 4, 1933. *Not published in pamphlet form.*

1. See bibliography at end of paper for numbered references.

Impulse Generator Circuit

The complete discharge circuit of the impulse generator, less charging equipment, is shown in Fig. 1, where, for convenience in analysis, it has been segregated into 4 distinct parts.

Part I represents the equivalent discharge circuit of the impulse generator proper. The capacitor units of the impulse generator (C) are usually of the oil filled type commonly used for power factor correction. They are compact, reliable, and readily procurable at reasonable cost. The discharge capacitance of the generator is that resulting from all the capacitors that discharge in series. The value of conductance G will depend primarily upon the values of the charging resistors in the circuit, but there may be also a small amount of leakage over the supporting frames to ground. The inherent resistance r of the impulse generator circuit, due to the resistance of the capacitors (0.01 to 1.00 ohm each), leads, and gaps, is ordinarily small, probably being less than 100 ohms even under transient skin effect conditions. The inherent series inductance L is due to the inductance in the capacitors (0.01 to 3.50 μh each) and to the inductive loops in the discharge circuit, this latter inductance being primarily a function of the length and configuration of the discharge circuit. A method of calculating it is shown in Appendix I. The terminal capacitance K includes the distributed capacitance of leads, capacitors, etc., to ground. Ordinarily it is too small to exert an appreciable influence on the wave applied to the test piece.

Part II of Fig. 1 shows the circuit for controlling

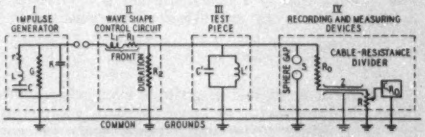


Fig. 1. Equivalent circuit of impulse testing equipment

C = generator capacitor units, arranged to be charged in parallel and discharged in series
G = leakage conductance of charging resistors and over generator frame (permits leakage of charge)
L = inherent inductance in generator circuit (retards wave front and causes oscillations)
r = inherent resistance in generator circuit (retards wave front, but not appreciably)
K = terminal capacitance due to gaps, leads, etc.
L_1 = inductance to retard wave front or to introduce oscillations
R_1 = resistance to control front of wave } depending also
R_2 = resistance to control duration of wave } on I and III
C′ = effective capacitance of test piece (affects voltage crest appreciably, depending on I and II)
L′ = effective inductance of test piece (affects wave duration appreciably and introduces oscillations)
S = sphere gap (measures voltage crests, except for extremely short waves)
R_0 = resistance of divider } determine voltage
Z = surge impedance of divider } reduction
R = Z = cable grounding resistor (potentiometer for CRO. R = Z prevents reflections)
CRO = cathode ray oscillograph

the shape of the wave applied to the test piece. Were it not for this circuit, the wave shape would be determined by the constants of the impulse generator and the test piece, and a desired wave shape (such as a 1.5 x 40-μsec wave) might not be obtained. Both the series inductance L_1 and the series resistance R_1 tend, in general, to retard the length of the wave front. The inductance also will introduce oscillations in the wave and for this reason is usually made as small as possible. The shunt resistance R_2 controls to some extent the duration of the wave; in general for small loads, the duration varies directly with the shunt resistance.

Part III represents the test piece or load. Where the load is a bushing, an insulator string, or a gap, it may be represented by a capacitance. Ordinarily, the test piece capacitance will be between 50 and 400 $\mu\mu$f; to this must be added the stray capacitance of the leads which, depending upon the shape of the test circuit, may vary between 50 and 400 $\mu\mu$f. An ungrounded transformer also can be represented by a capacitance, and a single-winding transformer with one end grounded can be represented by a capacitance in parallel with an inductance and a resistance in series. From the kilovolt (*kv*) and kilovoltampere (*kva*) ratings of the transformer 2 of these constants can be approximated by simple relations. The inductance relation

$$L = \frac{10\ (\%\ \mathrm{IX})\ (\mathrm{kv})^2}{2\pi f\ (\mathrm{kva})}\ \text{henries}$$

gives the equivalent inductance for the normal leakage reactance between 2 windings of a transformer. This inductance will have to be modified to suit the test arrangements, such as when the low voltage side of the transformer is connected to other apparatus for excitation. The resistance

$$R = \frac{10\ (\%\ I^2R)\ (\mathrm{kv})^2}{(\mathrm{kva})}\ \text{ohms}$$

is usually of negligible magnitude even when multiplied by some factor as large as 10 to compensate for skin effect. The capacitance may be considered in 2 parts: that of the bushing, which varies between 100 and 350 $\mu\mu$f; and that of the transformer winding, which varies between 200 and 1,000 $\mu\mu$f for ordinary transformers and is probably 10 times higher for shielded transformers.[5] The other capacitances to ground must be added, of course, to obtain the total load capacitance.

Part IV represents the recording and measuring devices. Both the sphere or other type of gap used to measure the test voltage and the divider resistance will have some capacitance to ground, which will add to the total load on the generator. The divider resistance also will offer another shunt resistance path to ground. The accuracy with which the test wave is recorded by the cathode ray oscillograph will depend to some extent upon how well the divider lead-in constants are balanced.[6] The cable grounding resistance R should be equal to the surge impedance Z of the lead-in cable to prevent reflections between the 2 when the divider resistance R_0 is large in comparison with Z, which is the usual case.[7] The small capacitance of the divider resistance and also the small capacitance of the cathode ray oscillograph deflector plates will not have an appreciable effect on oscillographs, except for chopped or peaked waves.[7,8] The cable may damp peaked waves considerably, the attenuating effect increasing with the shortness of the peak and with the length of the cable.[8]

It is evident that the complexity of the complete circuit of Fig. 1 precludes a rigorous solution thereof, but fortunately the circuit may be simplified greatly for analysis and without sacrificing necessary accuracy. The extent to which simplification may be carried depends, of course, upon the relative values of the circuit constants of a given test arrangement. Moreover, the reason for ignoring certain constants may depend on test results or engineering judgment rather than on calculation. Thus, in its simplest form the discharge circuit of an impulse generator with a capacitance load can be represented by 5

C_1 capacitance of impulse generator
L_1 total series inductance
R_1 total series resistance
R_2 shunt resistance
C_2 capacitance of test piece

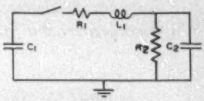


Fig. 2. Equivalent circuit of impulse generator

circuit constants as shown in Fig. 2. The circuit constants L_1 and R_1 include both the added and the inherent inductance and resistance while the stray capacitance to ground of the connecting leads has been considered part of the load capacitance.

Solution of Circuit

The shape of the voltage wave applied to the test piece can be obtained by calculating the impedance drop across the test piece. For illustrative purposes the circuit of Fig. 2 can be simplified into the circuit for eq 1 in Table I, by considering the load capacitance negligible; by Heaviside's notation the voltage drop across the resistance R_2 of that circuit is given by eq 1. This equation can be derived readily as follows:

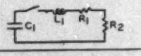
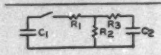
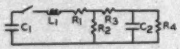
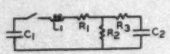
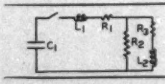
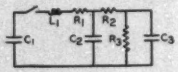
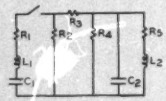
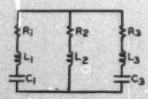
$$E = I\left(\frac{1}{pC_1} + pL_1 + R_1 + R_2\right)$$

$$E_{R_2} = IR_2 = \frac{EA_0p\ 1}{p^3 + A_1p + A_2}$$

The constant terms are defined in Table I. The solution of this equation can be obtained from a table of equivalent operators such as Bush's;[4] the particular form of the solution that will be used will depend upon whether the roots of the denominator are real or complex.

As more constants are placed in the impulse generator circuit, the solutions will become more complex. In the circuit for eq 2 of Table I the series inductance has been neglected, but the capacitance of the load has been considered and another resistance included. Ordinarily, most of the resistances that are in the series path with the load can be con-

Table I—Summary of Formulas for the Solution of Impulse Generator Circuits

Circuits	Equations	Constants
	$E_{R2} = I_{R2}R_2 = \dfrac{EA_0p1}{p^2 + A_1p + A_2}$ (1)	$A_0 = \dfrac{R_2}{L_1}$ $\quad A_1 = \dfrac{R_1 + R_2}{L_1}$ $\quad A_2 = \dfrac{1}{C_1L_1}$
	$E_{C2} = \dfrac{I_{C2}}{pC_2} = \dfrac{EB_0p\,1}{p^2 + B_1p + B_2}$ (2)	$B_0 = \dfrac{R_2}{C_2(R_1R_3 + R_1R_4 + R_3R_4)}$ $\quad B_1 = \dfrac{C_1(R_1 + R_3) + C_2(R_3 + R_4)}{C_1C_2(R_1R_3 + R_1R_4 + R_3R_4)}$ $\quad B_2 = \dfrac{1}{C_1C_2(R_1R_3 + R_1R_4 + R_3R_4)}$
	$E_{C2} = \dfrac{I_{C2}}{pC_2} = \dfrac{ED_0p1}{p^3 + D_1p^2 + D_2p + D_3}$ (3)	$D_0 = \dfrac{R_2}{C_2L_1(R_3 + R_4)}$ $\quad D_1 = \dfrac{1}{C_2R_4} + \dfrac{R_1}{L_1} + \dfrac{L_1 + C_2R_3R_4}{C_2L_1(R_3 + R_4)}$ $\quad D_2 = \dfrac{1}{C_1L_1} + \dfrac{R_1(R_3 + R_4 + R_4) + R_3(R_3 + R_4)}{C_2L_1R_4(R_3 + R_4)}$ $\quad D_3 = \dfrac{1}{C_1C_2L_1(R_3 + R_4)} + \dfrac{1}{C_1C_2L_1R_4}$
	$E_{C2} = \dfrac{I_{C2}}{pC_2} = \dfrac{EF_0p1}{p^3 + F_1p^2 + F_2p + F_3}$ (4)	$F_0 = \dfrac{R_3}{C_2L_1(R_3 + R_4)}$
	$E_{C1} = \dfrac{I_{C1}}{pC_1} = \dfrac{EF_0(pC_2R_3 + pC_2R_4 + 1)1}{p^3 + F_1p^2 + F_2p + F_3}$ (5)	$F_1 = \dfrac{L_1 + C_2(R_1R_3 + R_1R_4 + R_3R_4)}{C_2L_1(R_3 + R_4)}$
	$E_{L1} = I_{L1}pL_1 = I_{C1}pL_1 = \dfrac{EF_0(p^2C_2R_3 + p^2C_2R_4 + p^3)1}{p^3 + F_1p^2 + F_2p + F_3}$ (6)	$F_2 = \dfrac{1}{C_1L_1} + \dfrac{R_1 + R_3}{C_2L_1(R_3 + R_4)}$ $\quad F_3 = \dfrac{1}{C_1C_2L_1(R_3 + R_4)}$ $\quad F_4 = \dfrac{1}{C_2(R_3 + R_4)}$
	$E_{R2} = \dfrac{EG_0(p^2L_2 + pR_3)1}{p^3 + G_1p^2 + G_2p + G_3}$ (7)	$G_0 = \dfrac{R_2}{L_1L_2}$ $\quad G_1 = \dfrac{R_1}{L_1} + \dfrac{R_2}{L_1} + \dfrac{R_2}{L_2}$ $\quad G_2 = \dfrac{1}{C_1L_1} + \dfrac{R_1R_2 + R_1R_3 + R_2R_3}{L_1L_2}$ $\quad G_3 = \dfrac{R_2 + R_3}{C_1L_1L_2}$
	$E_{C3} = \dfrac{EH_0p1}{p^4 + H_1p^3 + H_2p^2 + H_3p + H_4}$ (8)	$H_0 = \dfrac{1}{C_1C_2L_1R_4}$ $\quad H_1 = \dfrac{1}{C_2R_3} + \dfrac{1}{C_1R_4} + \dfrac{1}{C_1R_3} + \dfrac{R_1}{L_1}$ $\quad H_2 = \dfrac{1}{C_1L_1} + \dfrac{1}{C_2L_1} + \dfrac{1}{C_1C_2R_3R_4} + \dfrac{R_1H_1}{L_1}$ $\quad H_3 = \dfrac{R_1 + R_3 + R_4}{C_1C_2L_1R_3R_4} + \dfrac{H_1}{C_1L_1}$ $\quad H_4 = \dfrac{1}{C_1C_2C_3L_1R_3R_4}$ $\quad H_5 = \dfrac{1}{C_1R_3} + \dfrac{1}{C_2R_4} + \dfrac{1}{C_3R_3}$
	$E_{C3} = \dfrac{EK_0(p^3L_3 + pR_4)1}{p^4 + K_1p^3 + K_2p^2 + K_3p + K_4}$ (9)	$K_0 = \dfrac{R_3}{C_2L_1L_3(R_3 + R_4)}$ $\quad K_1 = \dfrac{R_1 + K_5}{L_1} + \dfrac{K_6}{C_2} + \dfrac{R_3}{L_3}$ $\quad K_2 = \dfrac{1}{C_1L_1} + \dfrac{1}{C_2L_1}\left[\dfrac{R_3(R_3 + R_4)}{R_4(R_3 + R_4)} + R_1K_6\right] + \dfrac{1}{C_2L_3} + \dfrac{R_3}{L_3}\left[\dfrac{K_6}{C_2} + \dfrac{R_1 + K_5}{L_1}\right]$ $\quad K_3 = \dfrac{K_6}{C_1C_2L_1} + \dfrac{R_1 + K_5}{C_2L_1L_3} + \dfrac{R_3}{L_1L_3}\left[\dfrac{1}{C_1} + \dfrac{R_1K_6}{C_2} + \dfrac{R_3(R_3 + R_4)}{C_2R_4(R_3 + R_4)}\right]$ $\quad K_4 = \dfrac{1 + R_4K_4}{C_1C_2L_1L_3}$ $\quad K_5 = \dfrac{R_3R_4}{R_3 + R_4}$ $\quad K_6 = \dfrac{R_2 + R_3 + R_4}{R_4(R_3 + R_4)}$
	$E_{C3} = \dfrac{EN_0(p^3L_3 + pR_3)1}{p^4 + N_1p^3 + N_2p^2 + N_3p + N_4}$ (10)	$N_0 = \dfrac{1}{C_3(L_1L_2 + L_1L_3 + L_2L_3)}$ $\quad N_1 = \dfrac{L_1(R_2 + R_3) + L_2(R_1 + R_3) + L_3(R_1 + R_2)}{L_1L_2 + L_1L_3 + L_2L_3}$ $\quad N_2 = \dfrac{R_1R_2 + R_1R_3 + R_2R_3}{L_1L_2 + L_1L_3 + L_2L_3} + \dfrac{C_1(L_1 + L_3) + C_2(L_2 + L_3)}{C_1C_3(L_1L_2 + L_1L_3 + L_2L_3)}$ $\quad N_3 = \dfrac{C_1(R_1 + R_3) + C_2(R_2 + R_3)}{C_1C_3(L_1L_2 + L_1L_3 + L_2L_3)}$ $\quad N_4 = \dfrac{1}{C_1C_3(L_1L_2 + L_1L_3 + L_2L_3)}$

sidered equal to zero if desired. As the denominator of eq 2 is of the second degree, its solution is similar to that of eq 1. The circuit for eq 3 is nearly the same circuit as that in Fig. 2, except that resistance R_3 is in series with the load and resistance R_4 shunts the load as would a divider resistance. This resistance is omitted in the circuit for eq 4; if R_3 of that circuit be considered equal to zero, there is obtained the circuit for Fig. 2 which is probably the most condensed circuit describing an impulse generator with a capacitance load. The solutions for eq 3 and 4 are similar and take the forms shown by equivalent operators 1 and 3 of Appendix III, the form of the solution depending upon whether the 3 roots obtained by equating the denominator to zero are all real or 1 real and 2 complex. The denominators of both eqs 3 and 4 are of the third degree. As there were no available published equivalent operators above the second degree, third-degree equivalent operators were developed; these are listed as Nos. 1 to 5 in Appendix III.

In eq 5 of Table I, only the transient terms of the numerator should be used if the voltage drop across the generator capacitance be required; but if the total voltage on the generator or the total current through it be desired, the total numerator of the right hand term should be used. The complete denominator is used, of course, in both cases. Equation 6 will give either the voltage drop across the series inductance or the current through it, according to its arrangement and solution.

The circuit for eq 7 has an inductive load rather than a capacitive load. As the denominator is of the third degree, its solution is similar to that of eq 4.

The circuit for eq 8 has an extra shunt capacitance to represent the stray capacitance of the generator and leads to ground. The denominator of this equation is of the fourth degree. As with the third-degree equations, there were no available published equivalent operators; therefore, fourth-degree equivalent operators were developed, these being listed as Nos. 6 to 16 in Appendix III.

The circuit for eq 9 shows an impulse generator with a transformer load, where the inductance of the transformer is in the discharge circuit to ground. In the circuit for eq 10 each part of the circuit contains inductance so that its position effect can be analyzed. The solutions of both these circuits are fourth-degree equivalent operators as shown in Appendix III.

These fourth-degree equivalent operators take 3 forms depending upon whether the 4 roots obtained by equating the denominator to zero are all real, 2 real and 2 complex, or all complex. The solving of these third- and fourth-degree equations to obtain the exponents shown in the final solutions in Appendix III may require appreciable time. However, these roots can be determined to as high a degree of accuracy as desired by various methods.

For a third-degree equation, the exact values of the 3 roots in terms of the circuit constants can be obtained by Cardan's formula. For equations of the third or higher degree and where only 2 roots of the equation are complex, Horner's method of extracting approximated roots is applicable. A method that is similar to Horner's method, but which seems to contain less chances for error and which seems easier of solution, is shown in Appendix II. In higher than third-degree equations which may or may not contain more than one pair of complex roots, the root-squaring method of Dandelin, Lobachevsky, and Graffe[9] of extracting roots is applicable.

Waves Resulting From Circuit Calculations

The effect that each circuit constant has on the voltage wave applied to test piece can be shown best by varying each constant separately. The circuit constants of Fig. 2 representing an impulse generator with a capacitance load, were given practical values and by making a series of calculations their effects were shown. For an illustrative set of curves a practically smooth 1.5x40-μsec wave was used as the reference wave.

In this paper the first term of the impulse wave designation, as the 1.5 term, is the time in microseconds from zero time to the time of maximum crest; and the second term, as the 40 term, is the total duration in microseconds of the wave from zero time to the time of half crest amplitude on the tail or decreasing part of the wave. This "2-point" method of wave designation gives a good general description of the wave. The second term is used as the total duration of the wave from zero time to the time of half crest because it is determined easily when waves are calculated, and is easy to read from transcribed oscillograms because of the single time scale. When calculations are made the voltage equation takes the form of eq 3 in Appendix III, for example,

$$E = A[\epsilon^{-\alpha t} - \epsilon^{-\beta t}\{\cos \omega t + B \sin \omega t\}]$$

where A and B are constants. Suppose E_s is the crest voltage; then, since the oscillatory term usually becomes negligible long before the time to half crest is reached, the time t or the duration of the wave to half crest from zero time is given by

$$\frac{E_s}{2} = A\epsilon^{-\alpha t}$$

When the 2 terms of the wave are expressed as decimals, their exact values can be easily expressed and typed; and when the 2 terms are separated by a smaller letter "x," there is no confusion as to their meaning or limit, whereas a dash for separation might be taken as a range of values. This method of impulse wave designation is in accord with recommendations made by the lightning and insulator subcommittee of the A.I.E.E. committee on power transmission and distribution in a report presented at the 1933 A.I.E.E. winter convention (see "Recommendations for Impulse Voltage Testing," Electrical Engineering, v. 52, January 1933, p. 17–22).

Figure 3 shows several waves containing different values of series resistance. As the series resistance is increased the oscillations are damped out and the magnitude of the crest is decreased. The front of the wave first decreases up to some critical value of series resistance, and then increases; but the duration of the wave seems to vary nearly directly with

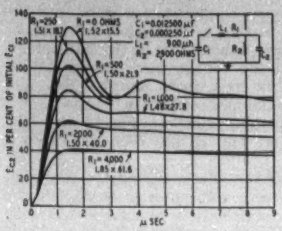


Fig. 3. Effect of varying R_1 on wave shape

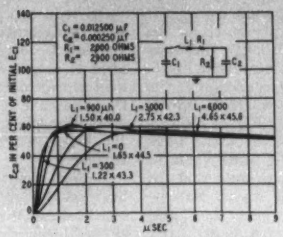


Fig. 5. Effect of varying L_1 on wave shape

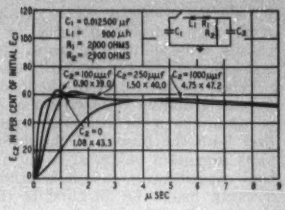


Fig. 7. Effect of varying C_2 on wave shape

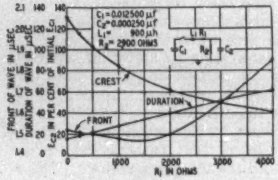


Fig. 4. Front, duration, and crest magnitude of wave vs. R_1

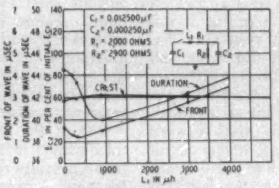


Fig. 6. Front, duration, and crest magnitude of wave vs. L_1

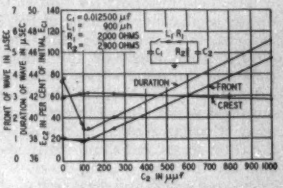


Fig. 8. Front, duration, and crest magnitude of wave vs. C_2

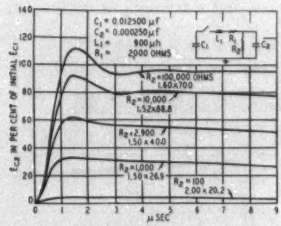


Fig. 9. Effect of varying R_2 on wave shape

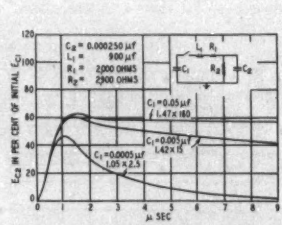


Fig. 11. Effect of varying C_1 on wave shape

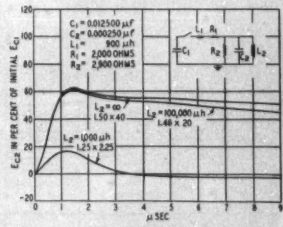


Fig. 13. Effect of varying L_2 on wave shape

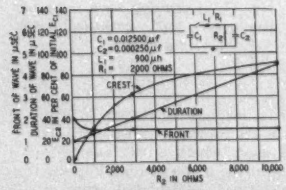


Fig. 10. Front, duration, and crest magnitude of wave vs. R_2

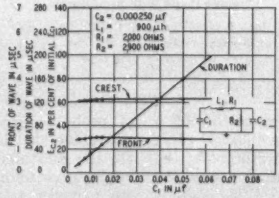


Fig. 12. Front, duration, and crest magnitude of wave vs. C_1

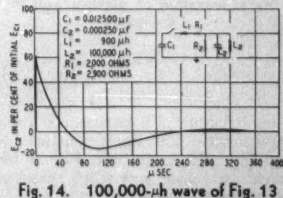


Fig. 14. 100,000-µh wave of Fig. 13 plotted to a smaller scale, showing that the wave is a damped oscillation

with the series resistance. This is shown clearly in Fig. 4. The crest variation also is shown in Fig. 4.

The series inductance was varied in Fig. 5 and the results are shown clearly in Fig. 6. Both the front and the duration of the wave have minimum values

Wave shapes calculated by means of formulas given in this paper (see Table 1). Circuit connections together with values of the circuit constants are indicated on each group of curves. All wave dimensions given are in microseconds as explained in the text

for slightly different values of inductance, but the crest magnitude does not seem to vary much for the chosen variation in inductance. Although the series resistance is high, the oscillating effect is seen in Fig. 5.

What might be termed the load regulation of the impulse generator is shown in Fig. 7, where the effects of variations in the load are shown. Figure 8 shows that both the front and the duration of the wave have minimum points at about the same value of load capacitance. It is interesting to note that for different loads the duration of the waves may be the same, but the front increases in general. Thus, waves with durations of 41 μsec have a 1-μsec front for a 60-$\mu\mu$f load and a 2-μsec front for a 350-$\mu\mu$f load. Figure 8 shows also that small variations in the load do not greatly affect the crest magnitude.

The damping effect that low shunt resistances have on the oscillations is shown in Fig. 9. In Fig. 10 it is evident that ordinarily the shunt resistance has only a small effect on the front of the wave, but that the duration varies almost directly with this resistance. Since it was shown in Fig. 4 that the duration varies almost directly with the series resistance, it seems evident that a relation exists between the total series and shunt resistance, R, in the circuit and the duration of the wave, t. For small loads, calculated waves and measured oscillograms show that the relation is $t \cong 0.7\ RC$. The constant C represents the capacitance of the generator, and if expressed in microfarads the time t is expressed in microseconds. This same relation exists in the simple circuit of a capacitance discharging through a resistance. The shunt resistance also has an effect on the crest magnitude, Fig. 10 indicating that the crest increases apparently exponentially with the resistance.

The fifth of the circuit constants to be considered is the capacitance of the impulse generator. Figure 11 shows that small variations in this capacitance do not alter the wave greatly. Figure 12 shows that the front and the crest are not changed appreciably by small variations in C_1, but that the duration varies nearly directly with C_1. This last observation is well expressed in the relation $t \cong 0.7\ RC$.

An inductance can be placed in parallel with the load capacitance so that a transformer load can be simulated. Figure 13 shows that as the load inductance is decreased the voltage wave applied to the load is decreased in crest, front, and duration, and that the wave is a damped oscillation. This damped oscillation effect is shown clearly in Fig. 14 where the 100,000-μh wave of Fig. 13 has been drawn to a smaller scale.

Besides showing the effects the circuit constants have on the test-piece voltage, other characteristics can be learned by calculations about the generator circuit during discharge. In Fig. 15 it is shown that at the first instant of discharge the entire voltage drop is across the series inductance; but this voltage drop soon decreases to zero and at that instant the current from the generator capacitance is a maximum. Figure 15 also shows that the charging current of the load is zero when the load voltage is a maximum. It is interesting to note that, although the components of the voltage drops are quite variable, the voltage of the generator capacitance decreases at a nearly smooth rate.

One of the primary values of impulse generator calculations is to prove that cathode ray oscillograms actually record the test-piece voltage. Figure 16 shows a calculated wave for a capacitance load and upon it is represented a transcribed oscillogram for the same circuit conditions. The 2 waves nearly coincide.

A calculated wave and a transcribed oscillogram of probably greater interest is shown in Fig. 17 where the load is a transformer. Figure 17 shows: (1) the measured wave which is the average of 3 oscillograms taken during a commercial impulse test on a power transformer; calculated waves; (2) neglecting the capacitance of the transformer load ($C_2 = 0$); (3) neglecting the inductance of the transformer load ($L_2 = \infty$); and (4) considering the inductance and capacitance of the transformer load. The close check between the oscillogram wave and the calculated wave where both the inductance and the capacitance have been considered shows the importance of considering the constants of the load

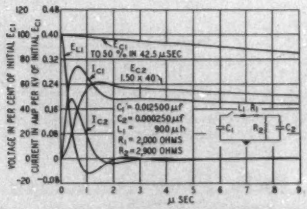


Fig. 15. Calculated wave shapes of waves impressed on different parts of the circuit

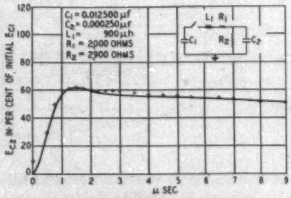


Fig. 16. Comparison of calculated wave shape with oscillogram

The calculated wave is 1.5x40 μsec; the oscillogram represented by the crosses apparently is the same

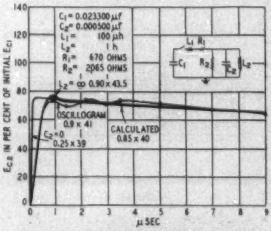


Fig. 17. Calculated wave shape for transformer load, compared with oscillogram

added to the impulse generator, and the agreement that can be obtained between oscillograms and calculations when the calculations are made correctly.

Appendix I—Inductance of Generator Circuit

By means of 2 formulas from the Scientific Papers of the U.S. Bureau of Standards,[10] the inherent series inductance in the discharge circuit of the impulse generator can be calculated.

The leads and the banks of capacitors will form V-shaped paths, the inductance of which may be considered that of 2 parallel wires of radius p centimeters, of length h centimeters corresponding to the height of the V, and of distance d centimeters apart equal to half the base of the V. The formula for each V is then

$$L = 4h\left(\log_e \frac{d}{p} + \frac{1}{4} - \frac{d}{h}\right) \times 10^{-3} \text{ microhenries}$$

The inductance of these V's form about $^2/_3$ of the inherent series inductance of the generator.

The remainder of the inherent inductance of the generator is approximately equivalent to $^5/_8$ of the inductance of a square of sides a centimeters in length. For ease in computation the conductor is considered of square section and of α centimeters on a side. Small variations in α do not affect the total inductance greatly. The formula for the total inductance of the square is

$$L = 8a\left(\log_e \frac{a}{\alpha} + 0.477\frac{\alpha}{a} + 0.033\right) \times 10^{-3} \text{ microhenries}$$

Of course, approximately only $^5/_8$ of this inductance will be added to the inductance of all the V's in order to determine the total series inherent inductance of the impulse generator circuit.

Appendix II—Method of Root Extraction for Equations Containing Not Over 2 Complex Roots

Suppose a third degree equation be considered.

$$p^3 + k_3p^2 + k_2p + k_4 = 0 = (p - p_1)(p - p_2)(p - p_3)$$

Arrange the coefficients of the equation so that the first root can be obtained by a method similar to long division.

$$\begin{array}{lll|l} 1 + k_2 & + k_3 & + k_4 & \\ \quad\alpha & + \alpha(k_2 - \alpha) & + \alpha[k_3 - \alpha(k_2 - \alpha)] & \alpha \\ \hline 1 + (k_2 - \alpha) & + k_3 - \alpha(k_2 - \alpha) & + \epsilon & \\ \quad\alpha & +\alpha(k_2 - 2\alpha) & & \\ \hline 1 + (k_2 - 2\alpha) & [k_3 - \alpha(2k_2 - 3\alpha)] & & \end{array}$$

The nearer that k_4 minus $\alpha[k_3 - \alpha(k_2 - \alpha)]$ or ϵ approaches zero, the more accurate the roots of the equation will be determined. If the difference, ϵ, is zero, the remainder $1 + (k_2 - \alpha) + [k_3 - \alpha(k_2 - \alpha)]$ may be written as $1 + (A) + (B)$. This corresponds to the quadratic equation $p^2 + Ap + B = 0$ with solutions

$$p_1 = \frac{-A + \sqrt{A^2 - 4B}}{2}$$

and

$$p_2 = \frac{-A - \sqrt{A^2 - 4B}}{2}$$

These roots, of course, may be real or complex. The first root would have to be real, and as determined above would be $p_1 = -\alpha$.

As long as there are not more than 2 complex roots in an equation of any degree usually the real roots can be extracted in a manner similar to the method by which the root $p_1 = -\alpha$ was obtained.

In the preceding development, should ϵ not be equal to zero upon the first trial, the division process may be repeated and a second remainder obtained. This second remainder $[k_3 - \alpha(2K_2 - 3\alpha)]$ may be divided into ϵ to obtain a correction for α. If the correction be positive, it should be added to the first value of α to obtain a more nearly correct value of α. If the correction be negative, α is too large by approximately that amount and should be reduced.

Appendix III—Equivalent Operators

Where $P_1 = -\alpha$, $P_2 = -\beta + \omega$, and $P_3 = -\beta - \omega$ for $n = 0, 1, 2$, or 3

$$\frac{P^n\,1}{P^3 + K_3P^2 + K_2P + K_4} = \frac{(-\alpha)^{n-1}\epsilon^{-\alpha t}}{(\alpha - \beta)^2 - \omega^2} + \frac{(-\beta + \omega)^{n-1}\epsilon^{(-B+\omega)t}}{2\omega(\alpha - \beta - \omega)} + \frac{(-\beta - \omega)^{n-1}\epsilon^{(-B-\omega)t}}{-2\omega(\alpha - \beta - \omega)} + R \quad (1)$$

$R = \frac{1}{K_4}$ for $n = 0$; $R = 0$ for $n = 1, 2$, or 3

Where $P_1 = \alpha$, $P_2 = -\beta + j\omega$, and $P_3 = -\beta - j\omega$

$$\frac{1}{P^3 + K_3P^2 + K_2P + K_4} = \frac{1}{(\alpha - \beta)^2 + \omega^2}\left[\begin{matrix}\epsilon^{-\alpha t}\\ -\alpha\end{matrix} - \epsilon^{-\beta t}\left\{\frac{\alpha - 2\beta}{\beta^2 + \omega^2}\cos\omega t + \frac{(\omega^2 + \alpha\beta - \beta^2)}{\omega(\beta^2 + \omega^2)}\sin\omega t\right\}\right] + \frac{1}{K_4} \quad (2)$$

$$\frac{P^1}{P^3 + K_3P^2 + K_2P + K_4} = \frac{1}{(\alpha - \beta)^2 + \omega^2}\left[\epsilon^{-\alpha t} - \epsilon^{-\beta t}\left\{\cos\omega t + \frac{\beta - \alpha}{\omega}\sin\omega t\right\}\right] \quad (3)$$

$$\frac{P^2\,1}{P^3 + K_3P^2 + K_2P + K_4} = \frac{1}{(\alpha - \beta)^2 + \omega^2}\left[-\alpha\epsilon^{-\alpha t} - \epsilon^{\beta t}\left\{-\alpha\cos\omega t - \frac{\beta^2 + \omega^2 - \alpha\beta}{\omega}\sin\omega t\right\}\right] \quad (4)$$

$$\frac{P^3\,1}{P^3 + K_3P^2 + K_2P + K_4} = \frac{1}{(\alpha - \beta)^2 + \omega^2}\left[\alpha^2\epsilon^{-\alpha t} - \epsilon^{-\beta t}\left\{(2\alpha\beta - \beta^2 - \omega^2)\cos\omega t + \frac{\beta^3 - \beta^2\alpha + \beta\omega^2 + \alpha\omega^2}{\omega}\sin\omega t\right\}\right] \quad (5)$$

Where $P_1 = -\alpha$, $P_2 = -\beta$, $P_3 = -\gamma$, and $P_4 = -\delta$ for $n = 0, 1, 2, 3$, or 4

$$\frac{P^n\,1}{P^4 + K_3P^3 + K_2P^2 + K_1P + K_5} = \frac{(-\alpha)^{n-1}\epsilon^{-\alpha t}}{A_1} + \frac{(-\beta)^{n-1}\epsilon^{-\beta t}}{A_2} + \frac{(-\gamma)^{n-1}\epsilon^{-\gamma t}}{A_3} + \frac{(-\delta)^{n-1}\epsilon^{-\delta t}}{A_4} + R \quad (6)$$

$R = \frac{1}{K_5}$ for $n = 0$; $R = 0$ for $n = 1, 2, 3$, or 4

$$\begin{aligned}
A_1 &= -\alpha^3 + \alpha^2(\beta + \gamma + \delta) - \alpha(\beta\gamma + \beta\delta + \gamma\delta) + \beta\gamma\delta\\
A^2 &= -\beta_3 + \beta^2(\alpha + \gamma + \delta) - \beta(\alpha\gamma + \alpha\delta + \gamma\delta) + \alpha\gamma\delta\\
A_3 &= -\gamma^3 + \gamma^2(\alpha + \beta + \delta) - \gamma(\alpha\beta + \alpha\delta + \beta\delta) + \alpha\beta\delta\\
A_4 &= -\delta^3 + \delta^2(\alpha + \beta + \gamma) - \delta(\alpha\beta + \alpha\gamma + \beta\gamma) + \alpha\beta\gamma
\end{aligned}$$

Where $P_1 = -\alpha$, $P_2 = -\beta$, $P_3 = -\gamma + j\omega$, and $P_4 = -\gamma - j\omega$

$$\frac{1}{P^4 + K_3P^3 + K_2P^2 + K_1P + K_5} = \frac{\epsilon^{-\alpha t}}{-\alpha A_1} + \frac{\epsilon^{-\beta t}}{-\beta A_2} + \frac{2\epsilon^{-\gamma t}}{A_3^2 + A_4^2}\left[\frac{(-A_3\gamma - A_4\omega)\cos\omega t + (A_3\omega - A_4\gamma)\sin\omega t}{\gamma^2 + \omega^2}\right] + \frac{1}{K_5} \quad (7)$$

$$\frac{P^1}{P^4 + K_3P^3 + K_2P^2 + K_1P + K_5} = \frac{\epsilon^{-\alpha t}}{A_1} + \frac{\epsilon^{-\beta t}}{A_2} + \frac{2\epsilon^{-\gamma t}}{A_3^2 + A_4^2}\left[A_7\cos\omega t + A_8\sin\omega t\right] \quad (8)$$

$$\frac{P^2\,1}{P^4 + K_3P^3 + K_2P^2 + K_1P + K_5} = \frac{-\alpha\epsilon^{-\alpha t}}{A_1} + \frac{-\beta\epsilon^{-\beta t}}{A_2} + \frac{2\epsilon^{-\gamma t}}{A_3^2 + A_4^2}\left[(-A_7\gamma + A_8\omega)\cos\omega t - (A_7\omega + A_8\gamma)\sin\omega t\right] \quad (9)$$

$$\begin{aligned}
A_1 &= -\alpha^3 + \alpha^2(\beta + 2\gamma) - \alpha(\gamma^2 + \omega^2 + 2\beta\gamma) + \beta(\gamma^2 + \omega^2)\\
A_2 &= -\beta^3 + \beta^2(\alpha + 2\gamma) - \beta(\gamma^2 + \omega^2 + 2\alpha\gamma) + \alpha(\gamma^2 + \omega^2)\\
A_7 &= -2\omega^2(\alpha + \beta - 2\gamma)\\
A_8 &= 2\omega(\gamma^2 - \omega^2 + \alpha\beta - \alpha\gamma - \beta\gamma)
\end{aligned}$$

$$\frac{P^3\,1}{P^4+K_3P^3+K_2P^2+K_4P+K_5}=\frac{\alpha^3\epsilon^{-\alpha t}}{A_4}+\frac{\beta^3\epsilon^{-\beta t}}{A_4}+\frac{2\epsilon^{-\gamma t}}{A_7^2+A_8^2}\cdot$$
$$\left[\left\{A_7(\gamma^2-\omega^2)-2A_8\gamma\omega\right\}\cos\omega t+\left\{2A_7\gamma\omega+A_8(\gamma^2-\omega^2)\right\}\sin\omega t\right] \quad (10)$$

$$\frac{P^4\,1}{P^4+K_3P^3+K_2P^2+K_4P+K_5}=\frac{\alpha^3\epsilon^{-\alpha t}}{-A_4}+\frac{\beta^3\epsilon^{-\beta t}}{-A_4}+\frac{2\epsilon^{-\gamma t}}{A_7^2+A_8^2}\cdot$$
$$\left[\left\{A_7\gamma(3\omega^2-\gamma^2)+A_8\omega(3\gamma^2-\omega^2)\right\}\cos\omega t+\right.$$
$$\left.\left\{A_7\omega(\omega^2-3\gamma^2)+A_8\gamma(3\omega^2-\gamma^2)\right\}\sin\omega t\right] \quad (11)$$

Where $P_1=-\alpha+j\omega$, $P_2=-\alpha-j\omega$, $P_3=-\beta+j\Omega$, and $P_4=-\beta-j\Omega$

$$\frac{1}{P^4+K_3P^3+K_2P^2+K_4P+K_5}=\epsilon^{-\alpha t}$$
$$\left[\frac{-(\alpha A_9+\omega A_{10})\cos\omega t+(\omega A_9-\alpha A_{10})\sin\omega t}{\omega(A_9^2+A_{10}^2)(\alpha^2+\omega^2)}\right]$$
$$+\epsilon^{-\beta t}\left[\frac{-(\beta A_{11}+\Omega A_{12})\cos\Omega t+(\Omega A_{11}-\beta A_{12})\sin\Omega t}{\Omega(A_{11}^2+A_{12}^2)(\beta^2+\Omega^2)}\right]$$
$$+\frac{1}{K_5} \quad (12)$$

$$\frac{P\,1}{P^4+K_3P^3+K_2P^2+K_4P+K_5}=\epsilon^{-\alpha t}\left[\frac{A_9\cos\omega t+A_{10}\sin\omega t}{\omega(A_9^2+A_{10}^2)}\right]$$
$$+\epsilon^{-\beta t}\left[\frac{A_{11}\cos\Omega t+A_{12}\sin\Omega t}{\Omega(A_{11}^2+A_{12}^2)}\right] \quad (13)$$

$$\frac{P^2\,1}{P^4+K_3P^3+K_2P^2+K_4P+K_5}=\epsilon^{-\alpha t}$$
$$\left[\frac{-(\alpha A_9-\omega A_{10})\cos\omega t-(\omega A_9+\alpha A_{10})\sin\omega t}{\omega(A_9^2+A_{10}^2)}\right]+\epsilon^{-\beta t}$$
$$\left[\frac{-(\beta A_{11}-\Omega A_{12})\cos\Omega t-(\Omega A_{11}+\beta A_{12})\sin\Omega t}{\Omega(A_{11}^2+A_{12}^2)}\right] \quad (14)$$

$$A_9=2\omega(\alpha-\beta)$$
$$A_{10}=(\Omega^2-\omega^2)+(\alpha-\beta)^2$$
$$A_{11}=2\Omega(\beta-\alpha)$$
$$A_{12}=(\omega^2-\Omega^2)+(\alpha-\beta)^2$$

$$\frac{P^2\,1}{P^4+K_3P^3+K_2P^2+K_4P+K_5}=\frac{\epsilon^{-\alpha t}}{\omega(A_9^2+A_{10}^2)}$$
$$\left[\left\{A_9(\alpha^2-\omega^2)-2A_{10}\alpha\omega\right\}\cos\omega t+\left\{2A_9\alpha\omega+A_{10}(\alpha^2-\omega^2)\right\}\right.$$
$$\left.\sin\omega t\right]+\frac{\epsilon^{-\beta t}}{\Omega(A_{11}^2+A_{12}^2)}\left[\left\{A_{11}(\beta^2-\Omega^2)-2A_{12}\beta\Omega\right\}\cos\Omega t+\right.$$
$$\left.\left\{2A_{11}\beta\Omega+A_{12}(\beta^2-\Omega^2)\right\}\sin\Omega t\right] \quad (15)$$

$$\frac{P^4\,1}{P^4+K_3P^3+K_2P^2+K_4P+K_5}=\frac{\epsilon^{-\alpha t}}{\omega(A_9^2+A_{10}^2)}$$
$$\left[\left\{A_9(-\alpha^3+3\alpha\omega^2)+A_{10}(3\alpha^2\omega-\omega^3)\right\}\cos\omega t+\right.$$
$$\left.\left\{A_9(\omega^3-3\alpha^2\omega)+A_{10}(-\alpha^3+3\alpha\omega^2)\right\}\sin\omega t\right]+$$
$$\frac{\epsilon^{-\beta t}}{\Omega(A_{11}^2+A_{12}^2)}\left[\left\{A_{11}(-\beta^3+3\beta\Omega^2)+A_{12}(3\beta^2\Omega-\Omega^3)\right\}\right.$$
$$\left.\cos\Omega t+\left\{A_{11}(\Omega^3-3\beta^2\Omega)+A_{12}(-\beta^3+3\beta\Omega^2)\right\}\sin\Omega t\right] \quad (16)$$

Bibliography

1. The Effect of Transient Voltages on Dielectrics, F. W. Peek, Jr. A.I.E.E. Trans., v. 34, 1915, p. 1857–1909.

2. Impulse Testing Technique, Foust, Kuehni, and Rohats. *Gen. Elec. Rev.*, July 1932, p. 358–66.

3. Characteristics of Surge Generators for Transformer Testing, P. L. Bellaschi. A.I.E.E. Trans., v. 51, 1932, p. 936–45.

4. Operational Circuit Analysis (a book), V. Bush. John Wiley and Sons, New York, N. Y.

5. Shunt Resistors for Reactors, Kierstead, Rorden, and Bewley. A.I.E.E. Trans., v. 49, 1930, p. 1161–77.

6. Laboratory Measurements of Impulse Voltages, C. M. Foust and J. C. Dowell. A.I.E.E. Trans., v. 52, 1933, p. 537–43.

7. Laboratory Measurements of Impulse Testing, L. V. Bewley's discussion of paper. A.I.E.E. Trans., v. 52, 1933, p. 555–7.

8. Effects of Short Lengths of Cable on Traveling Waves, McEachron, Hemstreet, and Seelye. A.I.E.E. Trans., v. 49, 1930, p. 885–94.

9. Calculus of Observations (a book), Whittaker and Robinson. D. Van Nostrand Company, New York, N. Y.

10. Scientific Papers of the U.S. Bureau of Standards, No. 169. Formulas and tables for the calculation of mutual and self-inductance. Dec. 1916.

Portable Schering Bridge for Field Tests

A portable Schering bridge which is applicable for power factor, dielectric loss, and capacitance tests on condenser bushings and other equipment of higher capacitance in the field is described in this paper, and operating procedure is given. Such tests are desirable for forestalling failures of equipment. Although earlier power factor tests on bushings have been made in the field, this is probably the first application of the Schering bridge to field tests.

By
C. F. HILL
MEMBER A.I.E.E.

T. R. WATTS
ASSOCIATE A.I.E.E.

G. A. BURR
ASSOCIATE A.I.E.E.

All of the Westinghouse Elec. and Mfg. Co., East Pittsburgh, Pa.

THE attention given to bushings in service has not kept pace with the increasing service demand throughout the years. This is not negligence on the part of the operating companies, as they have always serviced bushings by the best available means. Generally a bushing has been put into service and operated for life, or until it failed, with only routine surface inspection. The change of apparatus from indoor to outdoor operation, the

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Dec. 12, 1933. *Not published in pamphlet form.*

steady increase of line insulation to prevent circuit flashover, the extension and interconnection of lines have subjected bushings to higher and more frequent overvoltages.

The effort expended by operating companies to inspect and service apparatus in order to give to the public reliable and continuous service warrants a more effective test for bushings than has been available in the past. Dielectric loss measurements detect deterioration of insulation which might later cause failure. However, a portable instrument for the measurement of dielectric loss was not available for purchase and use by the power companies until the Schering bridge here described was developed. Although designed primarily for power factor, dielectric loss, and capacitance tests on condenser bushings in circuit breakers and transformers, this portable Schering bridge also is adaptable to the testing of equipment of higher capacitance, such as cables, and for miscellaneous laboratory uses.

Construction Features

In Fig. 1 is shown a schematic diagram of the apparatus, which is a Schering bridge designed for "inverted" operation, to permit testing capacitors having one terminal grounded. The testing potential is 13.8 kv, which has been found adequate for finding faults, even in 230-kv bushings.

In Fig. 2 is shown the experimental model of the portable inverted Schering bridge, as used in obtaining the results herein reported. The manually operated decade resistors, decade capacitors, shield balancing controls, galvanometer, and all the parts which in conventional laboratory bridges are very near ground potential, are at 13.8-kv potential from ground in this set. Therefore, they are enclosed in a metal box or shield which is balanced to galvanometer potential, and this box is enclosed in a grounded box. The knobs on the front panel are connected to their respective instruments by insulating shafts which have metallic bearings on the inner panel or shield to prevent shaft leakage currents from entering the bridge circuit. In the experimental unit, Fig. 2, the lower cabinet contains a small air cooled testing transformer, a panel of switches and signal lamps, and a cylindrical standard air capacitor of 165 $\mu\mu f$.

A new design, now built, includes a no-loss standard capacitor in the upper cabinet which utilizes the capacitance between the inner and outer boxes. A strip around the ends, top, and bottom of the inner box comprises the active electrode, while the front and back serve as guard rings. The transformer and the low voltage switching are mounted on the table which supports the instrument case, as shown in Fig. 3.

The cable which connects the set to the high voltage terminal of the capacitor under test has an inner shield which is balanced to the same potential as the central wire, thus eliminating losses from wire to shield; and also has an outer shield which is grounded.

A reflecting vibration galvanometer is used because of its simplicity and its sensitivity to the fundamental frequency only.

If desired, the set can be made convertible for use in the conventional laboratory manner (i. e., not inverted, but with ground at instrument end) for testing at voltages above 13.8 kv, with auxiliary standard capacitor and transformer designed for the voltage to be used.

Operation

The inverted Schering bridge is operated in the same manner as the conventional laboratory type.

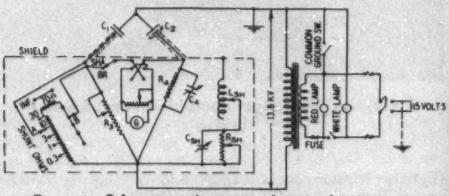


Fig. 1. Schematic diagram of complete circuit (except film cut-out)

Shunt switch points A and B are always opposite, being moved by same knob

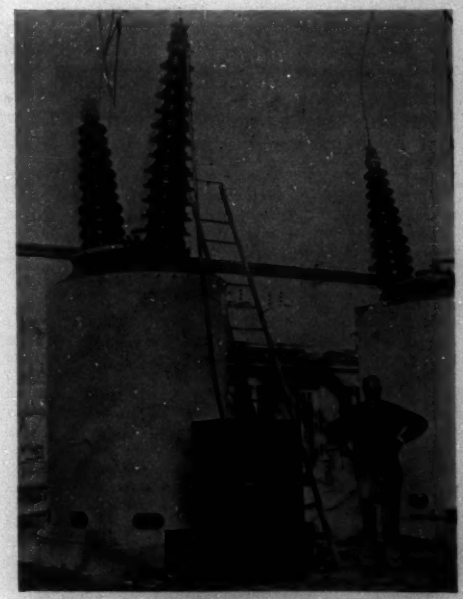


Fig. 2. Experimental model of the portable inverted Schering bridge used in obtaining the results given in this paper

Referring to Fig. 1, the galvanometer switch is turned to the shield position and the shield is balanced approximately by manipulation of the shield impedance, R_{SH}, L_{SH}, and C_{SH}. Then the galvanometer switch is turned to the bridge position, and balanced to a null reading by simultaneous manipulation of the decade resistors R_3 and the decade capacitors C_4. In most bushing tests the shield impedance can be shorted out entirely without appreciable error in readings, but in testing insulation samples of very small capacitance or very low power factor it is necessary to balance the shield if high accuracy is required.

The existence of interference affecting only the galvanometer, such as an alternating current magnetic field, can be detected by turning the galvanometer reversing switch. Such interference is nearly always negligible, but if not the bridge can be rebalanced with the galvanometer reversed, and the readings averaged.

Errors due to interference from an electrostatic field, such as from a high voltage line overhead, can usually be eliminated by averaging readings taken with the 115-volt supply line reversed, but occasionally special shielding may be required.

In the following equations, the symbols used are:

C_{1s} = equivalent series capacitance of the specimen
C_{1p} = equivalent parallel capacitance of the specimen
C_2 = fixed capacitance of standard air capacitor
C_4 = decade capacitor microfarads. (Range 0 to 11.111)
R_3 = decade resistor ohms. (Range 0 to 1111.11)
R_4 = fixed resistor ohms. $\frac{(100{,}000)}{2\pi f}$
Y = shunt ohms, indicated at shunt switch-point. (0.3, 1, 3, 10, or 30)
θ = phase angle. ($\cos\theta$ = power factor)

When the bridge is balanced:

$$\frac{C_4}{10} = \cot\theta$$

Specimens tested with less than 50 ma charging current (i. e., C_{1s} less than 9,600 $\mu\mu$f for 13.8-kv 60-cycle test) do not require the use of a shunt across R_3, and the shunt switch is placed at the "INF." point; then

$$C_{1s} = C_4\frac{R_4}{R_3}$$

For specimens of larger capacitance,

$$C_{1s} = C_4R_4\frac{100 + R_3}{YR_3}$$

The total resistance from the galvanometer terminal to the end of the shunts is 100 ohms. Although part of this resistance is connected in series with the specimen when using the shunts, its effect on the power factor of the specimen is negligible.

$$C_{1p} = C_{1s}\sin^2\theta$$

For low power factors it is permissible to assume

$$C_{1s} = C_{1p} \text{ and } \cos\theta = \cot\theta$$

Ordinarily no correction is required for power factors less than 0.10. In practice a correction curve is used which shows values of power factor and $\sin^2\theta$ corresponding to any value of C_4.

The proofs of the above statements are not given here, having been covered in previous Schering bridge literature. (See "Alternating Current Bridge Methods," by B. Hague, Sir Isaac Pitman and Sons, Ltd., revised, 1930; and "Testing High-Tension Impregnated Paper-Insulated, Lead-Covered Cable," by E. S. Lee, A.I.E.E. TRANS., v. 44, 1925, p. 104–16.)

It will be noted that the inverted bridge, Fig. 1, and the ordinary laboratory bridge, will not give exactly the same readings on the same condenser bushings when tested in the laboratory. The inverted bridge always reads the total capacitance between the high voltage terminal of the bushing and ground, which includes, in parallel with the internal capacitance of the bushing itself, the external capacitance from the high voltage ends of the bushing to all surrounding grounded objects. In the ordinary laboratory bridge circuit, the flange of the bushing is not grounded and the bridge reads the internal capacitance of the bushing plus the external capacitance from the flange to the ends of the bushing and the high voltage lead connected thereto. Thus the readings by the inverted bridge show a

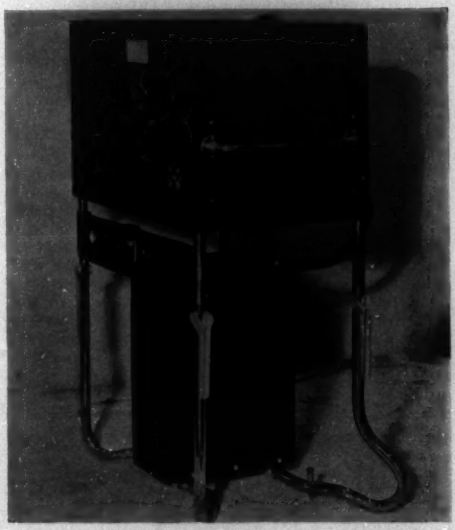


Fig. 3. A new design of portable inverted Schering bridge

slightly higher capacitance and a slightly lower power factor than is shown by the ordinary laboratory arrangement, but the difference is small. For example, a 66-kv bushing, set up in a vertical position on a wooden stand in the laboratory, measured 0.0115 power factor, 149.0 $\mu\mu$f by the in-

verted Schering bridge, and 0.0134 power factor, 137.3 $\mu\mu f$ by the same bridge used noninverted and also by a laboratory Schering bridge.

When the bushing is tested in its tank, the capacitance read by any method is that of the bushing plus its capacitance to tank wall, etc., and is not a true capacitance of the bushing. The small error due to inversion is therefore of no importance.

For laboratory work or where extreme accuracy is desired, the test specimen can be shielded so that both the error in capacitance and the error in power factor practically disappear.

Accuracy, Sensitivity, and Range

The accuracy of the bridge is dependent upon the accuracy of the calibrated resistors and capacitors, and also to a very large extent upon the proper shielding of the specimen.

The sensitivity is sufficient to read at least 3 significant figures in power factor and 4 significant figures in capacitance. The sensitivity depends upon the test voltage, the galvanometer, and the values of C_2, R_3, R_4, and C_4, and is not affected by the inversion of the circuit.

The range in power factor is from 0.0000 to about 0.7432 (i.e., to $\cot\theta = 1.111$). The minimum capacitance readable is determined by the capacitance of the standard C_2, the maximum resistance of R_3, and the frequency. For the bridge now being built the minimum is $C_{1s} = C_2 \frac{R_4}{R_3} = 200\ \mu\mu f \times \frac{100{,}000}{2\pi f \times 1{,}111.11 \text{ ohms}} = 200\ \mu\mu f \times \frac{90}{2\pi f} = \frac{18{,}000}{2\pi f}$. This minimum C_{1s} is therefore 47.8 $\mu\mu f$ at 60 cycles, 57.3 $\mu\mu f$ at 50 cycles, and 114.6 $\mu\mu f$ at 25 cycles. The maximum readable capacitance is determined by the current carrying capacity of the testing transformer and the shunts for the R_3 arm of the bridge.

The shunts in these sets, as ordinarily built, have a maximum current rating of 10 amp.

The field set uses a potential transformer. A larger transformer is required when the shunts are needed.

General Questions of Bushing Tests

Although the value of a-c loss tests for investigating insulation characteristics has been known for a long time, a test of this nature has been used as a field test only in recent years.

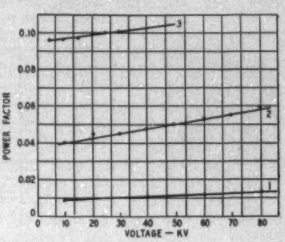
There may be some question raised as to the reliability of a power factor taken at 13.8-kv on bushings that have normal operating voltage above this test voltage. From curves in Fig. 4 it can be seen that the power factor change with increased voltage is not erratic, but is a gradual increase from 10 kv to voltage above the normal rating of the bushings. The curves show that the higher the power factor the greater is the change in power factor with increasing voltage. The curves show that a test at 13.8 kv is a very fair representation of the bushing loss at rated voltage. Wherever a test has shown a defective bushing at normal operating voltage, the bushing also has been shown defective on the 13.8-kv test.

Fig. 4. Power factor versus test voltage

Curve 1. 66-kv bushing. Operating voltage 39.9 kv

Curve 2. 115-kv bushing. Operating voltage 66.4 kv.

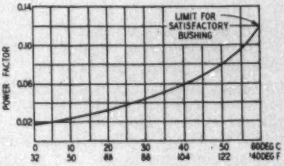
Curve 3. 34.5-kv bushing. Operating voltage 19.9 kv



There is an increase in power factor with increase of temperature and the higher the power factor the more rapid is the increase. The power-factor-temperature curve in Fig. 5 was created from laboratory investigations and has been used in our field tests for interpreting the test results on the condenser type bushings. We would expect any condenser bushing having a power factor falling on or below the curve to meet the standard one minute acceptance test. The curve has not been used as a sharp dividing line between what constitutes a good and a poor bushing. A bushing with a power factor approaching or extending slightly beyond the curve was held in suspicion, and the procedure taken depended upon whether periodic tests were to be made, whether the bushing was located where an interruption meant serious trouble, or whether the type of bushing had materials which might have inherent high losses. With all the data already obtained by the different companies, it will probably be several years before a fairly definite statement can be made as to the power factor which represents a satisfactory bushing for service. The power factor tests may eventually show the best results when interpreted on a comparison basis; that is, tests made

Fig. 5. Power factor limits for condenser bushing

Condenser bushings with power factors on or below curves are believed to be satisfactory. Immediately above curve and of uncertain height is a doubtful zone in which bushings are probably satisfactory



Tests should be made with the bushing disconnected from all lines
Testing when bushing is below 60 deg F is not recommended

periodically and compared with previous tests to show any changes which may have taken place. Comparisons with similar bushings will also be of value. A high power factor may be the natural power factor of the bushing, and if the power factor remains constant, satisfactory service should be expected. In other words, a 0.03 to 0.04-power

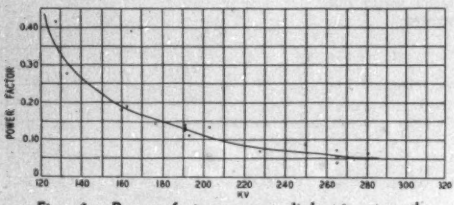


Fig. 6. Power factor versus dielectric strength

Power factor-voltage curve on experimental bushings of the same physical dimensions is shown

Power factor values were at 100 deg C

Voltage test with lower end of bushing in 70 deg C oil 130 kv applied for 10 hr and raised 15 kv each succeeding 10 hr

factor bushing that remains constant from year to year may be safe, whereas a bushing that changes from 0.01 or 0.015 power factor to 0.025 or 0.03 power factor may be unsafe.

The majority of bushing troubles are due to moisture entering the bushing. In most types of bushings the process of deterioration caused by the moisture is slow, and it is the authors' opinion that the presence of moisture in a bushing can be determined by the power factor test long before it reaches a dangerous condition. As power factor is more pronounced at higher temperatures it is preferable to make the test at a time when the temperature of the apparatus is not lower than 60 deg F.

Methods of Testing
Circuit Breakers in the Field

To test a circuit breaker, the leads are disconnected from the bushings at the top and the lead from the testing set is attached. Tests are made with the breaker closed, and then on each bushing by itself with the breaker opened. The combined readings give a definite story of the insulating condition of the oil, lift rods, and bushings of the breaker.

Testing without disconnecting the bushing from the lead to the disconnecting switch is faster, but has disadvantages which lessen the value of the bushing test. *First*, the disconnecting switch loss is included in the test. *Second*, the pick-up interference on the disconnecting switch and the lead between the bushing and the switch affects the reading, and makes it necessary to obtain a value from the average of 2 readings taken by reversing the 115-volt line to the testing set. *Third*, the capacitance of the bushing is not obtained. The capacitance of the bushings should be watched as closely as the power factor values. If the bushing is partly punctured and the punctured path charred so as to be conducting, the power factor will read normal. The capacitance will increase, and it is the capacitance which must be depended upon to detect the partial failure. *Fourth*, the comparison between tests is made difficult and uncertain.

An abnormal reading from a bushing tested alone, in the breaker, indicates bushing faults. Abnormal readings from both bushings, when tested separately on the same breaker unit, indicate both bushings at fault, or more likely high power factor oil. Normal readings on the bushings in a unit, and abnormal readings from the unit with breaker closed indicate lift rod and guide trouble.

Procedure for Localizing the Causes of Abnormal Values

If indications are that the bushing is at fault the following steps are taken. After each step the power factor test is repeated.

1. The exposed porcelain is shielded to eliminate surface leakage.
2. The oil is dropped in the circuit breaker and the porcelain arc shield surface is cleaned.
3. The porcelain arc shield is removed and the oil end of the bushing cleaned. If there is any question of the condition of the oil in the arc shield chamber, power factor and dielectric breakdown tests are made on it.

If the values are not reduced to normal by procedures 1, 2, or 3, above, the insulation of the bushing is at fault and the bushing is removed from service for reconditioning or salvaging.

The capacitance of a bushing is slightly higher in a breaker than when tested alone. The increase of capacitance is caused by the presence of tank wall and the contact parts. This increase in capacitance is very consistent for breakers of the same type and voltage class.

The power factor value with the breaker closed is generally found to be nearer that of the bushing with the lower power factor, rather than equalling the mean power factor of the 2 bushings. If the oil or lift rods have appreciable loss the above is not true and the power factor with breaker closed may become any greater value.

If indications are that the oil is at fault:

1. Power factor and dielectric breakdown tests are made on samples of the oil.
2. An analysis of the oil is made.
3. The oil is reconditioned or replaced with other oil.

Notes: New oil has a power factor well under 0.005. The tests have indicated that good oil from service measures less than 0.01 power factor at 20 deg C.

If indications are that the lift rod and guides are at fault:

1. The oil is dropped in the circuit breaker and the lift rod and guide are given a surface examination and tested for leakage paths with a megger.
2. The parts are cleaned and reëxamined and re-meggered.
3. The circuit breaker is closed and power factor retaken.

If the values cannot be brought to normal the lift rods or guides should be replaced. All lift rod and guide faults found so far have been due to surface

leakage due to deposits and have been eliminated by operation 2 above. With the circuit breaker closed, a power factor reading 0.005 or more in excess of the mean power factor of the 2 bushings of the same unit has been used to warrant an investigation of the lift rods and guides, provided the power factors of the 2 bushings are normal.

The actual time for testing a circuit breaker after it is prepared for test is very short. Only a few minutes are needed to take the 9 test readings for a 3-pole 3-tank breaker. The best record to date made in the field with the portable inverted Schering bridge was testing the bushings of 19 3-pole breakers and 12 potential transformers in one day without overtime. Four men were used on the test during this day. One man went ahead of the testing crew disconnecting leads, 2 men conducted the test, and the fourth man followed up the testing crew reconnecting the leads to the bushings. The number of circuit breakers that can be tested in a day depends largely upon the time taken to switch from one breaker to another, and the time required to localize a fault and remedy it.

Periodic power factor tests decrease circuit breaker maintenance as the electrical condition of the breaker is shown by the test.

Testing Transformer Bushings

The testing of a bushing on a transformer is approximately the same as for a bushing on a circuit breaker.

Table I—Results of Early Tests

Company	No. Bushings Tested	No. of Faults	No. of Bushing Faults	Other Faults (Lift Rod, Oil, Wdg., etc.)
A	376	14	10	4
B	930	45	39	6

To localize abnormal readings:

1. The exposed porcelain is shielded to eliminate surface leakage.
2. The oil end of the bushing is cleaned.

If the fault is not cleared by steps 1 and 2 above, the cause for abnormal power factor is in the bushing and it is removed from service.

On transformers it has been necessary, heretofore, to disconnect the winding from the bushing completely to make the tests, either by dropping the oil in the transformer tank and disconnecting the winding, or by attaching a rod of insulating material to the end of the lead and pushing it down and out of the central tube of the bushing. Obviously, this is a very undesirable procedure. With the inverted Schering bridge, the transformer lead requires very little insulation between it and the bushing, as the transformer lead is attached to the shielding circuit of the bridge and brought to the same potential as the bushing. In many of the transformers, the lead is taped all the way through the bushing, so that it is only necessary to disconnect it at the top of the bushing and attach it to the shielding of the testing set cable. The ground connection of the transformer must be removed during the test.

In the absence of tape on the lead, a thin-walled tube of insulating material usually can be pushed down through the bushing, surrounding the lead and insulating it from the bushing sufficiently for testing by the inverted Schering bridge method. As many as 3 transformer banks and 2 spare units have been tested in one day using the insulated lead method, while almost an entire day has been taken to test one transformer bank when the oil had to be dropped to disconnect the winding.

Potential and instrument transformers have been tested as a unit; that is, the tests are made on bushings and windings together. After a few tests are made, it is known just what one of the complete units should measure and a unit giving an abnormal reading is segregated to find the location of the fault. High loss oils, high loss winding, and high loss bush-

Table II—Typical Cases

Test No.	Kv Rating	Power Factor	Breakdown on Test	Remarks
1	44	0.046 at 23 deg C 0.097 at 50 deg C 0.27 at 80 deg C	160 kv while raising voltage to flashover	Bushing made before 1922. Trouble due to moisture entering bushing
2	66	0.077 at 20 deg C	183 kv after 58 sec	Bushing made before 1922. Trouble due to moisture entering bushing
3	132	0.075 at 20 deg C		Bushing made before 1922. Dismantled and a charred path 7 in. to 8 in. long over micarta insulation at top was found
4	66	0.0154 at 26 deg C		Capacitance was high. Oil end of bushing was found to be mechanically damaged
5	66	0.11 for complete unit 0.03 for bushing alone 0.002 for oil 0.15 for winding 0.0704 for winding after 4 days of drying at 70 deg C		Potential transformer. The high power factor of the winding was likely due to moisture. The winding was given further drying before putting into service. The bridge, however, was not available for making a test after this last drying operation
6	22	0.0626 for bushing No. 1 of unit 0.0606 for bushing No. 2 of unit 0.0666 for breaker closed 0.0856 for sample of oil 0.0205 for bushing No. 1 after cleaning oil end 0.0258 for bushing No. 2 after cleaning oil end		Circuit breaker. The abnormal power factor was due to the oil
7	66	0.0213 for No. 1 bushing 0.0188 for No. 2 bushing 0.0340 for breaker closed 0.0206 for breaker closed after lift rod and parts were cleaned		Circuit breaker. Abnormal power factor with breaker closed was due to deposits on the lift rod

ings have been found readily by this combination test. One disadvantage of the test is that the capacitance of the bushing cannot be determined.

Field Tests

Tests have been made on the properties of 10 operating companies with the set in its experimental form. On some systems the tests were an investigation of bushing troubles and on other systems were a general test on all bushings. We do not have a complete record of all actual faults found in the field as 2 of the operating companies conducted their own tests.

A fair conception of what to expect from the power factor test on a power system can be had from the results given from tests on 2 power companies' systems, and summarized in Table I. These represent the first field power factor tests made with the inverted Schering bridge. The number of faults will materially decrease with repeated tests. Table II gives some typical cases and conditions of bushings found by the tests.

The decrease in dielectric strength occurring with increasing of power factor is shown in Fig. 6.

A bushing operating on a line having a rated circuit voltage lower than the bushing normal voltage class may safely be left in service with a power factor higher than a bushing operating on a line at its normal voltage, and still be satisfactory.

Conclusion

The tests show that the power factor device actually does show deteriorated apparatus, provided the design of the equipment is known. A satisfactory device has been developed which will do the work quickly and with relatively little trouble. The use of the device, in coöperation with the manufacturer of the apparatus, will provide the user with experience in the location of insulation troubles and permit the user to detect defective equipment in time to prevent outages, and thus reduce operating expenses.

Pantograph Trolleys I—Design Features

Improvements have been made in practically every part of pantograph trolleys used for current collection on electric railways. As a result of these many improvements the pantograph of most recent design fulfills its important function in a highly satisfactory manner. Designs now are available for collecting currents of any magnitude found on either a-c or d-c roads at any speed up to 100 mph.

By
W. SCHAAKE
NONMEMBER

Westinghouse Elec. & Mfg., Co., E. Pittsburgh, Pa.

A SUPERFICIAL examination of a pantograph trolley would indicate that there had been very little change in design. As a matter of fact, however, there have been important changes involving practically every part of the pantograph. Serious troubles were experienced with original insulation. Improvements in insulation have been made so that insulator troubles are now unheard of. Operation was very sluggish, and pressure was very irregular. By use of tension springs, self-aligning bearings, and change in bearing location, friction has been almost eliminated, and almost uniform pressure has been obtained throughout the operating range.

Original pantographs had only small current collecting capacity. At present there are designs for collecting currents of any magnitude at any speed up to 100 mph, on either a-c or d-c systems. The range of operation has been increased to be suitable for 24-ft 6-in. operating height, and 15-ft 3-in. minimum operating height. In addition to original designs which were (1) spring-raised air-lowered, (2) air-raised gravity-lowered, and (3) air-raised spring-lowered, types have been developed that have elements of safety not found in original designs. The original designs of air raised pantographs also have been improved to give lower maintenance and greater safety.

Structural improvements have been made to give greater stability and a simpler structure. Parts have been standardized to reduce the number of types of component parts to a minimum. As a result of these many improvements, the pantograph collector of most recent design fulfills its important function in a highly satisfactory manner.

General

Pantograph trolleys were first developed in the United States in 1906, at which time the New York,

Full text of a paper recommended for publication by the A.I.E.E. committee on transportation and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 27, 1933; released for publication Dec. 1, 1933. *Not published in pamphlet form.*

New Haven, and Hartford electrification necessitated the use of this type of current collector. Various problems have been encountered in pantograph current collection; and although the general form of construction has not changed greatly from the original New Haven pantographs, the improvements which will be discussed were required to obtain higher operating speeds, greater collection capacity, uniformity of contact pressure, freedom from sluggishness, and more positive operation. While the improvements that have been made up to the present time are taking care of present conditions, further improvements must be made for speeds in excess of 100 mph. Experience indicates that these conditions can be met without great difficulty.

As the roller type of pantograph has proved to be inadequate and has been replaced with a sliding shoe, this paper will be confined to the latter type. The component parts of a modern pantograph collector are:

1. The collector shoe.
2. The movable framework consisting of an upper and lower member.
3. The cross shaft which supports the movable frame.
4. The pantograph base which carries the cross shaft bearings, operating air cylinders, main springs, jack shafts, and automatic latch.
5. The pantograph insulators to which the base is connected and which insulate the pantograph from the roof of the car or locomotive.

The simplest form is the hand operated pantograph in which the contact pressure is supplied by either tension, compression, or torsion springs. Lowering is accomplished by means of a rope passing over a series of pulleys. This lowering rope may have the end held positively in the down position, or the pantograph may be held down by a latch which is released by a rope. Hand operated pantographs are little used because of the greater ease with which the air operated pantographs are controlled.

Air Operated Pantographs

Air operated pantographs can be divided into the following 3 types:

1. Spring-raised air-lowered with automatic latch.
2. Air-raised gravity-lowered: (a) held in collapsed position by gravity only; (b) held in collapsed position by gravity and an automatic latch.
3. Air-raised spring-lowered without latch.

In the first design the pantograph is raised by springs. It is lowered by means of air pistons acting on levers that counteract the moment of the raising springs and return the pantograph to the latched height. At this point an automatic latch engages the frame and holds the pantograph in the latched position. To release the pantograph, air is admitted to the latch cylinder. This releases the latch and permits the pantograph to rise.

The raising and pressure mechanism consists of cams, cam chains, and tension springs (see Fig. 1); the lowering mechanism consists of push levers, air cylinders, and pistons (see Fig. 2).

Raising and Pressure Mechanism. Although fair results have been obtained by means of springs, connecting rods, and levers, it is impossible to locate the lever and connecting rods so that the moments obtained throughout the angular movement correspond closely with the combined moments of

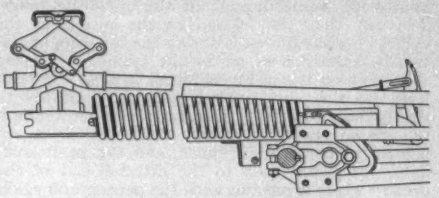


Fig. 1. Spring, cam, and chain

lower frame, upper frame, contact shoe, and required contact pressure. A tension spring is the simplest and most direct means of applying pressure. Tension adjustments are made very easily to vary the contact pressure of the pantograph shoe. The raising moment is imparted to the main shaft by tension springs connected to a cam by means of chains. The shape of the cam is such that the

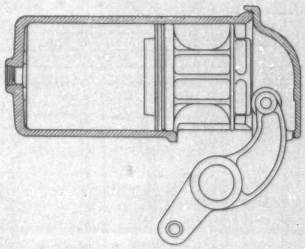


Fig. 2. Air cylinder and push lever

variable moments throughout the operating range are counteracted and sufficient pressure moment added so that approximately uniform pressure is obtained throughout the operating range. The flexible connection from operating springs to the cam may be a flexible band, cable, or chain. Of these means a flat link chain has been found most suitable, due to strength and facility of making the end connections to the cam and spring.

Lowering Mechanism. The lowering mechanism, Fig. 2, consists of a push lever keyed to the shaft, and air cylinders and pistons for exerting pressure against the push levers to produce a counter moment for lowering the pantograph. The push lever is provided with a roller at the point of contact with the piston to avoid the sliding resistance that otherwise would result at the end of the push lever. The lowering piston is provided with a suitable air packing at one end, and a loose sliding fit in the

cylinder at the other end to guide the piston in the cylinder and to prevent tilting. With this construction when the pantograph has attained its maximum height, the piston remains at the extreme end of the cylinder, and the push lever moves freely throughout its range of angular movement with no friction due to the piston during movements of the pantograph frame throughout the operating range. The only time the friction of the piston in the cylinder is encountered is during the lowering operation by admission of air to the cylinder. During this operation the piston is forced against the push lever and the pantograph is brought promptly to the latched position. In raising the pantograph the reverse operation results when the air is exhausted from the air cylinder, and the push lever forces the piston back to the extreme end of the cylinder where it remains until the pantograph again is lowered.

Retardation of Pantograph Movements

It is essential that simple means be provided against the pantograph being lowered too rapidly when air is admitted to the cylinders, and against raising too rapidly when the air is exhausted. This is accomplished very simply by a diaphragm in a pipe union between the air cylinder and equipment air piping. This diaphragm has a small hole in it which serves to check the admission of air to the cylinder and permits lowering in $1^1/_2$ to 2 sec to the latched position. This same diaphragm prevents too rapid raising by retarding the speed with which the air is exhausted from the cylinder. There will be a decided retardation in ascent even though the air in the main cylinders has only atmospheric pressure, as some compression will result when the piston moves forward. It is desirable, however, to admit air to the main cylinders before admitting air to the latch cylinder, so that there may be the added retardation in raising due to air under pressure being exhausted from the main cylinders.

In the second design (2a) the pantograph is raised by the admission of air to the main cylinders, which act through the springs, etc. In order to reduce the size of the main cylinders and also to aid

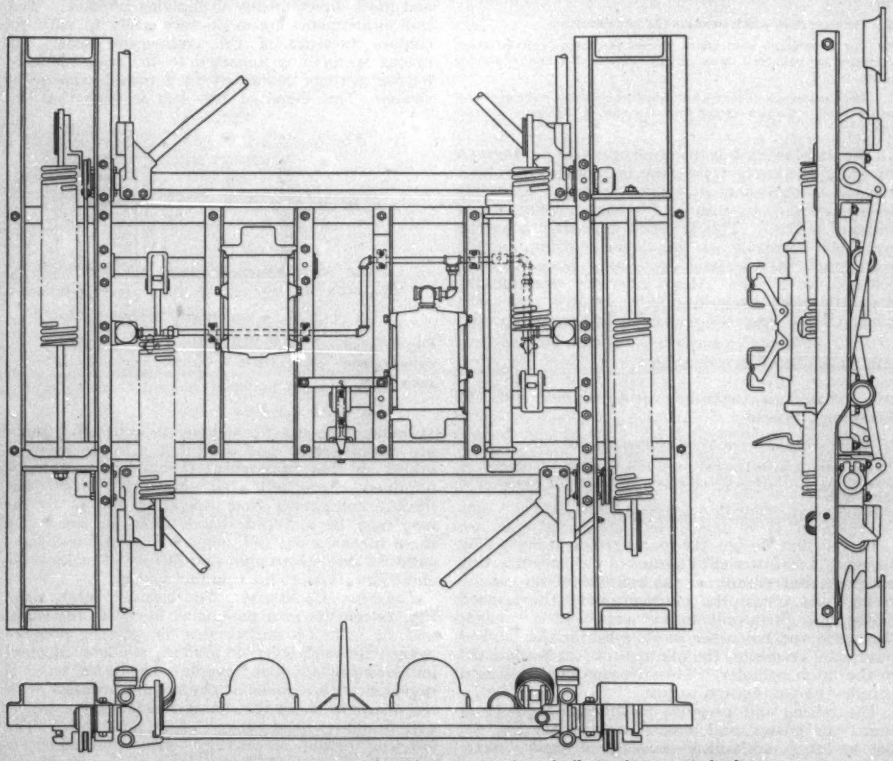


Fig. 3. Air raised pantograph with compressed air buffer and automatic latch

Fig. 5 (right). Air-raised spring-lowered pantograph

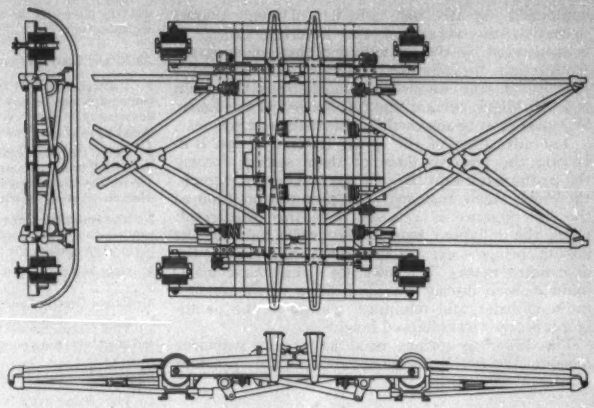
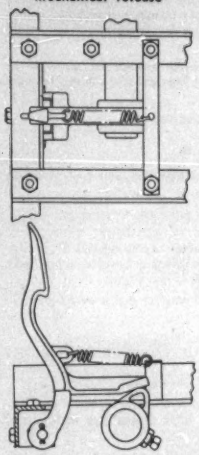


Fig. 4 (below). Latch and mechanical release



in retarding the lowering of the pantograph when the air is exhausted, 2 sets of springs are used: One set is for approximately balancing the dead weight of the pantograph; the other set may be called the pressure springs. Tension in these springs is supplied by means of air cylinders and pistons. When these springs are placed under tension, the pantograph begins to rise. When the piston is at the end of its stroke, full tension has been supplied to the pressure springs, and this condition is maintained as long as the pantograph is in operation. To lower the pantograph, the air is exhausted from the main cylinders and the pantograph comes to rest at the collapsed height. A careful predetermined relation must exist between the balancing and raising springs. If these springs are too evenly balanced, there is a decided slam when the pantograph reaches the buffers. The raising springs, therefore, should have sufficient tension in the collapsed height so that a force of 30 lb is required at the pantograph shoe to raise the pantograph. Owing to the low collapsed height at which a majority of pantographs are required to operate because of low minimum height of contact wire, a satisfactory simple type of buffer is difficult to design. About the only alternative is a compressed air buffer, as shown in Fig. 3.

This compressed air buffer consists of a small vertical air cylinder at either side of the pantograph. This cylinder is provided with a piston having a buffer that permits an air cushioned movement of about 2 in. Normally during operation of the pantograph this buffer is in an extended position due to air pressure exerted on the piston. When the air is exhausted from the main cylinders, the air also is permitted to flow from the buffer cylinders, but is retarded by means of an auxiliary air reservoir and a diaphragm in the air connection with only a $^1/_{32}$-in. hole permitting the air to flow from the auxiliary reservoir and buffer cylinders very slowly; thus there is still considerable pressure in the buffer cylinder when the pantograph frame comes into contact with the buffer. Without the auxiliary reservoir the air would be exhausted too rapidly from the buffer cylinder, and not much cushion effect would be obtained.

In design 2b a holding-down automatic latch, Fig. 4, has been added to the air raised design. This becomes necessary in some cases where for long distances the pantograph operates on a contact wire very close to the collapsed height of the shoe. As the movable parts are more or less balanced, and are held down only by gravity, there is some tendency for bouncing of the pantograph, so that the contact shoe may raise some distance above its collapsed height. This automatic latch holds the pantograph positively in the collapsed position and is applied as a safety measure under low wire. The latch is released when air is applied for raising the pantograph, by a cam on a jack shaft. See Figs. 3 and 4. This design is now in successful operation on the Cleveland (Ohio) Union Terminals Railway.

Air-Raised Spring-Lowered Pantograph

In this design, Fig. 5, the contact pressure is supplied by tension springs. These pressure springs are opposed by lowering springs which have sufficient strength to overpower the pressure springs and lower the pantograph. The lowering springs are

controlled by an air cylinder. During normal operation the action of the lowering springs is counteracted by the air cylinder, thus allowing the pantograph to raise and operate. To lower the pantograph the air is exhausted from the main cylinder which permits the full tension of the lowering springs to be opposed to the raising springs.

The advantage of the spring lowered design is in having the positive force of these springs forcing the piston back into the cylinder. The pantograph, therefore, starts lowering very promptly as soon as the air pressure is released. As the pantograph nears the collapsed height, the entire force of the raising springs is exerted to cushion the inertia of the descending mass. The lowering springs have maximum tension during the application of air pressure in the cylinder, and minimum tension as the pantograph reaches its collapsed height.

The lowering springs need have only sufficient tension to overbalance somewhat the pressure

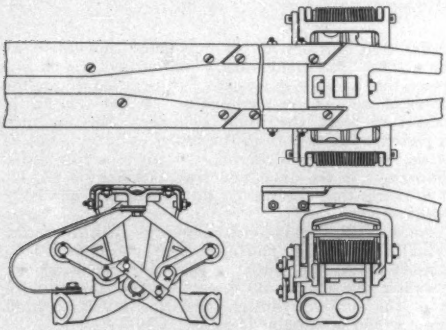


Fig. 6. Single contact shoe and accessories

moment of the raising springs plus the friction of the piston in the air cylinder, and the resistance of compressed air being forced from the cylinder. The air cylinder need have only sufficient capacity to overcome the full tension of the lowering springs plus the air piston friction.

Relative Advantages of Different Designs

Spring-Raised Air-Lowered Type

1. In case air pressure is not available, it is only necessary in most modern types to trip the automatic latch by means of a wooden pole with hook attachment, and a lever arm connected with the mechanical release mechanism which is at the side of the pantograph. This can be reached easily from the ground with the hook pole. See Fig. 10.

2. In lowering the pantograph, as soon as air pressure is supplied to the lowering cylinders the pantograph begins to lower and continues lowering rapidly until the latched height is reached.

3. In case of an air leakage so that there is a gradual reduction in air pressure, the pantograph is not affected when the shoe is in contact with the line.

4. In case the air cylinder packing may have slight leakage, this will take place only during the lowering operation, when leakage is not important.

Air-Raised Gravity-Lowered Design 2a

1. Pantograph is held in collapsed position by gravity only. The pantograph may be raised somewhat above the collapsed height by bouncing or by wind currents, but is secure against overraising to operating height except by application of air pressure.

2. In low collapsed height where action is rather sluggish, the design lends itself easily to the application of a compressed air buffer, which also has the valuable feature of making the pantograph rise promptly when air pressure is applied.

3. The balancing springs are practically without tension while the pantograph is in collapsed position. This will result in much longer life for these springs.

4. Only 1 air connection to insulate in place of 2.

Air-Raised Gravity-Lowered Design 2b

1. This pantograph has advantages Nos. 2, 3, and 4, of design 2a and in addition has a positive latch.

Air-Raised Spring-Lowered Type

1. This design has all the advantages of the air-raised gravity-lowered type, and in addition can be raised or lowered as promptly and uniformly as the spring-raised air-lowered type.

2. Less cylinder capacity is required than for the air-raised gravity-lowered design.

Relative Disadvantages of Different Designs

Spring-Raised Air-Lowered Type

1. This type is held in the collapsed position by means of an automatic latch. Should this latch not latch properly or shake loose, the pantograph will rise immediately.

2. In case of failure of the air supply, the pantograph would remain in contact with the line. In some cases this might be undesirable, as it might be safer and better to delay operation until the air supply is reëstablished.

Air-Raised Gravity-Lowered Type 2a

1. Difficulty in raising the pantograph without an air supply.

2. Excessive air leakage which may result because of air being applied continuously while the pantograph is in contact with the line.

3. Less speed and uniformity in raising and lowering.

4. Pantograph is not held positively in the collapsed position, and may be subject to bouncing which is objectionable on long stretches of low wire.

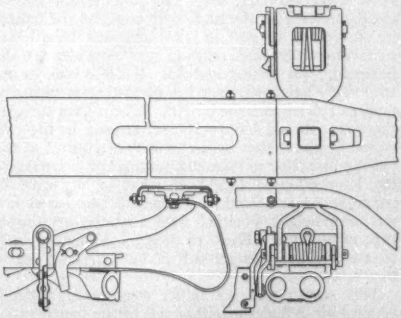


Fig. 7. Double contact shoe with wind vane

Air-Raised Gravity-Lowered Type 2b

1. Same disadvantages as type 2a, but is held positively in the collapsed position by an automatic latch.

Air-Raised Spring-Lowered Type

1. Pantograph is difficult to raise without an air supply.

2. Excessive air leakage may result because of the air being supplied continuously while the pantograph is in contact with the line.

Component Parts of the Pantograph

Contact Shoe. In the development of the pantograph shoe it has been found that a length of contact surface of 48 in. is sufficient for the majority of overhead construction now in operation. A length of 72 in. is found sufficient for the length over end horns. In the Virginian Railway electrification this distance was increased to 84 in. In this case it was believed that economy could be effected by using longer spacing of the overhead supporting structures resulting in greater displacement of the contact wire from the center of the track. This requires a longer shoe. Shorter shoes also are in successful operation. The Southern Pacific and

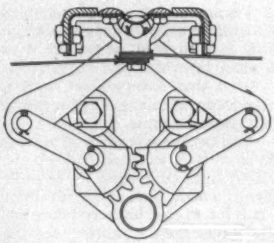


Fig. 8. Southern Pacific Railroad contact shoe

Key System use a shoe with a contact surface 36 in. long, and with a length over end horns of 72 in. In each of these cases the short length of shoe is due to the overhead structures being built so that the contact wire is nearer the center of the track than elsewhere. The Chicago, Milwaukee, St. Paul and Pacific Railroad uses a shoe with a contact surface only 34 in. long, and with an over-all length over end horns of 84 in. This short length was necessitated by tunnel conditions, and as the overhead construction was designed for a shoe of this length, satisfactory operation is obtained. The shape of the end horns is determined in several cases by low overhead clearances to which the end horn must conform.

Various materials have been tried for contact shoes. The aluminum bow which was used at first had a very short life. This was followed by a shoe having a wood base with a combination of aluminum and copper contact strips, and with a shoe made of sheet copper. This sheet copper shoe was followed by a sheet steel shoe, which still is used by important roads such as New York, New Haven & Hartford, Pennsylvania, Canadian National Sarnia Tunnel electrification, and Boston and Maine. These are all single-phase a-c systems. The standard construction generally adopted consists of a shoe with copper-bronze or steel wearing strips. This construction is shown in Fig. 6. In this design the shoe is an inverted trough section $4^1/_2$ in. wide, made of sheet steel or aluminum alloy $^1/_{16}$ in. thick. There are 2

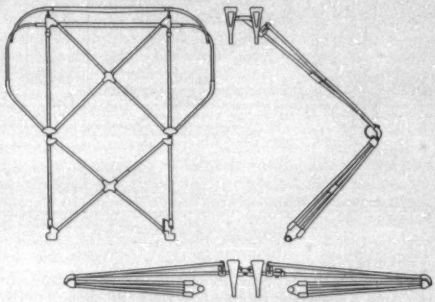


Fig. 9. Pantograph with side guards

long center wearing strips 24 in. long and 4 end strips 12 in. long. The center strips are 2 in. wide in the center and taper near the ends. Each of these strips is held with 4 flat-head bronze screws. This construction has been adapted to leave a clear central space of about 12 in. free from screw heads, as most of the wear occurs in that space. These strips have an outer edge with a $^3/_8$-in. radius to give an easy approach on the contact wire, and one that is less likely to catch onto projecting clamps.

A rather unique contact strip is used by the Southern Pacific and by the Key System. This is shown in a cross section of the shoe, Fig. 8. The outside strips are of bronze angle stock $1^1/_4$ x $1^1/_4$ x $^3/_{16}$ in. The inside strips are half oval 1 x $^7/_{32}$-in. open-hearth steel. A copper contact wire is used. The space between strips is filled with a grease and graphite compound. A nicely polished contact wire has resulted, and very little wear can be observed. The action of the steel and bronze combination is not understood exactly, but it is probable that any rough spots appearing on the contact wire are removed quickly by the action of the steel strips.

In a majority of single-phase 11,000-volt electrifications a single shoe has been found to satisfy operating conditions. For nearly all d-c electrifications, and some heavy traction a-c electrifications, a double shoe (Fig. 7) is found essential. With 2 shoes having independent flexibility and supported so that the shoes are about 12 in. apart center to center, almost sparkless collection will result with a flexibly supported catenary system, collecting current of 1,000 amp at 60 mph, and 2,500 amp when starting. For high speed operation at 50 to 75 mph, the wind

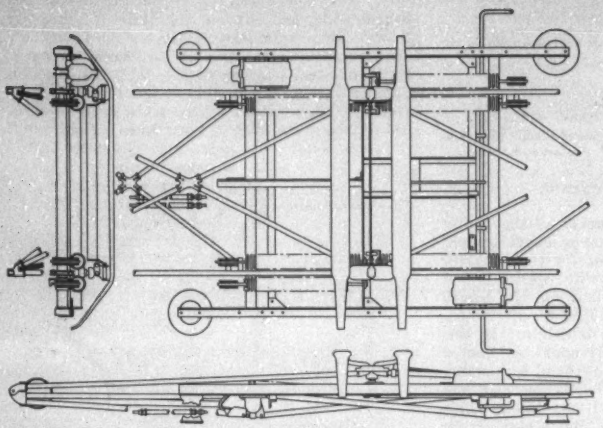


Fig. 10. Spring-raised air-lowered pantograph

pressure on the trailing shoe is found to be sufficient to cause a lowering moment so that the shoe actually will leave the wire. To correct this condition a wind vane is applied as shown in Fig. 7. This wind vane is located in the center of the pantograph, and is suspended at a sufficient distance below the shoes so that the wind pressure acting on it will produce a counter moment to that exerted on the trailing shoe; as a result, the shoe is held in contact with the line. It was found also that the shoe supporting arms must have a length of $7^1/_2$ in., thereby increasing the ratio of contact pressure moment to wind pressure moment. Without the wind vane an excessive length of arm would be necessary.

It is extremely desirable to have independent flexibility for the contact shoe. Owing to low minimum operating height and collapsed height, it is a difficult matter to obtain a suitable flexible shoe. In the double-shoe design a 2-in. range of movement is obtained with the design shown in Fig. 7. A 2-in. range also is obtained in the single-shoe design shown in Fig. 6.

Lubrication of the pantograph shoe is essential; without it excessive wear will occur on both the wearing strips and the contact wire. The space between contact strips provides a recess for the lubricant. A mixture of 1 part flake graphite and 2 parts motor grease has been used with good success.

In order to have a smooth passage of the contact shoe at sidings and crossings, the shoe is provided with end horns having a shape depending on overhead clearances in tunnels. In the first designs these end horns had a drop of 8 in. This has been increased in later designs to 12 in., to reduce the tendency for the contact wire to pass under the horn when the line is slack. In order positively to prevent the wire from being caught under the end horn, designs have been developed in which side guards have been added to the upper pantograph frame. This is shown in Fig. 9. These side guards are made of aluminum alloy tubing, and are clamped to a standard pantograph frame. Should the guards become damaged, they can be removed until repairs are made without taking the pantograph out of service. This is a decided advantage over some European designs in which the pantograph frame itself is so formed that a very short horn is required. In case the frame is damaged when acting as a guard, the pantograph becomes inoperative.

In pantographs with a considerable operating range and a double shoe, it is essential to keep the movable framework as light and rigid as possible to carry the collector weight and give sufficient contact pressure. It is found that high carbon seamless steel tubing best meets these conditions for the lower frame. For the upper frame maximum strength and minimum inertia are obtained with aluminum alloy tubing. It is essential that both upper and lower frames be cross-braced adequately, and that the frame connecting castings be machined carefully to eliminate loose connections. All the pin holes should have hardened renewable bushings, and all pins should be case hardened or heat treated to reduce wear of these parts.

Even though the upper and lower frames have excellent lateral rigidity, a decided side sway of the pantograph may result because of the torsion of the main shaft. When a lateral force is applied to the pantograph, this force causes a moment about the pantograph base. The upper frame is supported by the lower frame, and this moment of the upper frame including shoes is resisted by the lower frame; thus a twisting moment is applied to the shaft at one side of the pantograph, which is opposed to the twisting moment at the opposite side. Any twisting of the shaft is multiplied greatly at the end of the lower frame, and results in a rocking or side sway of the pantograph. It is essential, therefore, that for high speed operation the pantograph shafts have great torsional rigidity. A hollow shaft of large diameter meets this requirement. It is essential

also that there be no lost motion between the lower frame and the main shaft. In older designs solid cross-shafts and keyed frame connections were used. In a recent modern design the connection of the lower frame to the main shaft consists of steel plates welded to the shaft. The lower frame tubing is flattened and fastened to these shaft plates by 4 $^3/_8$-in. ream bolts in double shear.

Pantograph Bearings. In older designs not much attention was paid to the main bearings. The general arrangement was such that in some designs 8 bearings were used. In modern designs only 4 bearings are used, and these are self-aligning roller bearings. This results in a very free response of the pantograph frame, and friction amounting to only $1^1/_2$ to 2 lb measured at the shoe throughout the pantograph operating range. Figure 11 shows a roller bearing in which the bearing itself is self-aligning. The bearing support has an end play arrangement which permits longitudinal adjustment. Both types of bearing are provided with "alemite" fittings for lubrication, and felt washers to exclude dust.

Pressure Adjustment. In order to have a good range of pressure adjustment, an adjustable cam has been developed; this is shown in Fig. 12. By means of the set screw shown, a decided increase or decrease in pressure can be obtained at the lower or upper part of the operating range.

Latching Arrangement. The most satisfactory location for the latch is found to be near the center

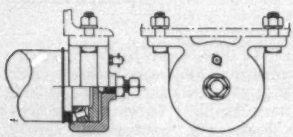


Fig. 11. Self-aligning roller bearing

of the pantograph, both transversely and longitudinally. A great many designs have the latch engage the cross casting on the upper frame. For a long range pantograph with aluminum alloy tubing, the latch at this point causes considerable sag of the upper frame, and does not permit such a low latched height as where the latch is located near the center. The shape of this latch is such that the pantograph frame will engage the latch when lowered from a height 3 in. above the latch height of shoe.

Frame Details. Although a rather minor detail, the hinge connection between upper and lower frame has an important bearing on a freely operating pantograph without excessive side play. In a late design, Fig. 12, this connection is provided with a hardened bushing and hardened hollow pin with "alemite" fitting to provide for good lubrication. To reduce wear in the joint, brass washers are inserted in the hinge.

Base Frame. In order to simplify the pantograph base, the latest high speed design has an angle-iron base with only a single angle on each side, and 3 transverse angles. Gusset plates are provided to make a rigid frame. The side angles are adapted for resting on top of pillar type insulators. Figure 10 shows the angle iron base as a part of a complete pantograph.

Insulators. Marked improvement has been made in pantograph insulation. The insulation of the pantograph from the roof of the car or locomotive requires 4 insulators. These may be of either spool or pin types. The spool type of insulator is satisfactory for voltages up to 1,500 volts. For voltages over 1,500 up to 3,000 volts, a petticoat type of insulator is desirable. This insulator consists of a one-piece porcelain insulator provided with a malleable iron shield, adapter, and base.

For 11,000 volts a pin type insulator is required. This is a 2-piece porcelain insulator provided with malleable iron cap and base. It has been used successfully by the New York, New Haven, and Hartford Railroad. This design does not have a metal shield protecting the porcelain. The flashover voltage of the latter design is only about 60,000 volts as compared with 80,000 volts without shield.

The insulator with shield is used successfully by the Pennsylvania, Norfolk & Western, Virginian, and the Reading roads in 11,000-volt operation, but in addition to the primary set of insulators on the pantograph, there is a set of secondary insulators applied to an insulated base so that double insulation is obtained.

A one-piece porcelain pillar type of insulator is especially well adapted for 11,000-volt pantograph insulation by using 2 sets of insulators. The pantograph shown in Fig. 10 rests on 4 primary insulators. These primary insulators rest on an insulated base which rests on the secondary insulators. Failure of either a primary or secondary insulator will not delay operation, as either insulator has

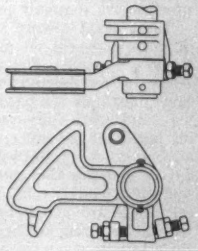


Fig. 12. Adjustable cam

sufficient capacity to provide insulation for a long period. This design is now in use on the Pennsylvania Railroad passenger locomotives.

An insulated air connection also is required. This insulation is supplied by a rubber hose. Recently a porcelain tube insulator has been developed which gives promise of supplanting the rubber hose and thus decreasing maintenance cost. The end connections have rubber packing which gives a certain amount of flexibility and thereby avoids fracture of the porcelain tube.

Pantograph Trolleys
II—Operating Features

Satisfactory current collection on electric railways using pantograph trolleys depends on the ability of the pantograph to follow irregularities in the height of the contact wire at all operating speeds and within a limited range of pressures between the contact wire and the shoe. In this paper operating characteristics of pantograph collectors are outlined, and operating data for 3 typical pantographs are given.

By
B. M. PICKENS
ASSOCIATE A.I.E.E.

Blissfield, Mich.

SATISFACTORY current collection by electric cars and locomotives using pantograph collectors depends on the maintaining of a constant pressure by the collector on the contact wires. This pressure is limited to a very small range. At high speeds of operation the collector must accelerate rapidly to follow variations in the height of the contact wires. If all the available spring force is used accelerating the pantograph there is none left to produce the required pressure against the wires.

The vertical upward acceleration of a pantograph depends inversely on its inertia and friction. The friction is small. The inertia may be expressed in terms of an "equivalent weight" which has the same inertia as the pantograph itself at the contact wire, and which consequently varies with the operating height of the collector. In this paper are given a formula for computing the equivalent weight, and curves showing the equivalent weights of 3 representative pantographs. The possible rates of acceleration are given for these 3 pantographs at various operating heights.

Curves are given for one of the pantographs showing its upward rise for certain time intervals, and for horizontal travel when operating at various speeds. These curves show the limits of the pantograph's ability to follow the wire at high speeds, which limits should be taken into account when designing overhead contact systems for high speed operation. For speeds of 100 mph or more both pantographs and contact systems will have to be improved for satisfactory current collection.

Full text of a paper recommended for publication by the A.I.E.E. committee on transportation and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 9, 1933; released for publication Dec. 1, 1933. *Not published in pamphlet form.*

Pantograph Pressures

The ability of a pantograph to maintain pressure against the contact wires of the overhead catenary system on which it operates, at high speeds of operation, with variations in the space between the car or locomotive roof on which it is mounted and the contact wires, depends directly on the pressure it can exert against the contact wires and inversely on the friction and the inertia of the moving parts. The pressure is limited by 2 main considerations: danger of entanglements with the wires of the overhead system, and danger of excessive wear on the contact wires. In general the lighter the contact system, the lower must be the pantograph pressure

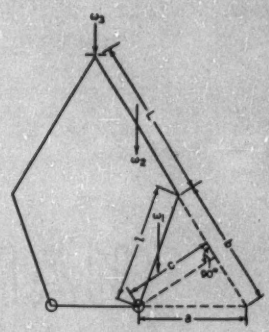


Fig. 1. Line diagram of pantograph

for safe operation. It has been found that the maximum normal pressures that can be used safely are about 18 lb for a single-shoe pantograph and 35 lb for a double-shoe pantograph. These are the pressures required to lower the pantograph slowly. Since the pantograph pressure is limited by the contact system on which it will operate, the only way of improving the operating characteristics is by reducing the friction and the inertia of the moving parts.

On modern pantographs for high speed operation where roller main bearings are used, friction has been reduced to 5 or 6 per cent of the total pressure in the case of double-shoe pantographs. There is some possibility of reducing this still more, but the reduction would be small and so far has not been found necessary. Friction adds to the force necessary to lower a pantograph and reduces the pressure against the contact wires when the pantograph is rising.

The inertia of a pantograph depends on the weight and arrangement of its moving parts, and also varies with the position of the pantograph. The several moving parts have varying influence on it: The shoe, which is directly in contact with the overhead system and which must follow all variations in the height of the contact wires to remain in contact with them, has the most. The upper frame, which supports the shoe at its apex, does not have to move its entire mass quite as fast as the shoe,

particularly in the lower range of operation, and thus has less influence on the inertia. The lower frame has still less.

It is possible to determine an equivalent weight for any position of the pantograph, which, if placed at the contact wire, would have the same inertia as the pantograph itself. This equivalent weight can be used to calculate the acceleration, or the force at the apex of the pantograph necessary to accelerate the pantograph, in a vertical direction. The ability of a pantograph to follow the contact wire at high operating speeds depends inversely on this equivalent weight. It varies with the height of the pantograph, increasing rapidly as the maximum height is approached. The formula for determining the equivalent weight is obtained by assuming that a force acts on the apex of a pantograph through a small distance; from an energy equation the velocity of the apex is found, taking into account the energy of each moving part due to the linear motion of its center of gravity and its energy due to rotation; then a weight is found which if acted on by this same force through the same distance would

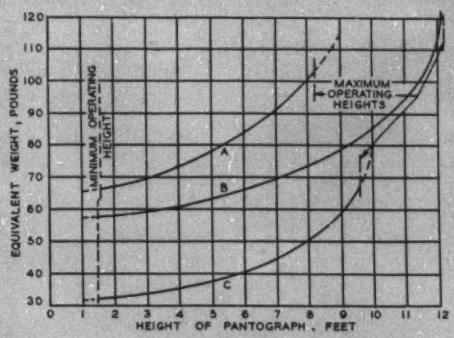


Fig. 2. Equivalent weights of pantographs A, B, and C

obtain the same velocity. This weight is the equivalent weight. The formula is

$$W_e = w_3 + w_2 \frac{(12\,c^3 + b^3)}{6\,a^3} + w_1 \frac{(2\,l^3)}{3\,a^3}$$

where
W_e = the equivalent weight
w_3 = weight of shoe (or shoes) and supporting mechanism
w_2 = weight of one-half upper frame
w_1 = weight of one-half lower frame
l = length of the lower frame
a, b, and c are as shown in Fig. 1

A high contact wire is desirable from the standpoint of safety to trainmen, but it makes the problem of designing a pantograph for high speed operation more difficult. A high contact wire requires a long range pantograph operated near its upper limit, as there is no extensive electrification without low bridges or tunnels which set the lower limit of operation. The pantograph also must have a low collapsed height, as there is usually little space between the top of the locomotive or car and the minimum height of the contact wire. A pantograph does not accelerate as rapidly near its upper limit as can be seen from the equivalent weight and acceleration curves given later. It is also difficult to maintain the full pressure near the maximum height of operation.

Table I—Data for 3 Typical Pantographs (See Fig. 1)

Pantograph	Total Weight, Pounds	No. of Shoes	Operating Range, Inches	Inches l	Inches L	Pounds w_1	Pounds w_2	Pounds w_3
A	840	2	79.5	54	71³/₄	87	23	39
B	1,135	2	129	66	99	42	22	50
C	620	1	97	54	76	35	15	27

Some data on 3 typical pantographs which will be studied are given in Table I. Figure 2 gives the equivalent weights of these 3 pantographs calculated by the preceding formula. The heights are given above the center of the main shafts, and the maximum and minimum operating heights are indicated.

From these equivalent weights and the pantograph pressure the free vertical acceleration of the pantograph can be calculated starting from any given operating height. The free acceleration is obtained when all of the available spring force is used to accelerate the pantograph upward, with no resistance except the inertia of the pantograph itself. The equivalent weight also can be used to calculate the added force necessary to lower the pantograph at given rates of acceleration.

When there is any slope to the overhead wires

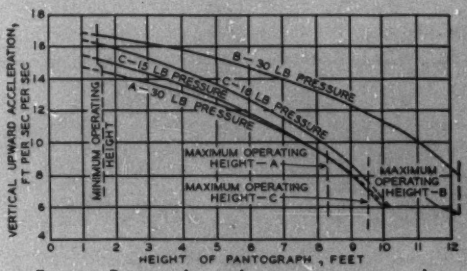


Fig. 3. Pantograph accelerations vs. pantograph height

which forces the pantograph downward, the pressure on the contact wires is increased by the amount of force necessary to accelerate the pantograph. When the slope permits an upward movement the pressure on the contact wires is reduced by the amount necessary to accelerate the pantograph upward. At slow operating speeds these variations are not great; but as the speed of the car or

locomotive is increased, a large part of the pantograph pressure may be used accelerating the moving parts, or the pressure on the contact system may be increased to a point where excessive wear occurs. Where the pressure is decreased, it may become so low that arcing occurs which also will cause excessive deterioration of the contact wire. There is a certain limited range of pressure where the maximum life of the pantograph wearing strips and contact wire is obtained. For pressures lower than this the wear increases, and for higher pressures the wear also increases.

The curves in Fig. 3 have been drawn to show how the 3 pantographs being studied will accelerate at various operating heights. These curves are based upon the assumption that all of the available pressure is used to accelerate the pantographs. In Fig. 4 the curves have been changed to show the possible acceleration at any given percentage of the maximum operating height. The flatness of the curve for pantograph *A* is due to its short operating range compared with the other 2 pantographs. Oscillograph tests made several years ago on pantograph *A* indicate that the actual curve is even flatter than the calculated one. The calculated values check the test values very closely near the upper part of the operating range, but in the lower part the test values are somewhat less than the calculated values.

In Fig. 5 curves have been plotted showing the rise of pantograph *B* (in feet) for time intervals from 0 to 1.4 sec for 3 different operating heights. They show the rate of rise starting from these heights with all available pressure being utilized to produce the rise. The normal operating height with a 24-ft contact wire has been indicated on the curves.

In Fig. 6 the vertical rise of pantograph *B* in inches is plotted against its horizontal movement in feet for various speeds of travel. These curves are based upon the rates of acceleration obtained near the normal operating height and all of the pressure being used to produce the rise. At 100 mph the

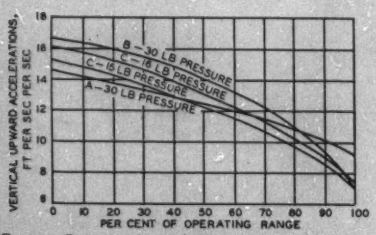


Fig. 4. Pantograph accelerations vs. per cent operating range

pantograph can rise 1 in. in 15 ft, 3 in. in 29 ft, and 12 in. in 62 ft of horizontal travel. If the pantograph is being forced down, the pressure between the shoe and the contact wires will be doubled if forced down at these rates.

In order to follow the contact wire better and to reduce excessive pressures which might be caused by small grades in the contact system, auxiliary springs are introduced between the pantograph shoe and the supporting frames. This reduces the mass making small movements and tends to keep the pressure of the shoe against the wire more nearly constant. In the case of pantograph *B* each shoe weighs 16 lb. The force necessary to accelerate these shoes through 1 in. in 0.1 sec (the time for the pantograph to travel 15 ft at 100 mph) is only 5 lb per shoe or 10 lb for the 2 shoes, while 31 lb would be required if the entire frame moved the same distance in the same time. Pantograph *B* has a pressure of 31 lb going up and 35 lb coming down throughout most of its operating range; the friction is 2 lb. If there is a rise of 1 in. in the contact system and the springs are effective, the pressure on the contact wires would be 21 lb for a speed of 100 mph; if there was a fall of 1 in. the pressure on the contact wires would be 45 lb.

In this connection it should be noted that these auxiliary springs are not always effective. Each end of the shoe is supported independently and the movement of the shoe is limited to about 2 in. When the contact wire is at the center of the shoe the pressure is transmitted equally through each shoe supporting spring. When the contact wire is near the end of the shoe practically all of the

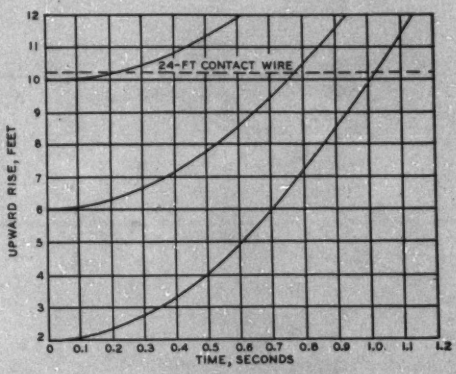


Fig. 5. Rate of rise of pantograph B

pressure is transmitted through one spring. If the shoe springs are adjusted so that they come into play with the contact wire at the center of the shoe, then they will be solid and ineffective in cushioning downward movements when the wire is at one end of the shoe. If a stiffer spring be used it will not be useful in following rises in the contact wire with the wire at the center of the shoe, but will follow rises with the wire at the end of the shoe and will act as a cushion where the slope of the contact system is downward.

Where high operating speeds are to be used, it is

necessary to depend on the contact system for a flexible path that will not require too rapid accelerations of the pantograph shoe; great care must be used in designing the contact system, and a pantograph designed especially for high speed operation should be used. Particular care must be used in designing the contact system at approaches and exits from low bridges and tunnels where changes in grade are large, and where clearances require a fairly rigid construction under the bridge or tunnel changing to the more flexible regular construction outside.

The normal catenary construction should be made as flexible as possible at the support so as not to

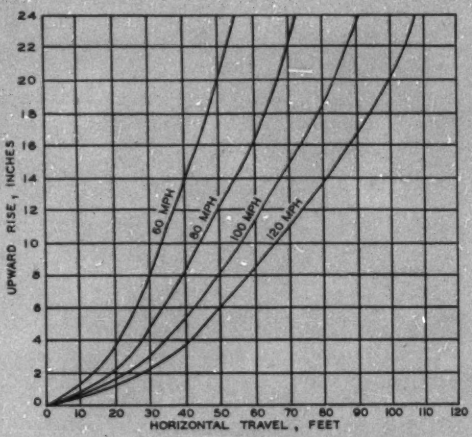


Fig. 6. Upward path of pantograph B vs. horizontal travel

require such a rapid change in direction that the pantograph might not be able to follow the contact wire. In the span the pressure of the pantograph reduces the load on the messenger causing it to lift the contact wire. The rise is maximum at the center of the span. At the support the pantograph pressure lifts the wire very little so that as the pantograph moves from span to span it rises and falls in each span.

Suppose the pantograph has a horizontal speed of 150 ft per second (approximately 100 mph) and that it is moving along a section of track having 300-ft spans that permit the pantograph to rise 1 ft higher in the center of the span than at the support (see Fig. 7). In 1 sec the pantograph will rise 1 ft; in the next it will be forced down 1 ft. If the acceleration up and down is constant, the average vertical velocity will be 1 ft per second and the maximum 2 ft per second. The maximum velocity will occur at the quarter points in the span. If the acceleration gives a velocity of 2 ft per second in the time it takes the pantograph to travel over a quarter of the span ($^1/_2$ sec) then the rate of acceleration is 4 ft per second per second. The acceleration and velocity are both upward in the first quarter of the span. The velocity changes from zero at the support to the maximum of 2 ft per second at the end of the quarter span. In the second quarter

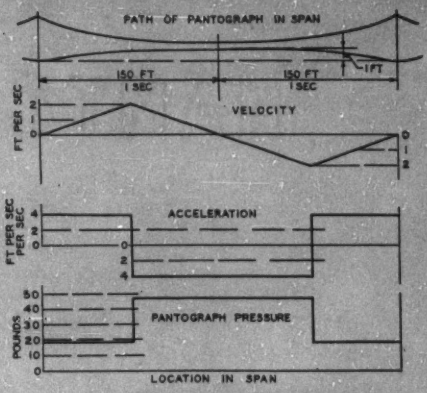


Fig. 7. Variation in pressure, acceleration, and velocity of pantograph B at a speed of 150 ft per sec over a typical 300-ft span

of the span the velocity is still upward, but the acceleration is downward which changes the velocity to zero at the center of the span. In the third quarter the acceleration and the velocity are both downward with the velocity reaching a maximum at the end of the quarter. In the fourth quarter the acceleration changes to upward while the velocity continues downward and reaches zero at the end of the span. Pantograph *B* with a pressure of 31 lb going up has an acceleration of approximately 10 ft per second per second. An acceleration of 4 ft per second per second is required to follow the wire. The pantograph pressure on the contact system will be decreased by about $12^1/_2$ lb where the acceleration is upward, and increased by a like amount where the acceleration is downward. In the first and last quarters of the span the pantograph will have a pressure of about $18^1/_2$ lb against the contact wire while in the second and third quarters the pressure will be $47^1/_2$ lb. This tends to increase the uplift at the center of the span and decrease it at the support.

The assumption that the contact wire at the center of the span is lifted 1 ft higher than at the support in a 300-ft span is not an unusual condition nor is it necessarily a maximum condition. A single pantograph probably would not have enough pressure to lift this amount on most main line catenary systems but 3 or more pantographs close together, as when double-heading locomotives, could do it. Also the same condition can result from temperature changes. Any catenary system using

a bronze or composite messenger will lift or sag more than 1 ft at the center of a 300-ft span when extreme temperatures are experienced. With a heavy catenary system the sagging at the center of the span due to high temperatures will bring about a condition where the pantograph will be more than 1 ft lower at the center of the span than at the support. In this case the pantograph will exert a minimum pressure against the wires in the central half of the span, and will not lift the wires very much because its pressure will be small compared with the total load carried by the messenger.

With so large a variation in the pantograph pressure against the contact wires at high speeds, under normal operating conditions any additional small irregularities in the contact system may require accelerations that would reduce or increase the pressure more and result in collection troubles. It is doubtful if current collection will be satisfactory on most present-day catenary systems, even with the latest designs of pantographs, at speeds of 100 mph or more. If speeds of this order are to be used, both the catenary system and the pantographs will have to be improved and designed for them.

High Frequency Induction Furnaces

By
C. A. ADAMS
PAST PRESIDENT A.I.E.E.
Harvard University, Cambridge, Mass.

J. C. HODGE
NONMEMBER A.I.E.E.
The Babcock & Wilcox Co., Barberton, Ohio

M. H. MACKUSICK
NONMEMBER A.I.E.E.
The Babcock & Wilcox Co., Barberton, Ohio

In language understandable by the average electrical engineer, this paper presents a brief outline of the theory of the electric induction furnace and of the application of that theory to the operating characteristics and limitations of such furnaces. From a metallurgical standpoint the chief advantages associated with the use of induction furnaces are: freedom from contamination of the melt, the high temperatures obtainable, and the circulation of the molten charge by the electromagnetic forces within it. The immediate acceptance by the industry of this comparatively new melting tool indicates that more extensive use of high frequency induced heat is to be expected in the future.

SO MUCH has been written on the subject of the high frequency electric induction furnace, particularly by Dr. E. F. Northrup, Ajax Electrothermic Corporation, Trenton, N. J., who may well be called the father of induction furnaces, that little of the original can be claimed for the conclusions reached. It is hoped, however, that the manner of presentation may appeal to many Institute members who are not already familiar with the subject. The appendix presents some interesting relationships between the operating characteristics and the size of the furnace in a very roughly approximate form, which may be of interest even to those already familiar with the subject.

An induction furnace is essentially a transformer, the secondary of which is the charge of metal to be melted. There are 2 principal types. First is the core or ring type, in which the charge forms a secondary circuit surrounding or ringing the magnetic core as in an ordinary power transformer. This type, which is adapted to low frequencies, will not heat up with a cold scrap charge but must be started with a complete or continuous secondary circuit of metal consisting of either a cold metal ring or a portion of the preceding molten charge left in the furnace for starting purposes.

The second type is the coreless furnace consisting usually of a helical inductor coil or primary winding and a cylindrical or nearly cylindrical crucible of refractory material concentrically located inside of the inductor coil. When supplied with electric power at a relatively high frequency this second type of furnace will melt easily a charge of cold scrap of any size. Even at 60 cycles such a furnace will operate satisfactorily except when starting with a cold scrap charge. It even will start cold at 60 cycles if supplied with a large plug of solid metal in the bottom of the crucible or hot with 25 or 30 per cent of the preceding molten charge left in for starting purposes.

The present paper deals entirely with this second or coreless type of furnace as applied to the melting of steels.

Full text of a paper recommended for publication by the A.I.E.E. committee on electrochemistry and electrometallurgy, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23-26, 1934. Manuscript submitted Nov. 13, 1933; released for publication Dec. 6, 1933. *Not published in pamphlet form.*

The single-phase power required by these furnaces is usually supplied by a high frequency alternator driven by a polyphase motor. Frequencies vary, but in general do not exceed 2,000 cycles per second, while 2,000 volts appears to be the present safe upper limit of voltage applied to the primary winding. In regard to capacities of induction furnaces now in use, sizes up to 3,000 lb are common, while one plant at present is using a 4-ton furnace; it is believed that the future trend undoubtedly will be toward larger units. Power consumption varies greatly in different plants, but as low as 600 kwhr per ton of steel is claimed for large furnaces.

Outline of Theory

When an alternating current flows through a metal conductor the distribution of the current density over the section of the conductor is never uniform. In the case of an isolated conductor the law of electromagnetic induction operates to yield the highest current density at the surface. When the frequency of the current and the permeability of the conductor are relatively high and the resistivity relatively low, the current will be confined largely to a thin surface layer or skin.

Theory shows that in such a case the problem may be handled as if the current were distributed uniformly over a skin depth of $T = \frac{1}{2\pi}\sqrt{\frac{\rho}{\mu f}}$, where ρ is the resistivity of the conductor in absolute cgs units, μ is its magnetic permeability, f is the frequency in cycles per second, and T is in centimeters. In this case the effective or equivalent a-c resistance of the conductor will be the resistance of the skin layer as defined, and its equivalent reactance will be equal to its resistance, this reactance being the portion due only to the flux within the skin layer and not to any flux outside of the conductor.

The preceding formula applies strictly only to the case of the current flowing through a flat plate of indefinite extent, but for practical purposes it applies with sufficient accuracy to a round conductor the diameter of which is large as compared with the skin depth; it applies also with sufficient accuracy to the cylindrical current flowing around the outer wall of the charge in a coreless induction furnace as well as to the primary current flowing around the inner wall of the inductor helix, although in none of these cases is it exact.

The only reasonably exact theory that can be applied to the high frequency coreless furnace is that involving Bessell's functions and even then only when the length of the helix is very large as compared with its diameter. In other words, in a furnace of normal proportions where the diameter and length of the helix are about equal, the end effect is large and complicated corrections have to be made in order to yield even fairly accurate results. The best attempt in this direction is given in a little book by C. R. Burch and N. R. Davis entitled "An Introduction to the Theory of Eddy Current Heat" published by Ernest Bent, Ltd., London, Eng.

Several other methods of attack have been employed, but the one that seems most suitable for the average electrical engineer is that which deals with the induction furnace in the light of conventional power transformer theory with some necessary variations. In this outline the charge will be assumed in the molten condition since any other condition renders the problem too complicated for practical purposes.

Although there is no available experimental data on the resistivity of molten steel, it will be sufficiently accurate to assume this to be 200 microhm-centimeters, which seems to give satisfactory results when applied to this problem. The magnetic permeability of the molten steel may be taken as unity. From these figures and the given frequency the equivalent skin depth then is calculated.

Assuming a cylindrical skin layer of current around the outer wall of the molten charge of such magnitude as to develop the desired amount of power in the charge, the resistance of the skin layer having been computed from its radial depth, resistivity, and dimensions of the crucible, this current will require an induced secondary voltage equal to the current times the resistance times $\sqrt{2}$, since the reactance is equal to the resistance. This secondary induced voltage must be produced by the vertical flux linking with the skin layer and passing through the cylindrical space within this layer. Its density then can be computed by the well-known formula. The exciting current can be computed by the familiar method, account being taken of the end or outside reluctance.

This gives the foundation for the equivalent transformer diagram, namely, the secondary voltage, the secondary current lagging 45° behind the voltage, and the exciting current 90° ahead of the voltage. From these 2 currents primary ampere turns may be computed.

Next compute the skin depth and resistance of the primary circuit reduced to a one-turn basis. Then compute the leakage reactance voltage of the primary due to the flux produced by the primary ampere turns, and passing through the annular cylindrical space between the primary and secondary current sheets. In making this calculation the end effect also must be considered. The primary voltage per turn then will be the sum of 3 components: (1) the voltage balancing that induced by the working flux which passes inside of the secondary current sheet; (2) the ohmic drop in the primary; and (3) the reactance drop in the primary. This will give the volts per turn from which the necessary number of turns can be computed according to the chosen supply voltage.

The copper loss, electrical efficiency, and power factor then may be computed by well-known methods.

This method of procedure makes no claim to theoretical rigidity but results check with experimental tests closely enough for all practical purposes.

The purpose of the outline at this point is chiefly to make more intelligible the discussion of the several vital factors given in subsequent portions of this paper by outlining the language to be employed. In an appendix a brief algebraic analysis of the gen-

eral problem of design based upon this outline of theory is given.

Single-Phase Versus Polyphase Furnaces

The foregoing outline assumes a single-phase supply. Although many attempts have been made to design polyphase coreless induction furnaces, several fundamental considerations make them undesirable. As far as the authors are aware, no successful polyphase high frequency coreless furnace is in operation today. Therefore, it will be assumed that hereinafter this paper deals only with single-phase furnaces.

Generating Equipment

It will be assumed in this connection that the equipment in question is for a relatively high frequency, say approximately 1,000 cycles per second, since this frequency has become almost standard for this type of furnace in sizes employed for melting steel. The only dependable commercial supply at this frequency is the single-phase alternator usually driven by a polyphase synchronous motor although, of course, it would be possible to drive such an alternator either from a high speed steam engine or from a steam turbine.

For frequencies much higher than 1,000 cycles per second the inductor type of generator probably would be more satisfactory, everything considered, but it is very difficult to say at just what frequency this advantage would be realized. For very much higher frequencies individual furnaces of laboratory size with mercury gap oscillators often are employed. Small furnace units also have been made using electronic rectifier and inverter tubes for the generation of high frequency currents, but as yet this method has not been developed to a point of commercial practicability.

Since the power factor of this type of furnace is inherently low, ordinarily not much higher than 10 per cent, it is obvious that the capacity of a high frequency alternator to supply an induction furnace direct would be enormous—in fact, prohibitive. It is customary, therefore, to use capacitors to supply the large quadrature lagging current required by the furnace. The actual cost of these capacitors at 1,000 cycles is a small fraction of the additional cost that would be involved if the generator had to supply this lagging current direct. This relatively low capacitor cost is due, of course, to the high frequency; at 1,000 cycles it amounts to about $1.50 per kva, whereas at 60 cycles it is more nearly $20 per kva.

Thus, the generating or supply equipment consists ordinarily of a single-phase high-frequency alternator driven by a polyphase synchronous motor with a bank of capacitors adjustable by relatively small steps and connected in parallel with the furnace coil.

Frequency

Although the factors involved in the choice of frequency are numerous, it will be sufficient here to discuss only those of major significance. Consider first the furnace itself in the light of the brief outline of theory already given. Assuming a certain power delivered to the charge of a given furnace, the resistance of the cylindrical skin layer of the charge will be proportional to the square root of the frequency, and the current inversely proportional to the square root of this resistance. Thus the current will be inversely proportional to the fourth root of the frequency and, therefore, will vary only slightly for moderate changes of frequency. Similarly, the induced voltage in the secondary or charge circuit will be directly proportional to the fourth root of the frequency and, therefore, nearly constant for moderate changes of frequency.

The flux density inside of the secondary current sheet will vary inversely as the frequency, and the exciting current likewise will be inverse to the frequency. In other words, for a high frequency the secondary current will be slightly smaller, the secondary induced voltage slightly larger, and the exciting current considerably smaller than for a low frequency; for moderate changes of frequency, the primary ampere turns will vary only slightly with the frequency, since the primary current is the vector sum of the exciting current and the negative of the load current.

If, however, the variation of frequency under consideration is a large one, for instance a jump from 960 cycles to 60 cycles, the secondary current at 60 cycles will be just double that at 960 cycles and the

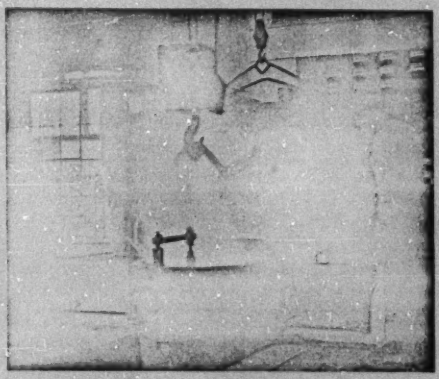


Fig. 1. Pouring a heat of stainless steel from a 3,000-lb tilting type coreless induction furnace at the plant of The Babcock & Wilcox Company, Barberton, Ohio

resistance $^1/_4$ so that the induced voltage will be $^1/_2$ and the exciting ampere turns 8 times as great; thus the total primary ampere turns will be more than twice as great for 60 cycles as for 960 cycles. However, since the copper skin depth at 60 cycles is 4 times as great, the resistance loss in the primary coil will be only slightly greater than at 960 cycles

by an amount depending upon the relative magnitude of the exciting current, that is, in its relation to the magnitude of the working or load current.

The other factor involved is the leakage reactance voltage of the primary winding. The total leakage flux will be proportional to the primary ampere turns which for 60 cycles will be somewhat more than double that for 960 cycles; but since the frequency in the latter case is 16 times that in the former, the reactance voltage at 960 cycles will be about 6 or 7 times as great. Thus, the power factor of the 60-cycle furnace is considerably higher than that of the 960-cycle furnace—in fact, more than double for furnaces of the same size and proportions.

To sum up, the low frequency furnace will have larger copper loss, lower efficiency, and higher power factor than the high frequency furnace.

Consider next the influence of frequency on the generating equipment and its first cost. Although the lower frequency means higher power factor and a somewhat smaller quadrature lagging current, it also means larger capacitors. In fact, the cost of the capacitors for complete neutralization or unity power factor on the generator, decreases with increase of frequency about proportionally to the $^2/_3$ power of the frequency. The cost of the generator itself, however, increases rapidly with increase of frequency, particularly when the frequency exceeds 400 or 500 cycles, and very rapidly when it exceeds 1,000 cycles. As it can be assumed that moderate changes in frequency do not seriously affect the furnace itself, it is obvious that there will be an optimum frequency from the standpoint of the first cost of the generating equipment, and that this optimum frequency will vary with the unit cost of the capacitors as well as with the unit cost of the generators.

It has been pretty fairly established that this optimum frequency for relatively large furnaces is about 1,000 cycles per second.

Voltage

For furnaces of large size such as those under consideration, a high voltage is desirable in order to reduce the size of bus bars and other leads as well as to reduce the corresponding copper loss. At the same time, the necessity for some exposed conductors as well as the limitations in the insulation of the furnace coil itself make it necessary to keep the voltage within limits. Most of the plants of this type are operating with voltages of the order of 1,000 volts, but one of the largest plants in the country has been operating for several years at 2,000 volts without experiencing any trouble on this score. This is probably the safe upper limit.

Primary or Inductor Coil

Already it has been explained that within the frequencies under consideration (excluding the extreme 60-cycle case) the number of ampere turns on the primary or inductor coil is practically independent of frequency, other things being equal. These primary ampere turns may be considered as a single current sheet flowing in the cylindrical skin wall of the primary helix, the radial depth of which skin is fixed by the frequency. It is thus obvious that the primary copper loss within the frequency range under consideration also is fixed. As a matter of fact, while the ampere turns increase slightly with decreasing frequency, skin depth also increases although to a less extent, and the copper loss is more nearly constant than the total ampere turns. This statement holds true regardless of the voltage and the number of turns, except insofar as the higher voltage and larger number of turns involve a corresponding increase in the total vertical height of the insulation between turns thereby reducing the effective vertical height of the skin section through which the total current flows. This difference is small within the range of voltage considered.

Because this practically fixed copper loss is relatively high, it has been found very difficult to keep the temperature of the primary coils within reasonable limits by any other method than that commonly employed, namely, water cooling. The conductor is made in tubular form, sometimes circular and sometimes rectangular, and is wound as a simple helix with water circulating through the conductor.

In furnaces of the sizes under consideration, excluding the 60-cycle furnace, and with voltages as previously indicated, the number of turns is relatively small, say from 10 to 20, and the coil is wound in a single layer. As the skin depth in copper at 1,000 cycles is approximately 0.1 in., it is obviously useless to make the tube wall much thicker than that except for mechanical reasons.

This type of coil is practically universally used in high frequency coreless induction furnaces of the sizes under consideration. However, complete calculations have been made looking toward the possibility of employing what may be called a "band wound" coil in which each conductor consists of a thin sheet of copper with a width equal to the full vertical height of the coil, and the several turns wound concentrically one over the other with a thin layer of refractory insulation between them. In this case the distribution of current across the radial thickness of each conductor will differ materially according to the location of the conductor from the inside to the outside, and this difference may be so great as to produce a total copper loss even greater than that of the simple helical coil although the apparent skin section is increased enormously. In other words, the ordinary skin depth approximation no longer holds; in fact, in some of the turns current will be flowing in opposite directions on the 2 sides of the same sheet or band. Moreover, there will be an uneven vertical distribution of current in the individual sheets. For each number of turns there will be an optimum thickness of sheet, and it is possible to design such a coil for say 1,000 cycles that will have a copper loss approximately half that of the conventional helical coil; but as it is practically impossible to water-cool a coil of this kind, and as air cooling makes necessary vertical annular spaces between the individual turns or groups of turns of the coil—an arrangement involving consider-

able structural complications and expense, it has not as yet been developed into a commercially satisfactory design.

Shielding

One of the practical difficulties in the design of this type of furnace arises from the fact that the relatively powerful high frequency magnetic field throughout the region of the furnace structure causes induced parasitic currents in any metal parts of that structure. Therefore, it has been necessary to reduce these metal parts to a minimum and to design them so as to reduce parasitic currents in the individual parts. At best the losses in these parts are appreciable although probably not more than 1 per cent or possibly 2 per cent.

In order that a substantial external steel supporting frame may be used without incurring excessive losses, it is possible to shield the frame from any considerable stray field by employing a closed copper tertiary or shield circuit inside of the frame, this circuit consisting of a thin copper cylinder concentric with the inductor coil, but far enough outside of it to permit the total magnetic flux of the furnace to pass between the inductor coil and the shield without the necessity for any excessive shielding current.

The magnitude of this shielding current can be computed easily from the furnace design since its magnetomotive force for perfect shielding will be equal to the drop of magnetic potential due to the total flux as it passes through the annular space between the inductor coil and the shield. It is thus obvious that the larger the diameter of the shield for a given sized inductor, the lower will be the flux density in this annular space and the less the shielding current. Moreover, since the shield current will be confined to the same skin depth as that of the current in the main coil, there can be no gain by making this shield thick. If the shield is of insufficient diameter the shield copper loss may be more than the parasitic losses that are eliminated. As a matter of fact, such a shield is practically useless from the standpoint of efficiency unless its diameter is considerably larger than is permissible on the ordinary furnace. Moreover, in such a case, while the outside steel structure may be completely shielded it cannot carry the inner structure without some supporting connection, and it is practically impossible to provide such a supporting connection without metal parts within the region of the main magnetic field, particularly on the top of the structure.

In lieu of a complete cylindrical shield such as described, flat copper plates sometimes have been employed on the 4 sides of a square frame. While this arrangement is claimed to be fairly satisfactory, no quantitative evidence is available.

If the full thickness of a thick copper shield could be employed for current conduction, the shield problem would be a fairly simple one. It would be possible, of course, to employ a multiple layer band shield, such as described for the primary "band wound" coil, with the outer and inner ends connected by stranded conductors passing through holes in the several layers. If properly designed such a shield would reduce the shield loss considerably, but its complications involve considerable expense and this expense hardly is warranted by the power saved. It is thus unlikely that any of the shielding schemes thus far proposed result in any considerable saving in the structural losses.

Magnetic Yokes

In order to reduce the reluctance of the return path, experiments have been made with magnetic yokes consisting of vertical stacks of laminated steel just outside of the inductor coil, running downward from the top of the coil and underneath the bottom of the furnace until they come together. These yokes improve the power factor by reducing the exciting current; but since in high frequency furnaces the exciting current represents a relatively small part of the total reactive kilovoltamperes, and since the reluctance of the return magnetic circuit is a small part of the total, the gain is very small. Moreover, since such yokes also reduce the reluctance of the return part of the leakage path they increase the leakage reactance of the primary coil enough practically to balance the gain in exciting current; thus, for high frequency furnaces the increased cost and structural complications are not warranted by the doubtful gain in power factor.

In the 60-cycle furnace, however, where the exciting current is many times larger and the leakage reactance small, considerable improvement in the power factor is possible and such yokes are at present in successful operation on at least one 60-cycle furnace. It is interesting to note that in this case the yoke provides the opportunity for using a copper shield of much smaller diameter than is possible without the yoke; the 60-cycle furnace referred to has such a shield in successful operation with a very substantial steel frame surrounding it. The structural strength of such a furnace is excellent. (See Fig. 3.)

Power Factor

Power factor of an induction furnace of any given frequency depends largely upon the ratio of the inner diameter of the primary coil and the outer diameter of the charge. Unfortunately, the necessity for a considerable radial depth of a refractory lining within this space makes the power factor of such furnaces very low. For example, at 1,000 cycles it will vary from 10 to 12 per cent within the size range under consideration, although it is possible to increase these values considerably by employing a thinner lining. This, however, would increase greatly the risk of a run-out, which is an expensive procedure particularly if the molten metal damages the inductor coil.

During actual operation the lining varies considerably in radial depth because of its erosion. When this erosion reduces the thickness to a danger point it is reinforced on the inside to its maximum thickness. Thus the power factor will vary from maximum to minimum with lining wear and the maxi-

mum often will exceed considerably the values given in the preceding paragraph.

Electrical Aspects of Melting a Charge

When starting cold the initial secondary heating currents are induced in the individual pieces of scrap, since the resistance at the contacts between the several pieces is sufficient to prevent any considerable circuital currents around the charge as a whole. At low frequencies, say 60 cycles, it is practically impossible to get a magnetic field strong enough to generate the necessary currents in individual pieces of a charge unless these pieces are unusually large, even though the cold permeability of the steel may be very high. At the higher frequencies no such difficulty arises, although even with these higher frequencies it is not ordinarily possible to deliver as much power to the cold charge with the same voltage impressed upon the primary coil as will be absorbed when the charge is in the molten condition. On this account it is usually necessary during the starting period to increase the primary

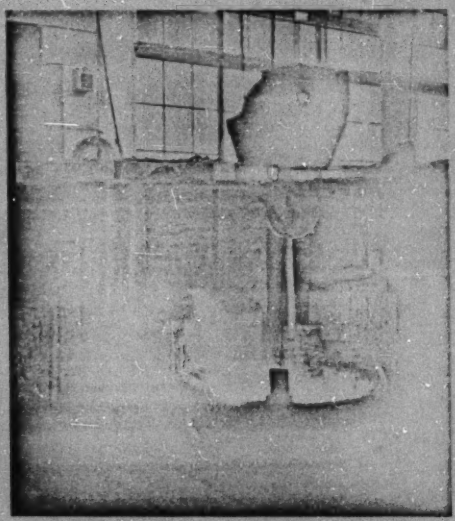


Fig. 2. Tapping a heat of stainless steel from a 3,000-lb stationary coreless induction furnace with bottom tap-hole. Compare the size of this furnace with that shown in Fig. 1, and note rugged appearance of stationary furnace

volts per turn. This makes necessary the provision of 1 or more, usually 2, additional taps on the primary coil with the necessary switches, preferably on the switchboard itself for the convenience of the operator. These taps usually are connected to one of the generator leads. Thus, the furnace coil acts as a step-up autotransformer to increase the voltage at the inductor terminals and hence across the capacitors which are connected in parallel with the inductor.

It is fairly obvious that during the starting period when the permeability of the steel is high, the exciting current will be reduced considerably, the power factor increased, and a smaller number of capacitors required. In other words, the number of capacitors required for complete neutralization will vary considerably from the cold starting to the finish of the heat; the maximum change takes place when the temperature of the metal passes the recalescence point and its permeability drops to unity. However, this change does not take place in all the metal at the same time so that the change of power factor as a whole is fairly gradual.

It is also obvious in this connection that the cold starting power absorbed will depend not only upon the size of the pieces of scrap but also to some degree upon the total amount of metal in the initial charge, which with odd shaped scrap may be less than $^1/_4$ of the final charge. It is thus possible with badly shaped scrap that the initial power in starting may be low even when the lowest tap is employed on the primary coil.

Electromagnetic reactions within the molten charge of the coreless induction furnace are such as to cause a stirring or boiling of the metal which increases at low frequency, since in that case both the secondary current and the magnetic field within the bath are larger, the same power being assumed. It is obvious that at any given frequency the amount of stirring would be approximately proportional to the square of the power delivered. The charge circulates in 2 distinct zones, 1 in the upper and 1 in the lower half of the furnace.

Although it would be entirely possible to supply sufficient power to a furnace of this type to complete the melting in less than one hour, there are some objections to rapid melting. When a heat is started at a high rate, portions of the metal quickly become molten and run to the bottom of the crucible. Because this molten layer receives more power than any similar quantity of the unmelted scrap it becomes superheated, boils violently, oxidizes readily, and causes serious erosion in the bottom of the furnace. Moreover, a solid lump of steel in the middle of this molten metal receives less power than it would before the molten metal was present, because it is shielded by the circular current around the wall of molten pool. Thus it receives heat mostly by conduction and melts rather slowly, while the metal surrounding it is superheated. Obviously, then, there is a limit to the melting time below which it is undesirable to go. On the other hand, the total heat leak obviously increases with the time of heating since the average temperature throughout the melting period is nearly constant. Thus we find again the necessity for some compromise or happy medium in the melting period, and a little consideration will indicate that the larger the furnace the longer should be the melting period. For small furnaces, of say 500-lb capacity, this period may be as short as 1 hour; but as the size

increases, it is desirable to increase the melting period to 2 or 3 hours.

Size Limits

Although no experience has been had with furnaces of this type which indicated any difficulty on the score of size, the following considerations would indicate a difficulty that might arise in furnaces of large diameter.

Since the total charge of a furnace of this type never can be held by the crucible in cold scrap form, it is necessary to keep feeding in scrap as the melt proceeds. Imagine a large piece of this cold scrap dropped into the center of the molten pool. As this piece would receive heat almost solely by conduction as already indicated, it might take so long in melting that the molten pool surrounding it would be superheated for a considerable period before the cold piece was thoroughly melted. This could be prevented, of course, by slowing down the heat and lengthening the melting period; it is for this reason that large furnaces must have a longer melting period. It is thus conceivable that a diameter may be reached which corresponds to a melting period too long for commercial efficiency. However, this limit has not been reached yet and experience alone can tell what the maximum diameter of the crucible may be; it is, of course, possible that no such limit will be reached on this particular score.

The influence of size and diameter upon several other operating characteristics and factors of interest is considered more quantitatively in an appendix.

Linings

For lining small induction furnaces, users prefer a one-piece crucible with heat insulation between crucible and coil. This type of lining, however, is very expensive for large furnaces, and several methods for installing built-in linings have been devised with varying degrees of success. The patented Rohn process produces a fritted lining by fritting a tamped refractory which has been placed between the coil and a steel sleeve. A modification of this method uses an asbestos sleeve in place of the steel sleeve. In both methods the steel sleeve or asbestos sleeve is fused away during the first heat. A third type of lining used extensively consists of a bonded refractory rammed in the furnace without the use of a sleeve. Fritted magnesite, acid ganister, or quartz linings may be produced by these methods.

Linings may be acid, basic, or neutral, magnesite commonly being used for a basic lining, zircon for a neutral lining, and ganister or a silica sand for an acid lining. Excellent results have been obtained using very pure silica sand of suitable grain size mixed with 15 per cent silica flour and moistened to a ramming consistency with a silicate of soda solution.

The life of the lining depends upon numerous factors. A highly refractory basic lining of sintered magnesite probably will give longest life if the lining can be handled so that cracks do not develop from sudden thermal strains. Magnesite linings may crack also due to bridging of the charge during melting with resultant heating of the metal below the bridge, or due to large pieces of scrap expanding. Magnesite linings do not flux appreciably. The average life of magnesite linings in 400- and 600-lb furnaces is 30 to 35 heats in the melting of stainless alloys. Neutral zircon linings have not been found generally satisfactory within the somewhat limited experience of the authors with this type of refractory. The ganister or silica sand lining is not as refractory as the magnesite or zircon linings, but will stand temperatures up to 3,000-deg F for short holding periods, and this limiting temperature is sufficiently high for most steel foundry melting. Acid linings do not crack readily, but wear away gradually by fluxing. With proper handling the acid or silica sand lining will give more than 100 heats of miscellaneous alloy melting before a complete new lining has to be installed. The bottom half of the lining usually requires patching after 10 or 15 heats because of the more severe erosion in that zone. Acid linings have a decided cost advantage over basic magnesite or neutral zircon linings, ganister being approximately $18 per ton as compared with $100 to $240 per ton for magnesite and zircon.

The question of correct grading of the dry refractory material is very important in securing satisfactory lining life, this subject being covered in a paper "Refractory Materials for the Induction Furnace" by J. H. Chesters and W. J. Rees. The refractory problem in the high frequency furnace has been one of the hardest problems to solve in the development of this furnace because of the high temperature gradient within the lining and because of the terrific thermal stresses set up during the tapping of a heat.

Metallurgical Considerations

The most interesting and important metallurgical features of the induction furnace are:

1. Freedom from contamination of the melt by reason of the absence of products of the heating process.
2. The high temperatures attainable.
3. The circulation of the molten charge due to electromagnetic forces within the bath.

All other characteristics of induction furnace melting, such as rapidity of melting, are subsidiary, and the field of application of the induction furnace has been governed largely by these 3 characteristics.

The first 2 characteristics have resulted in the application of the induction furnace to the production of low carbon alloys such as low carbon stainless irons and magnetic alloys; to the melting of highly refractory melts such as tungsten, molybdenum, cobalt, chromium, and alloys thereof; and to the production of tool steels, high nickel alloys, and corrosion and heat resisting iron-chromium or iron-nickel-chromium alloys. Considerable tonnage of low carbon stainless iron is produced by remelting scrap of corresponding analysis which could not be reclaimed conveniently by any other melting process. The great flexibility of induction furnaces in changing from heat to heat of varying analyses is of de-

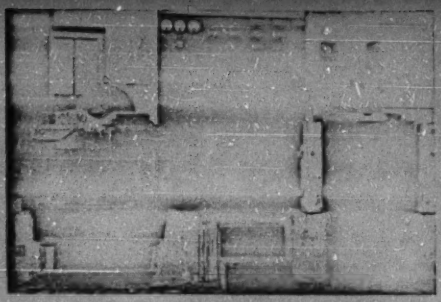


Fig. 3. Sixty-cycle 1,000-lb furnace of the shielded yoke type at the left. High frequency 1,000-lb furnace at the right; note experimental bottom-tap spout on this furnace

Note the relatively rugged structure of the 60-cycle shielded-yoke type of furnace. The 3 control panels are, left to right: 60-cycle furnace control; motor panel for high frequency motor-generator set; furnace control panel for high frequency 150-kva furnaces

cided advantage in producing alloys of the foregoing types which are melted in comparatively small sized heats and usually produced in a large variety of compositions.

Mention already has been made of the effect of rapid melting on the behavior of the first pool of molten metal formed which rapidly may become superheated, resulting in rapid oxidation of the metal and in abnormal reactions between the metal and the refractory lining. This may be remedied to some extent by limiting the rate of heating and by sprinkling the hot but unmelted pieces with slag forming material to prevent undue oxidation. The local overheating of the first molten metal may be avoided also by leaving in the furnace sufficient molten metal from the previous heat when the chemical natures of the 2 successive heats are not in conflict. Where successive heats of radically different compositions are to be melted, it may be necessary to melt an intermediate wash heat of low carbon iron to prevent contamination of the second melt from the slight "skull" left in the furnace from the previous heat.

Agitation of the metal after complete melting must be controlled to prevent boiling up of the molten metal through the slag covering with resultant exposure of the molten metal to the air. This movement in the low frequency furnace is particularly violent as evidenced by a nitrogen content of 0.117 as compared with a nitrogen content of 0.030 for the same type of alloy (18 per cent chromium, 8 per cent nickel) melted in a high frequency heat. Fortunately, movement of the bath can be controlled readily within limits by the regulation of the power input.

The possibility of refinement of molten metal under a slag in the induction furnace was recognized early, and many papers have been published showing the rapid removal of carbon, phosphorus, and sulphur under oxidizing and reducing slags. The elimination of oxygen from steels made in the induction furnace, however, is of much greater importance than the elimination of these metalloids, and presents great although not unsurmountable difficulties. Refinement of a metal under a slag in the induction furnace is aided by the agitation of the metal and is restricted by the quiescence and low temperature of the slag. The low temperature of an induction furnace slag could be overcome by supplying an auxiliary heating unit such as an arc or burner just sufficient to maintain the slag at the proper temperature. This expedient is probably unnecessary, however, if slags are employed which have a melting point so low as to remain liquid by transfer of the heat from the surface of the molten metal bath. Regardless of the melting point of the slag, provided it is lower than that of the melt, the slag layer at the interface of the melt surface and the slag is at the same temperature as the metal bath, and therefore is molten. Reactions between this slag layer and the bath proceed and are aided by the agitation of the melt, so that rapid attainment of equilibrium between the slag and melt is produced.

Choice of slag naturally will depend upon whether a basic or acid lining is used, and upon the nature of the alloy being melted. The use of slag possessing a high fluxing power for iron oxide or chromium oxide in the case of the corrosion resisting and heat resisting alloys is favored. Ground sodium silicate separated from the surface of the lining by an outer ring of silica is being used with success in furnaces having acid linings. Various lime-silica mixtures may be used with both acid and basic linings. Small additions of fluorspar may be made to the slag.

Deoxidation of the metal in the furnace is produced through the slag, i. e., the deoxidizer in finely ground form is mixed intimately with the ground materials of the slag makeup. That this procedure is quite effective in producing a reducing slag and a deoxidized condition of the metal may be shown by the control analyses of the slags of a stainless 18 per cent chromium, 8 per cent nickel heat made in a basic magnesite lined high frequency furnace which had ferrous oxide (FeO) contents of 16.01, 4.90, 2.20, 2.01, and 1.70 per cent in 5 successive slags removed during the refining period of 1 hr, 40 min of the heat.

Basic induction furnace slags have been produced with low oxide content. An analysis of a final refining slag of this type compared with a typical slag from a basic electric arc furnace, both on a low carbon stainless steel, is as follows:

	Basic Induction Furnace Slag	Electric Arc Furnace Slag
Silica	28.30	31.00
Lime (CaO)	57.68	56.00
Iron oxide (FeO)	0.28	Undetermined
Chromium oxide (Cr_2O_3)	0.13	0.80
Manganese oxide (MnO)	0.32	0.80
Magnesia (MgO)	10.97	3.00
Alumina (Al_2O_3)	Undetermined	4.00
Fluorine	Undetermined	4.00

The analyses of these slags are approximately the same, and refinement of the metals in both furnaces should proceed to the same degree provided final establishment of equilibrium between the slag

and metal is permitted in each case. Acid slags may be worked similarly, the analyses of 4 successive slags from a 1,500-lb heat of 18 per cent chromium, 8 per cent nickel iron in a ganister lined furnace being as follows:

	Slag 1	Slag 2	Slag 3	Slag 4
Silica (SiO_2)	58.15	54.62	60.04	58.01
Lime (CaO)	32.88	40.50	32.14	29.04
Iron oxide (FeO)	2.20	1.82	0.87	0.30
Chromium oxide (Cr_2O_3)	1.30	2.39	2.39	5.10
Manganese oxide (MnO)	1.08	1.59	2.11	5.72
Magnesia (MgO)	0.46	0.44	0.72	1.02

The greater deoxidizing ability of the acid-lined furnace in melting steel of this composition readily is shown by the analyses of the 4 slags in which the chromium and manganese contents increase with each succeeding slag. On the other hand, the ferrous oxide (FeO) content of the slag is reduced with each succeeding slag. One of the difficulties of working a heat under a slag in an induction furnace lies in the considerable erosion of the furnace lining around the slag zone.

The rapid agitation of the metal, which serves in hastening reactions between metal and slag and thus in refining the melt, produces an accompanying disadvantage in attempting to produce steel of low sonim content. Slag particles are drawn into the melt by the agitation, and it reasonably may be expected that the particle size of the entrained slag is small and kept small by the rapid movement of the bath. It is well known that the particle size of the slag is the most important factor in the elimination of slag inclusions, and, unless coalescence of the slag particles occurs, the steel produced will show a high inclusion count under microscopic examination. Due to the rapid agitation generally present in induction furnace melting, the slag particle size is small, the inclusions therefore are not elimininated readily, and the induction furnace steels are generally somewhat less clean than electric arc furnace steels. An inclusion count of several induction furnace and arc furnace steels of the same analyses show values of 0.13 to 0.53 and 0.087 to 0.13 for the area occupied by inclusions in per cent of total area of field examined under the microscope for the 2 types of steel, respectively. That clean induction furnace melted steels may be produced is evidenced by the values of the inclusion count on the low side of the range just given.

It should be appreciated also that the rate of coalescence of the slag particles depends upon the chemical nature of the slags. The governing factors in the coalescence of inclusions have been described by Herty and his co-workers, and a complete study of this problem as applied to induction furnace melting would be extremely valuable. Some evidence is available to show that the slag particles of basic furnace induction heats are generally larger than those of acid heats, and that basic heats are slightly cleaner than acid heats, due probably to more rapid coalescence and elimination of the basic slag particles as compared with the glassy acid slag particles.

No difficulty is experienced in melting steel of any composition in this type of furnace. No excessive loss of the usual alloying elements occurs with the exception of the readily oxidizable elements such as silicon, manganese, and aluminum, which are present only in small quantities in the usual commercial steels, and the loss of which can be compensated readily by small additions previous to tapping. The normal chromium loss in melting 18 per cent chromium, 8 per cent nickel irons either from scrap or virgin materials is only 0.5 per cent. The type of lining will be governed largely by the type of metal melted and by the affinities of the elements of the melt for oxygen as related to the stability of the oxides, magnesite, or silica, of the basic or acid linings. Alloys containing appreciable quantities of aluminum, vanadium, manganese, and other elements of high affinity for oxygen are melted in magnesite linings to prevent the undue loss that would occur in acid lined furnaces.

In view of the fact that induction furnaces require a comparatively short melting period, it is not feasible to take samples of a heat prior to tapping for check analysis. Induction melting, therefore, requires that the analysis of the charge be known exactly, and careful handling and sorting of scrap for the storage bins is required. Very little trouble has been experienced on this score at the plant of The Babcock & Wilcox Company in spite of the fact that this plant regularly produces alloy steels of some 30 different compositions and a much larger number of special alloys. Heat after heat of a given composition within a limited range for the individual elements may be produced by induction furnace melting. Ten successive heats of a 4–6 per cent chromium, $^1/_2$ per cent molybdenum steel showed but slight variations in the amounts of the individual elements, the spread of the percentage contents over the ten heats being as follows:

Carbon	0.24
Manganese	0.11
Silicon	0.15
Chromium	0.34
Molybdenum	0.37

Experience of the authors has been limited to furnaces of 3,000-lb maximum capacity. The future trend undoubtedly will be to larger melting units; one steel plant is using at present a 4-ton furnace, and it is expected that the use of these larger units will simplify greatly the problems arising from the rapid agitation of the molten bath of small induction furnaces. With these larger melting units a better comparison then may be made between induction furnace melting and other steel melting processes in units of approximately equal tonnage.

Commercial Cost Comparisons

The investment cost of high frequency melting equipment is roughly 4 times as great as the investment cost of arc melting equipment on a comparative daily tonnage basis; but this cost alone does not give a fair picture. The melting of small heats at frequent intervals is often very advantageous in

that the building space required for mold capacity is reduced very much; the outlay for ingot molds is less, the capacity of handling equipment such as overhead cranes and hoists may be reduced considerably. Also, in ingot production, it is quite probable that soaking furnace equipment might not be as costly, due to size for induction melting. D. F. Campbell claims that the capital cost for a steelworks of 6,000 tons per week capacity would be less if induction melting equipment were used in place of open-hearth furnaces. Moreover, the operating advantages would be numerous due to the flexibility of the induction equipment.

Power consumption varies greatly in different shops due to variation in steel making practices. Many users of induction furnaces claim as low as 600 kwhr per ton for large furnaces. In general it is probably true that arc melting is somewhat less costly from a power consumption standpoint but the added cost for electrodes more than balances the difference. Moreover, the arc furnace load is less desirable on a demand basis compared with a synchronous motor driven load for the induction furnace. The power factor of the load is better and the load fluctuations are not as great for the induction equipment.

Based upon an approximate monthly production of 200 tons melted in 3,000-lb and 1,500-lb furnaces using a 1,250-kva 960-cycle generator, the cost of acid furnace linings at one plant is approximately $1.30 per ton. On the same tonnage basis the cost of maintenance for the entire melting equipment, exclusive of furnace linings, is about $0.90 per ton.

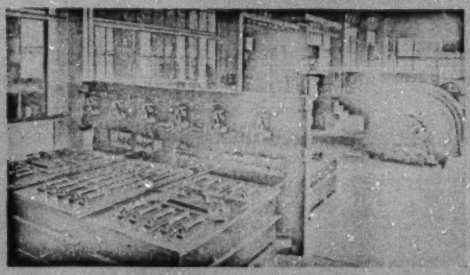


Fig. 4. High frequency motor-generator sets in the plant of The Babcock & Wilcox Company, Barberton, Ohio

1,250-kva 960-cycle set in foreground; 150-kva 2,040-cycle set in background. Note oil filled condenser tanks and magnetic contactors in 2 banks on either side of control switchboard

For smaller melting units or for a smaller tonnage these figures, of course, would be higher.

Continuity of production with induction melting usually is maintained by having a spare furnace on hand so that lining repairs may be made without loss of time. The cost of a spare unit adds only about 5 per cent to the original investment.

The question of metal loss during the melting operation is of minor importance, but over a long period of time it might amount to a considerable sum. No rigid data on melt loss in induction furnaces is available; but it is safe to say that such loss is in all probability considerably less than in other types of melting equipment. This is because the metal is the hottest part of the furnace and, moreover, the melting time is usually very much less. Hence, less loss by oxidation and through slagging operations takes place.

The immediate acceptance by the industry of this comparatively new melting tool indicates that more extensive use of high frequency induced heat is to be expected. In addition to advances in melting equipment, future development is likely to reveal new economies and uses for this type of heating in continuous furnaces for heat treating and processing of steel and other metals. Doctor E. F. Northrup in his paper "Practical Methods for Inductively Heating Solids," presented at a meeting of the Association of Iron and Steel Electrical Engineers in January 1933, offers some interesting and ingenious methods of employing high frequency heating.

The first commercial installation of high frequency melting was a 150-kva unit installed some 7 years ago. The development in this short period has been rapid, and today 2 generating units of 1,250-kva capacity are in operation in 2 large midwestern plants; numerous other units of intermediate sizes have been installed in plants scattered throughout the country. Only time can tell what the future holds in store for induction heating.

Appendix I—Relation of Size to Electrical Characteristics

The purpose of this appendix is to give a rough idea of the relationship between the electrical characteristics of the furnace and a basic linear dimension, namely, the inner diameter of the crucible. To this end, all other dimensions are assumed to bear a constant relation to this diameter within the range of sizes considered, namely, from 1 to 4 tons capacity. This assumption of constant proportions does not accord strictly with design practice, but is close enough within the range of sizes under consideration. It is assumed also that the frequency in every case is 960 cycles per second.

In order to reduce the results to their simplest form, it has been necessary to make some rather crude approximations. This does not involve any appreciable error for the 2-ton size of furnace, the error for the limits of the range being given in each case.

The only result that might seem a little abnormal is in connection with the power factor, which is found to vary roughly inversely as the diameter. In an actual design the thickness of the refractory wall would not increase quite as rapidly as the diameter, which, together with some of the approximations made, would tend to make the power factor more nearly constant. If, for example, the refractory wall were of constant thickness for the different sizes, the power factor would be constant, although the omission of the approximations would make it even a little larger for the larger sizes. With normal designs, the power factor actually would be a trifle smaller for the larger sizes.

In any case, it must be remembered that the approximations apply only to the size range mentioned, and cannot be extended beyond this range without serious error. Another assumption which, although in general rational, is nevertheless not strictly according to practice, is that the melting time is proportional to the diameter according to a particular numerical ratio. All of these assumptions and limitations must be borne in mind when interpreting the results.

Consider only from 1-ton to 4-ton size range. In order to simplify otherwise complicated expressions, assume proportional

dimensions. (This assumption, while not strictly according to actual designs, is close enough within the range considered.)

Let

d = mean outside diameter of charge (inches)

d_1 = inside diameter of coil = approximate diameter of skin current

t_1 = radial thickness of lining = $0.12d$

l = vertical height of inductor = vertical depth of charge

l/d_1 = 0.9, or $l = 0.9d_1 = 1.115d$

V = volume of charge (cubic inches)

W = weight of charge (pounds)

Then

$$d_1 = d + 2t_1 = d + (2 \times 0.12d) = 1.24d$$

$$V = \frac{\pi}{4} d^2 l = \frac{\pi}{4} d^3 \times 1.115d = 0.875d^3$$

$$W = 0.27V = 0.236d^3$$

Allowing for heat leakage and radiation, total gross heat to charge $= 230W$, in watt hours.

Let T = total melting period in hours = $0.075d$ (estimated from experience)

Then average power to charge, $P_{1A} = \dfrac{230W}{T} = \dfrac{230 \times 0.236d^3}{0.075d} = 727d^2$ watts

And maximum power to charge at full melt = $P_1 = 1.375P_{1A} = 1{,}000d^2$ watts (the 1.375 is an estimated constant)

Assume

Frequency, $f = 960$ cycles per second

Resistivity of molten charge = $\rho_2 = 200 \times 10^{-6}$ ohm-cm

Magnetic permeability of molten charge = $\mu = 1$

Then charge skin depth, $t_2 = \dfrac{1}{2\pi}\sqrt{\dfrac{\rho_2 \times 10^9}{\mu f}} = 5030\sqrt{\dfrac{\rho_2}{\mu f}} =$ 2.30 cm = 0.903 in.

Secondary resistance, $R_2 = \dfrac{\rho_2 \times l_2}{A_2} = \dfrac{\rho_2 \times (d - t_2)\pi}{l \times t_2 \times 2.54}$

$$= \frac{(200 \times 10^{-6})(0.965d)}{1.115d \times 0.903 \times 2.54} = 2.37 \times 10^{-4}$$

ohms (error < 1 per cent)

$(d - t_2) = 0.965d$ within 1 per cent error within size range considered; an approximation.

Secondary current, $I_2 = \sqrt{\dfrac{P_1}{R_2}} = \sqrt{\dfrac{1000\,d^2}{2.37 \times 10^{-4}}}$

$= 2{,}055d$ (error < 0.5 per cent)

Secondary voltage, $E_2 = \sqrt{2} \times I_2 R_2 = 0.707 \times 2{,}055d \times 2.37 \times 10^{-4}$
$= 0.688d$

But $E_2 = 4.44 \times B_{2M} \times S_2 \times f \times 10^{-8}$

where

B_{2M} = maximum flux density linking charge

S_2 = area of flux path in charge

$= \dfrac{\pi}{4}(d - 2t_2)^2 = \dfrac{\pi}{4}(d - 1.8)^2 = \dfrac{\pi}{4}(d^2 - 3.6d + 3.24)$

$= 0.785\,(d^2 - 3.5d)$ (approximation, error < 4 per cent)

$= 0.785d\,(d - 3.5)$

Then

$$B_{2M} = \frac{0.688d \times 10^8}{4.44 \times 0.785d\,(d - 3.5) \times 960} = \frac{20{,}600}{d - 3.5} = \frac{20{,}600}{0.865d}$$

$$= \frac{23{,}800}{d} \text{ (approximation, error < 4 per cent)}$$

Primary exciting ampere turns, $NI_0 = 0.221\,B_{2M} \times l \times K_0$ where $K_0 = 1.5$ is a constant to account for the end and return path reluctance

Then

$$NI_0 = \frac{0.221 \times 20{,}600 \times 1.115d \times 1.5}{(d - 3.5)} = \frac{7{,}620d}{(d - 3.5)} = \frac{7{,}620d}{0.865d} \text{ (roughly)}$$

$= 8{,}810$ ampere-turns (approximation, error < 4 per cent)

Since NI_0 is only 12 to 18 per cent of NI_1 (total ampere-turns) the approximate value will serve the purpose of this general analysis.

$NI_1 = I_2 + 0.75NI_0$ (very closely for range and conditions assumed)

$= 2{,}055d + 0.75 \times 8{,}810$

$= 2{,}055d + 6{,}608$

$= 2{,}055\,(d + 3.22)$

NI_1 = approximately $2{,}055\,(d + 0.125d) = 2{,}310d$ (approximation, error < 3.2 per cent)

Primary copper loss:

Resistivity of copper at 90 deg C = 2.2×10^{-6} ohm-cm = ρ_1

Skin depth = $t_1 = 5{,}030\sqrt{\dfrac{2.2 \times 10^{-6}}{1 \times 960}} = 0.241$ cm = 0.0950 in.

R_1' = equivalent resistance of single-turn inductor = $\dfrac{R_1}{N^2}$ where

N = number of turns

$R_1' = \dfrac{\rho_1 \times l_1}{A_1}$

where l_1 = mean length of path of primary current, and A_1 = mean area of cross section of primary current path

$A_1 = K \times t_1 \times l$ where $K = 0.85$ to account for insulating space factor between turns

Then

$$R_1' = \frac{2.2 \times 10^{-6} \times \pi\,(d_1 + t_1)}{K t_1 l}$$

$$= \frac{\pi \times 2.2\,(1.24d + 0.0950)}{0.85 \times 0.0950 \times 1.115d + 2.54 \times 10^6}$$

$$= \frac{30.4\,(1.24d + 0.0950)}{10^6 \times d} = \frac{37.5\,(d + 0.0766)}{10^6 \times d}$$

$$= \frac{37.5(d + 0.003d)}{10^6 \times d} = 37.6 \times 10^{-6}$$

(approximation, error < 0.1 per cent)

$$I_1^2 R_1 = (NI_1)^2 \frac{R_1}{N^2} = (NI_1)^2 R_1' = \frac{37.6}{10^6} \times [2{,}055\,(d + 3.22)]^2$$

$= 37.6 \times 4.22\,(d + 3.22)^2$

$= 158.7\,(d + 0.125\,d)^2$

$= 201.0\,d^2$ (approximation, error < 6.0 per cent)

Electrical efficiency = $\dfrac{P_2}{P_2 + I_1^2 R_1} = \dfrac{1{,}000d^2}{1{,}000d^2 + 201d^2}$

$= 83.3\%$ (error < 1.0 per cent)

Primary reactance volts:

B_{1M} = Primary leakage flux density

$$= \frac{3.2\,NI_1 \times \sqrt{2}}{l \times K_l}$$

where $K_l = 1.35$ is a constant to account for the end and return field reluctance.

$$B_{1M} = \frac{3.2 \times \sqrt{2} \times 2{,}310d}{1.115d \times 1.35} = 6{,}940$$

(approximation, error < 3.2 per cent)

$\dfrac{E_x}{N}$ = Reactance volts per turn

$= 4.44 \times f \times B_{1M} \times S_l \times 10^{-8}$

where S_l = area of leakage path = $\dfrac{\pi}{4}(d_1^2 - d^2) = \dfrac{\pi}{4} d^2(1.24^2 - 1^2)$

$= 0.422\,d^2$

$\dfrac{E_x}{N} = 4.44 \times 960 \times 6{,}940 \times 0.422d^2 \times 10^{-8}$

$= 0.1248 \times d^2$ (approximation, error < 3.2 per cent)

$\dfrac{E_1}{N}$ = Total primary volts per turn (neglecting small primary IR drop)

$= \dfrac{E_x}{N} + 0.83E_2$ (very close for range and conditions assumed)

$= 0.1248d^2 + 0.688d \times 0.83$

$= 0.1248d\,(d + 4.57) = 0.1248d\,(d + 0.178d)$

$= 0.1470d^2$ (approximation, error < 7.1 per cent)

Power Factor = $\dfrac{P_2 + I_1^2 R_1 + (\text{stray losses})}{\dfrac{E_1}{N} \times NI_1}$

$= \dfrac{1{,}000d^2 + 201d^2 + 10d^2}{0.1470d^2 \times 2{,}310d}$ (stray losses = about 1 per cent of P_2)

$= \dfrac{3.56}{d}$ (approximation, error < 10 per cent)

SUMMARY

Weight of charge $W = 0.236d^3$
Power input $P = 1{,}201d^3$
Efficiency $E = 83.3$ per cent
Primary amp. turns $NI_1 = 2{,}310d$
Volts per turn $E_1/N = 0.1470d^2$
Power factor $PF = 3.56d^{-1}$

Hence, for a 2-ton furnace

$$d = \sqrt[3]{\frac{4{,}000}{0.236}} = 25.63 \text{ in.}$$

Power input $= 1{,}201 \times 25.63^3 = 788$ kw
Volts per turn $= 0.1470 \times 25.63^2 = 96.6$

$$\text{Turns (for 1,000 volts)} = \frac{1{,}000}{96.6} = 10.36 \text{ or } 11.$$

$$\text{Current} = \frac{2{,}310 \times 25.63}{11} = 5{,}380 \text{ amp}$$

$$\text{Power factor} = \frac{3.56}{25.63} = 0.1388$$

Selected Bibliography

(Courtesy of Ajax Electrothermic Corporation, Trenton, N. J.

[**Editor's Note.**—Lack of time precluded the reconstruction of this reference list in the complete and convenient form adopted as standard for ELECTRICAL ENGINEERING. Therefore, the list is reproduced as supplied by the authors.]

General Theory and Apparatus

(Listed in order of date of publication)

SOME NEWLY OBSERVED MANIFESTATIONS OF FORCES IN THE INTERIOR OF AN ELECTRIC CONDUCTOR, by E. F. Northrup. *Phys. Rev.*, v. 24, No. 6, June 1907.

PRINCIPLES OF INDUCTION HEATING WITH HIGH-FREQUENCY CURRENTS, by E. F. Northrup. *Trans.* of the Am. Electrochem. Soc., v. 35, 1919.

UNIFORM HIGH TEMPERATURES THROUGHOUT A LARGE VOLUME, by E. F. Northrup. *Journal of Ind. and Eng. Chem.*, July 1921.

ELECTRIC HEATING BY IRONLESS INDUCTION, by E. F. Northrup. *Gen. Elec. Rev.*, Nov. 1922.

CONVERSION OF ELECTROMAGNETIC ENERGY INTO USEFUL HEAT, E. F. Northrup. *Research Narrative No. 55*, published by the Engineering Foundation, New York, N. Y., April 1923.

FOURS À INDUCTION, Ribaud. *Fours Electriques et Chimie*, Chap. V, p. 325–70, published under the direction of Paul Lebeau.

DEVELOPMENTS IN HIGH-FREQUENCY INDUCTIVE HEATING, Dudley Willcox. *Metal Industry*, Feb. 1925.

HIGH-FREQUENCY INDUCTION FURNACES, by D. F. Campbell. *Trans.* Iron and Steel Institute (British) 1925.

A HIGH-FREQUENCY INDUCTION FURNACE PLANT FOR THE MANUFACTURE OF SPECIAL ALLOYS, P. H. Brace. A.I.E.E. TRANS., 1925.

INDUCTIVE HEATING, E. F. Northrup. *Journal of the Franklin Inst.*, Feb. 1926.

ZUR KENNTNIS DES HOCHFREQUENZ-INDUKTIONSOFENS I, Franz Wever and Wilhelm Fischer. *Proc.* of the Kaiser Wilhelm Institute for Iron Research, v. 8, 1926, Part 10.

ELECTRICITY IN THE FOUNDRY, C. R. Burch and N. R. Davis. Metropolitan-Vickers *Gazette*, Feb. 1927.

HIGH-SPEED HIGH-FREQUENCY INDUCTIVE HEATING, by E. F. Northrup. *Trans. of the American Electrochemical Society*, 1927.

HIGH-FREQUENCY INDUCTION MELTING, D. F. Campbell. Iron and Steel Institute (British) fall meeting, 1927; Summary in *Electrician* (London) Nov. 25, 1927.

FOURS À INDUCTION, G. Ribaud. *Revue Trimestrielle Canadienne*, March 1928.

INDUSTRIAL ELECTRIC HEATING, N. R. Stansel and E. F. Northrup. *General Electric Review*, April 1928.

HIGH-FREQUENCY ALTERNATORS FOR INDUCTION FURNACES. *English Electric Journal*, July 1928.

FOURS À INDUCTION À HAUTE FREQUENCE ET À CREUSET CONDUCTEUR, Marcel Mathieu. *Arts et Metiers*, Sept. 1928.

I FORNI E INDUZIONE SENZA NUCLEO MAGNETICO, L. A. Finzi. *L'Elettrotecnical*, Nov. 15, 1928.

ENTWICKLUNGSSTAND DES KERNLOSEN INDUKTIONSOFENS, M. Tama (Development Status of the Coreless Induction Furnace). Presented at the Nov. 27, 1928, session of the Stahlwerkausschuss des Vereins Deutscher Eisenhuttenleute.

THE HIGH-FREQUENCY INDUCTION FURNACE FOR CHEMICAL PREPARATIONS ABOVE 1000 DEG C. C. N. Schuette and Chas. G. Maier. *Trans.* of the Am. Electrochem Soc., 1928.

PRODUCTION OF IRON AND STEEL IN THE ELECTRIC FURNACE (refers mostly to arc furnaces), Dr. Alfred Stansfeld. *Fuels and Furnaces*, Feb. 1929.

HIGH-FREQUENCY FURNACES USED IN MELTING ALLOY STEELS, R. N. Blakeslee. *Fuels and Furnaces*, July 1929.

FORTSCHRITTE IM BAU VON HOCHFREQUENZ-OFENANLAGEN, M. Tama. *Stahl und Eisen*, Nov. 15, 1929.

HÖGFREKVENSUGNENS PLATS BLAND ANDRA I SVERIGE ANVÄNDA UGNAR FOR STALFRAMSTÄLLNING. C. Gejrot. *Teknisk Tidskrift*, March 1930 (Swedish).

Metallurgical

(Listed in order of date of publication)

DECARBURIZATION OF FERROCHROMIUM BY HYDROGEN, Louis Jordan and F. E Swindells. *Scientific Paper* of the U. S. Bureau of Standards *No. 448*.

PERMALLOY, ALLOY OF REMARKABLE MAGNETIC PROPERTIES, H. D. Arnold and G. W. Elmen. *Telegraph and Telephone Age*, Dec. 1, 1923.

UEBER DIE VERWENDUNG DER HOCHFREQUENZ-INDUKTIONSOFEN FÜR DIE EDELSTAHLERZEUGUNG, Friedrich Korber, Franz Wever, and Heinz Neuhaus. *Stahl und Eisen*, Nov. 25, 1926.

ZUR KENNTNIS DES HOCHFREQUENZ-INDUKTIONSOFENS II, Franz Wever and Heinz Neuhaus. *Proc.* of the Kaiser Wilhelm Institute, v. 8, Nov. 11, 1926.

ELECTRIC FURNACES IN NONFERROUS METALLURGY, D. F. Campbell. *Trans.* Institute of Metals (British) 1927.

ZUR METALLURGIE DES HOCHFREQUENZ-INDUKTIONSOFENS, Franz Wever and Gustav Hindrichs. *Stahl und Eisen*, Jan. 5, 1928.

CRUCIBLE STEEL PRODUCTION IN A HIGH-FREQUENCY ELECTRIC STEEL FURNACE. *Ry. Engr.*, January 1928.

STEELS MADE UNDER NEW CONDITIONS. *The Iron Age*, April 19, 1928 (Abstract of paper by Wever and Neuhaus, translation prepared by W. Adam, Jr.)

PROGRESS IN THE PRODUCTION OF CRUCIBLE STEELS. *Iron and Steel Ind.*, Aug. 1928.

MAGNESIA GRAPHITE REACTION AT HIGH TEMPERATURE, F. T. Chesnut. *Chem. and Met. Engr.*, Nov., 1928.

DEVELOPMENTS IN THE CORELESS INDUCTION FURNACE, Dr. H. Neuhaus. Paper presented at the Nov. 27, 1928, session of the Stahlwerkausschuss des Vereins Deutscher Eisenhüttenleute.

MELTING STERLING SILVER IN HIGH-FREQUENCY INDUCTION FURNACES, Robert H. Leach. *Trans.* of the Am. Electrochem. Soc., 1928.

HOCHFREQUENZ-TIEGELSTAHL, Hohage and B. Matuschka. *Schoeller-Bleckmann Nachrichten*, March 1930.

INDUCTION FURNACES FOR NONFERROUS AND IRON FOUNDRIES, Manuel Tama. *Trans.* Am. Foundrymen's Assn., 1930.

SOME ALLOYS FOR USE AT HIGH TEMPERATURES, W. Rosenhain and C. H. M. Jenkins. *Engg.* (British) June 13, 1930.

PREPARATION DES ACIERS SPECIAUX AU FOUR ELECTRIQUE À HAUTE FREQUENCE, by M. A. Lacrois (Preparation of Special Steels in High Frequency Induction Furnace). *Journal du Four Electrique*, July 1930.

ELEKTRISCHE SCHMELZÖFEN FÜR NICHTEISENMETALLE, by M. Tama.

Additions (Unclassified)

BRONZE MELTED ECONOMICALLY IN HIGH FREQUENCY FURNACE, J. Howard Williams. *Metal Progress*, Jan. 1931.

TONNAGE MELTING BY CORELESS INDUCTION, E. F. Northrup. *Iron Age*, Jan. 15, 22, 29, 1931.

THE CORELESS INDUCTION FURNACE IN A NEW RÔLE, A. G. Robiette. *The Iron & Steel Ind.*, Jan. 1931.

THE CORELESS INDUCTION FURNACE IN THE STEEL INDUSTRY, E. F. Northrup. *Iron and Steel Engr.*, May 1931.

DEVELOPMENTS IN HIGH FREQUENCY FURNACES FOR STEEL, N. Broglio. *Stahl und Eisen*, May 14 and 21, 1931.

HIGH FREQUENCY INDUCTION FURNACES—Part V, Franz Wever and Gustav Hindricks. *Mitteilungen Kaiser Wilhelm Institut für Eisenforschung*, v. 13, 1931.

THE HIGH FREQUENCY FURNACE AND ITS USE FOR THE MANUFACTURE OF STEEL CASTINGS, T. R. Middleton. *Foundry Trade Jl.*, Jan. 28, 1932.

LARGE HIGH FREQUENCY FURNACES, D. F. Campbell. *The Iron and Steel Ind.*, Feb. 1932.

SOME FEATURES OF CORELESS INDUCTION FURNACES, A. D. Meyer. *Heat Treating and Forging*, April 1932.

FOUR-TON CORELESS INDUCTION FURNACE INSTALLED, Dudley Willcox. *Steel*, May 30, 1932.

CORELESS INDUCTION FURNACES, R. N. Blakeslee, Jr. *The Foundry*, July 1932.

INDUCTION MELTING OF ALLOY STEELS, M. H. MacKusick. *Elec. World*, July 30, 1932.

DEVELOPMENT OF HIGH FREQUENCY METALLURGICAL FURNACES, Manuel Tama. *Zeitschrift des Vereines Deutscher Ingenieur*, Feb. 25, 1933.

PRACTICAL METHODS FOR HEATING SOLIDS BY INDUCTION, E. F. Northrup. *Iron and Steel Engr.*, March 1933.

Control of Distance Relay Potential Connections

By A. R. van C. WARRINGTON
ASSOCIATE A.I.E.E.
General Elec. Co., Philadelphia, Pa.

By means of the automatic switching of potential connections to distance relays according to type of fault, each distance relay may be made to do the work of 2 or 3 such relays. The cost of distance relay installations may be reduced considerably by this automatic control of potential connections, and consequently their use should become more widespread.

DURING the past 5 years distance relays gradually have become more popular for the protection of important transmission lines on account of their rapid action and their immunity from the effects of variations of system set-ups and generating conditions. Their application, however, has been confined hitherto almost exclusively to networks above 110 kv and protection against faults involving more than one phase. Since financial outlay is the main reason for not extending their application further it is the purpose of this paper to show how more and better protection can be obtained per dollar's worth of distance relay.

In Continental Europe, distance relays have enjoyed a much wider popularity than in this country although the relays used there are, in general, slower. Automatic potential switching has had a good deal to do with their wide application. One distance relay is made to do the work of 2 or 3 by automatically providing it with potential from the proper phase upon the occurrence of a fault.

While this subject therefore is not entirely new, it has not previously appeared in publications in this country, as far as the author is aware. The schemes described are mostly based upon European practice modified where necessary for use with modern American high speed distance relays. They are suitable for either impedance or reactance relays except where mentioned.

Conclusions which may be drawn from the methods described in this paper are that with automatic potential switching the application of distance relays can be extended as follows:

1. The expense of a complete set of distance relays on lines of secondary importance can be avoided by making one distance relay protect all 3 phases against interphase faults (Figs. 1 and 2).

2. On certain lines one distance relay can be made to protect a 3-phase line against ground faults (Fig. 3).

3. Three distance relays can be made to protect against ground faults in addition to interphase faults (Figs. 8 and 9).

4. With lessened accuracy and rather complicated switching a single distance relay can be made to provide protection against interphase and ground faults (Fig. 7).

Full text of a paper recommended for publication by the A.I.E.E. committee on protective devices, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 25, 1933; released for publication Dec. 5, 1933. *Not published in pamphlet form.*

In each scheme auxiliary relays (referred to as selector relays) are provided which are associated with individual phases or with the residual circuit. The potential circuits of the distance relays are connected to the appropriate phases of the secondary potential supply by the selector relays according to which phases are involved in the fault. This may be done either directly through contacts on the selector relays (as in Figs. 1, 2, 3, 4, 7, 9, and 10) or indirectly through contacts on d-c auxiliary relays, called a transfer relay (as in Figs. 5 and 8).

Where the fault current always exceeds the load current, the selector relays can be simple instantaneous overcurrent relays, as indicated in Figs. 1–4, 7, and 10 and can sometimes be mounted within the distance relay itself. In the less frequent cases where operation is desired on faults with less than normal current, voltage restraint coils can be added to prevent them from picking up under normal conditions (see Figs. 5, 8, and 9).

One Distance Relay for Interphase Faults

In Fig. 1 is shown a Continental arrangement, using one distance relay instead of 3 for faults between phases. In order to prevent operation normally while the potential circuit of the distance relay is short-circuited, it should have a starting unit which cannot operate on current alone. Table I shows how the distance relay is energized for faults between the various phases. It will be noticed that a fault between phases 1 and 2 or a 3-phase fault provides current from both the current transformers, but the distance measurement is kept the same by bypassing half the current through the "impedor" Z.

In Fig. 2 and Table II is shown an alternative arrangement which avoids the special connection of the current transformers by means of double current windings on the distance relay. In this dia-

Table I—Methods of Energizing Distance Relay of Fig. 1

Fault	Potential	Current	Ohms
3-phase	E_{12}	$^1/_2(I_1 - I_2)$	$2X_p$
Phases 1-2	E_{12}	I_1	$2X_p$
Phases 2-3	E_{23}	$-I_2$	$2X_p$
Phases 3-1	E_{31}	$^1/_2(I_1 - I_2)$	$2X_p$

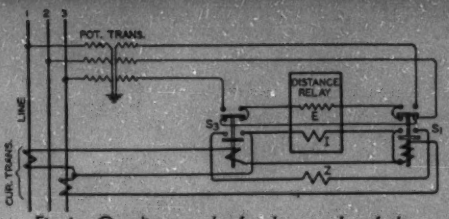


Fig. 1. One distance relay for phase-to-phase faults

S_1 and S_2. Selector relays
E and I. Potential and current windings of distance relay
Z. Impedance equal to that of current winding for equalizing the relay current during similar faults on different phases

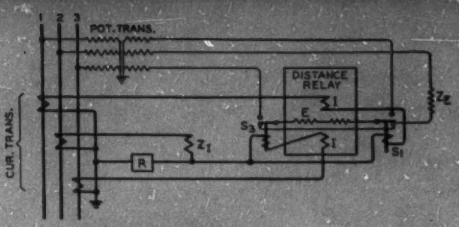


Fig. 2. One distance relay for phase-to-phase faults

S_1 and S_2. Selector relays
E and I. Potential and current windings of distance relays
R. Residual current circuit
Z_E. Impedance equal to that of E windings for equalizing the ohmic measurement
Z_I. Impedance equal to that of I windings for balancing current transformer burdens

gram also the impedor is in the potential circuit, thus eliminating the low resistance type of contacts necessary in Fig. 1 for short-circuiting the impedor in the current circuit. On the other hand, while the selector relays can be made more simply, the distance relay itself must be of superior design because it receives approximately double current and voltage for faults involving phases 1 and 3, and must still give the same distance measurement and operating time though influenced by 4 times the power.

The economy realized from the elimination of 2 relays out of each set enables distance relays to be used on lines whose importance does not warrant the expense of 3 distance relays per breaker, in spite of their superior protection and greater flexibility.

One Distance Relay for Ground Faults

Similar but even simpler switching means can sometimes be used in the case of a ground distance relay (see Fig. 3). In this circuit the current coils are supplied with residual current and the potential coils with potential from phase 1 normally. Upon the occurrence of a fault in phases 2 or 3, the line current operates the corresponding switching relay to switch it to the proper phase-to-neutral potential.

It will be seen that during 2-phase faults the distance measurement will be inaccurate. The error will be on the high side with impedance relays so that back-up protection will be given to the interphase distance relays. Reactance relays will require an additional selector relay in the third phase with a contact arrangement similar to that of Figs. 5 and 8, to prevent action on faults involving more than one phase; otherwise, the phase angle on interphase faults could cause underestimation of the distance.

The reactance measured by a relay supplied with wye voltage and residual current during a single-phase-to-ground fault (see Appendix B) is $\frac{1}{3}\left(X_s + \frac{A+B}{C} \times X_p\right)$ where A, B, and C are factors dependent upon magnitude and location of the generation and grounding points (see Appendix A) and X_s and X_p are respectively the zero phase sequence and positive phase sequence reactance between the relay and the fault.

The distance measurement is therefore affected by change in system set-up and would only be constant on lines not subject to wide variations in system arrangement. However, the protection afforded to most lines would be better than that obtainable from the ordinary residual time-power relay.

Three Relays for Complete Protection

In cases where 3 distance relays are already installed for protection against interphase faults, their duties can be extended to single-phase ground faults also by providing potential switching means as shown in Fig. 4.

The distance relays are supplied with wye current. Their potential circuits are connected to the cor-

Table II—Methods of Energizing Distance Relay of Fig. 2

Fault	Potential	Current	Ohms
3-Phase	E_{12}	$I_1 - I_3$	X_p
Phases 1-2	$\frac{1}{2}E_{12}$	I_1	X_p
Phases 2-3	$\frac{1}{2}E_{23}$	$-I_3$	X_p
Phases 3-1	E_{31}	$I_1 - I_3$	X_p

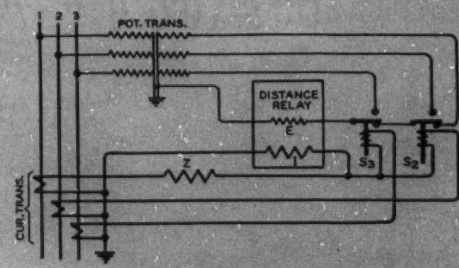


Fig. 3. One distance relay for phase-to-ground faults

S_2 and S_3. Selector relays
E and I. Potential and current
Z. Dummy impedance to balance current transformer burdens

responding delta voltages normally and during faults not involving ground. Upon the occurrence of a ground fault, the potential circuits of the distance relays are transferred to wye voltage by a selector relay in the residual circuit.

During faults between conductors the distance relay in phase 1 measures $\frac{E_{12}}{I_1}$ which is 2 X_s when only 2 conductors are involved. During ground faults $\frac{E_1}{I_1}$ is measured which on single-phase-to-ground faults is $X_s + \frac{X_s - X_s}{1+\frac{A+B}{C}}$. The impedances Z_1, Z_2, and Z_3 are provided for making the distance measurement as nearly as possible the same for phase faults and ground faults. Their value depends upon the value of A, B, and C for the particular line and can range from zero to the impedance of the potential circuit for one distance relay. These impedances would tend toward zero on lines with no ground wires. The distance measurement does not depend upon which phases are involved because the connections are symmetrical.

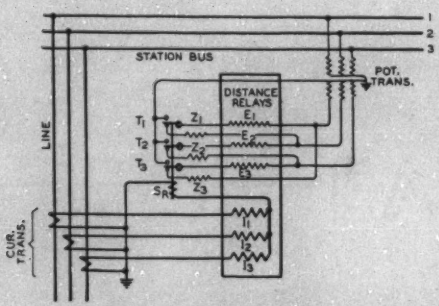


Fig. 4. Three distance relays for interphase ground faults

E_1, E_2, E_3. Potential circuits of distance relays
I_1, I_2, I_3. Current circuits of distance relays
S_R. Selector relay
T_1, T_2, T_3. Potential transfer contacts
Z_1, Z_2, Z_3. Equalizing impedances

Double Ground Faults

With wye current it is preferable to use delta voltage on double ground faults, because the current flowing between the conductors is generally much larger than the current flowing in the ground, and the delta voltage is therefore more nearly proportional to the distance to the fault than the wye voltage. This is still more worthy of consideration in reactance relays where the effect of phase angle is such as to reduce the distance measurement with wye voltage sometimes to zero on a double ground fault (see Fig. 6).

Accordingly in Fig. 5 the selector relay in the residual circuit is replaced by 3 selector relays in the phase circuits. The contacts of the selector relays are so arranged that the potential circuits of the distance relays are connected to wye voltage only upon the occurrence of a single-phase-to-ground fault, i. e., if one but not more than one of the selector relays operates. The distance relays remain connected to delta voltage during normal conditions, power swings, 3-phase faults, phase-to-phase faults, and double ground faults.

The potential transfer relay has about 0.04-sec. delay which is provided in case the 2 selector units do not operate simultaneously on a double ground fault, and permit the distance relay to be switched to wye voltage, which might cause low distance measurement, as just explained, since zero sequence

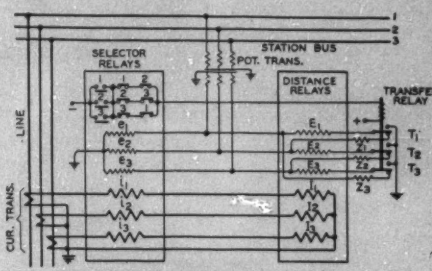


Fig. 5. Three distance relays for interphase and ground faults

E_1, E_2, E_3. Potential circuits for distance relays
I_1, I_2, I_3. Current windings of distance relays
T_1, T_2, T_3. Contacts of transfer relay
e_1, e_2, e_3. Potential windings of selector relays
i_1, i_2, i_3. Current windings of selector relays
1, 2, 3. Contacts of selector relays
Z_1, Z_2, Z_3. Equalizing impedances

compensation is not provided in the scheme.

It will be seen that the distance relays are allowed to operate immediately on all interphase faults. Upon the occurrence of a single-phase-to-ground fault the distance relay will not operate (unless the fault is close to the bus) until the potential has been switched from delta to wye. The tripping is held up in this case by the safety delay of 0.04 sec in the transfer relay; but this small delay in clearing single-phase-to-ground faults would not endanger stability and, therefore, would seldom be objectionable.

More accurate measurement of distance would be obtained if the distance relays were provided with wye voltage during 3-phase faults which would make it read the same distance as with delta voltage on phase-to-phase faults (if provided with equalizing impedances to halve the delta voltage on phase-to-phase faults). If the 3-phase fault were not balanced the relay in the most severely faulted phase would read substantially correctly, the other 2 higher.

Though employed later, this connection is not used in Fig. 5 because the latest type of distance relays would often operate before the transfer to wye voltage took place. The difference in distance measurement in the 2 types of faults would be 1 to

1.15 in the impedance relay and $\frac{1 \text{ to } 1.15 \sin \phi}{\sin (\phi + 30 \text{ deg})}$ in the reactance relay. The ratio is unity in the reactance relay on lines where ϕ is 60 deg and greater than unity for more-lagging lines. The ratio is less in both types of relays if the 3-phase fault is not exactly balanced.

The use of 3 impedance units as selector relays might give the impression that the total number of distance relays has not been reduced. These impedance units, however, are simply instantaneous overcurrent relays with voltage restraining coils to raise their pick-up at normal voltage while permitting them to operate on faults of less than normal current. They can be small and of the simplest construction since only an approximate impedance characteristic is required.

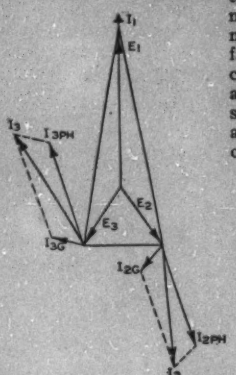


Fig. 6. Vector diagram showing that wye current and wye voltage will not allow a distance relay to measure correctly in a double-ground fault

E_1, E_2, E_3. Wye voltages
I_1, I_2, I_3. Wye currents
I_{ph}. Current flowing between conductors
I_g. Current flowing in ground

One Distance Relay for Complete Protection

The duties of the distance relays can be extended, of course, more and more, using auxiliary relays with suitably connected contacts, until the limit is reached when only one distance relay is used for protection against all phase and ground faults. Such an arrangement is shown in Fig. 7, which is based upon a circuit developed abroad.

The contacts *a*, *b*, *c*, and *d* of the selector relays are shown separately from their corresponding coils *A*, *B*, *C*, and *D* in order to simplify the diagram. Letters are used to indicate these relays, instead of the designation S_1, S_2, S_3 used elsewhere, because there are additional intermediate selector relays *F* and *G* and because a distinctive marking is necessary to locate quickly the coils and various contacts of each selector relay.

Table III—General Operation of Relay of Fig. 7

Fault	Selectors	Potential	Current
3-phase	D, B, C	$-KE_3$	$-\frac{1}{3}(I_2 - I_1)$
1-2	A, B	KE_3	I_3
2-3	B, C	KE_1	I_1
3-1	A, C	$-KE_2$	$-\frac{1}{3}(I_3 - I_1)$
1 to ground	A, D, F	E_1	I_1
2 to ground	B, D, F, G	E_2	I_2
3 to ground	C, D, F	$-E_3$	$-I_3$
1-2-ground	A, B, D	KE_{23}	I_1
2-3-ground	B, C, D, F	KE_{31}	I_2
3-1-ground	A, C, D, F	$-KE_{12}$	$-\frac{1}{3}(I_2 - I_1)$

The contacts *g* cut in the winding W_3 of the auxiliary current transformer only during single-phase faults between phase 2 and ground. The windings W_1 and W_2 are used for all other faults. Both windings are energized simultaneously only in the case of a fault between phases 1 and 3, but the impedance Z_4 bypasses enough current to keep the relay current the same as for a similar fault between one of the other pairs of phases. The compensating impedances in series with the potential transformer secondaries have to be adjusted to obtain the same distance measurement on phase-to-phase faults as on single-phase-to-ground faults.

The economy of making one distance relay do the work of 6 is acheived somewhat at the expense of performance. The distance relay must not be allowed to trip until all the selector relays have operated that should operate; and, in order to be sure of this, the selector relays must be more rapid than the distance relay over the range of current expected, or the distance relay must be suitably delayed. Furthermore, the continuity of the potential circuit depends upon the perfect operation of the several contacts in series with it.

The ohmic measurement varies somewhat for different types of faults, and for this reason could

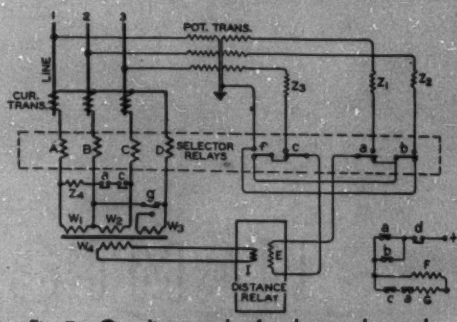


Fig. 7. One distance relay for phase-to-phase and phase-to-ground faults

A, B, C, D. Selector relay coils
a, b, c, d. Selector relay contacts
G, F and g, f. Auxiliary relay coils and contacts
W_1, W_2, W_3, W_4. Windings of auxiliary current transformer
Z_4. Impedance for halving current in W_1 and W_2
Z_1, Z_2, Z_3. Impedances for equalizing measurement of distance relay on phase and ground faults

not be applied to important lines. For instance, for faults involving phase 2 a certain amount of current may be supplied from phases 1 and 3 if some of the fault current returns along those conductors. The general operation is as shown in Table III.

The factor K is less than unity and is introduced by the equalizing impedances Z_1, Z_2, Z_3 in order to make the distance measurement on interphase faults as nearly as possible the same as that on single-phase-to-ground faults. With the former (with delta voltage) there is twice the impedance

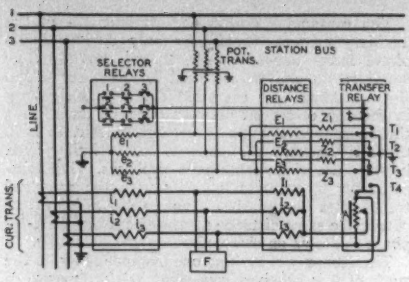


Fig. 8. Zero sequence current compensation with one current switch

E_1, E_2, E_3. Potential circuits for distance relays
I_1, I_2, I_3. Current windings of distance relays
T_1, T_2, T_3, T_4. Contacts of transfer relay
T_4 is a vacuum contact in the current circuit
F. Zero sequence current filter
e_1, e_2, e_3. Potential windings of selector relays
i_1, i_2, i_3. Current windings of selector relays
1, 2, 3. Contacts of selector relays
A. Tapped auto current transformer for adjusting ratio of residual to phase current
Z_1, Z_2, Z_3. Equalizing impedances

in series with the relay potential coils as with the latter (with wye voltage).

Accuracy

In the foregoing 3 schemes where the same distance relays operate on interphase faults (with delta voltage) and single-phase-to-ground faults (with wye voltage), the current provided should be a compromise between the currents most desirable for correct indication for interphase and for ground faults. Wye current was used in the schemes just described (Figs. 4, 5, and 7). This is satisfactory on the great majority of lines, but close settings cannot be obtained on lines where impedance of the ground circuit varies considerably with system connections (see Appendix *A*).

However, in the few cases where it is necessary to limit the instantaneous zone of the distance relays to only 50 per cent of the protected section on single-phase-to-ground faults, the protection secured will still be better than that afforded by inverse time-current or time-power relays supplied from the residual circuit.

On lines of primary importance if the system set-up is liable to be considerably varied to meet load conditions it is evident that the use of one distance relay for complete protection is not flexible enough for accurate distance measurement without making the circuit still more complicated. With 3 distance relays, however, the switching circuit is easier to handle because it is symmetrical. Each distance relay protects one phase in exactly the same manner as the 2 in the other 2 phases and any desired compensating feature can be added directly by means of contacts on the transfer relay which switches the 3 distance relays simultaneously and similarly.

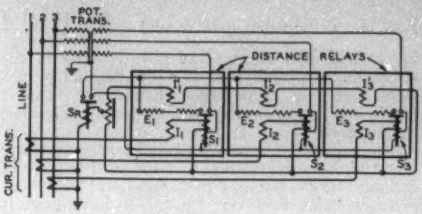


Fig. 9. Zero sequence current compensation without current switching

S_1, S_2, S_3. Phase selector relays
S_r. Residual selector relay
E_1, E_2, E_3. Potential circuits of distance relays
I_1, I_2, I_3. Phase current windings of distance relays
I_1', I_2', I_3'. Residual current windings of distance relays

Connections Required

Having tentatively decided on 3 distance relays for protection against all types of line faults, we shall see what can be done to make the distance measurement as nearly as possible the same in all cases. Table IV shows the connection desirable for the different types of faults (see appendix).

Table IV—Connections for Different Types of Faults

Type of Fault	Suitable Connections	Alternatives
3-phase	$\frac{E_{delta}}{I_{delta}}$	$\frac{E_{wye}}{I_{wye}}$
Phase-to-phase	$\frac{E_{delta}}{I_{delta}}$	$\frac{E_{delta}}{I_{wye}}$
Double ground	$\frac{E_{delta}}{I_{delta}}$	$\frac{E_{wye}}{I_{wye} + KI_{residual}}$
		$\frac{E_{delta}}{I_{wye} - \sqrt{3}I_{residual}}$
Single ground	$\frac{E_{wye}}{I_{wye} + KI_{residual}}$	

Since delta current is not desirable in single-phase-to-ground faults the use of it would involve switching in the current circuits. This presents more difficulty than in potential circuits because: (1) the amount of current, and therefore the contact duty, is more severe; (2) low resistance contacts must be maintained in order to avoid heating and imposing extra current burden; (3) the current transformers must never be open-circuited; and (4) the switching must be completed in a fraction of a cycle. Vacuum switches are now available for meeting these requirements but at present a group such as would be needed would be bulky and expensive and require appreciable force to operate. Consequently, we shall decide on wye current for interphase faults. The residual current required for ground faults can be controlled without transfer switches, as shown in Figs. 8 and 9. The potential connections are now fixed by the choice of wye current.

Complete Protection With Current Compensation

The connections of Fig. 8 are similar to those of Fig. 7 except that the circuit is modified in accordance with the table of connections (Table IV), required for greatest accuracy. Delta voltage is used for double ground faults in order to avoid the use of an extra selector relay in the residual circuit for distinguishing between double-ground and phase-to-phase faults. The current circuit is so arranged that while residual is added in the relay coils during single-phase-to-ground faults it is removed during double-ground faults leaving the relay with only the positive and negative sequence components of voltage and current.

The contacts in the potential and current circuits are operated together. The figure shows the contacts as they would be for normal conditions, power swings, 3-phase faults, and single-phase-to-ground faults; the distance relay potential circuits have the phase-to-neutral voltages and their current circuits have wye current plus the proper proportion of the residual current (in single-phase-to-ground faults).

Only upon the occurrence of a phase-to-phase or a double-ground fault is the transfer relay permitted by the selector relays to pick up. The distance relay potential circuits are then switched from wye to delta voltage and the zero sequence current is bypassed (in the case of double-ground faults) through the zero sequence filter which is of low impedance compared with the alternative path through the relays and the autotransformer.

As an alternative the current contacts on the transfer relay could have been eliminated by providing a selector relay in the residual circuit with its contacts in parallel with the group of contacts of the existing selector relays. In this way, during a double-ground fault the relay would receive E_{wye} and $I_{wye} + KI_{residual}$.

Instantaneous operation is obtained on 3-phase faults (where the risk of instability is a maximum) and single-phase-to-ground faults, while the small delay of the selector relay occurs only on 2-phase faults. This is preferable on some systems wehre prompt removal of a single-phase fault to ground may prevent the arc from spreading to a second phase.

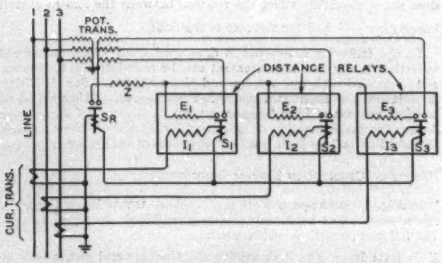


Fig. 10. Voltage compensation in 3 distance relays

S_1, S_2, S_3. Phase selector relays
S_r. Residual selector relay
E_1, E_2, E_3. Potential circuits of distance relays
I_1, I_2, I_3. Phase current windings of distance relays

Zero Sequence Compensation Without Current Switching

In Fig. 9, which is based upon a European circuit, the switching contacts are reduced to a minimum and the connections are simple. One distance relay is used per phase for all types of faults. Each distance relay contains a small instantaneous overcurrent or impedance selector unit which connects one end of the potential circuit to the corresponding phase of the secondary potential bus when that phase of the protected line becomes involved in a fault. The other ends of the potential circuits of the distance relays are connected together to form a star point. This point is connected to the neutral of the secondary potential bus if the fault is to ground.

The current circuits of the distance relays have double windings. One winding is supplied with current from the same phase as the potential and the other is connected to a tapped auxiliary current transformer in the neutral circuit of the line current transformers. By means of the taps the amount of residual current supplied to the distance relays can be adjusted according to the ratio of X_z to X_p as explained previously.

A fault between any 2 phases causes 2 of the distance relays to receive the current flowing in the affected phases and half the voltage between them, i. e., $\frac{1/2\, E_{delta}}{I_{wye}}$, which is X_p. In a 3-phase fault the distance relays receive wye current and the corresponding wye voltage, i. e., $\frac{E_{wye}}{I_{wye}}$, which is also X_p.

When one phase has a fault to earth the residual overcurrent relay picks up so that the corresponding distance relay receives the wye voltage of that phase. The 2 current coils of the relay are energized with the phase current and residual current respectively so that the ohmic indication is $\frac{E_{wye}}{I_{wye} + KI_{residual}}$ which is also X_p.

In a double ground fault the residual relay causes the 2 affected distance relays to have wye potential

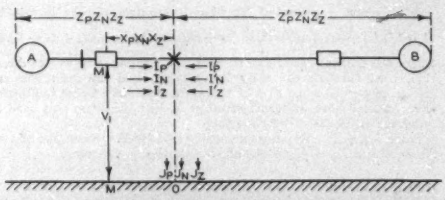


Fig. 11. Definitions of symbols used in analysis of relay instrument during ground fault

while their current circuits have phase plus residual current so that the distance measured is

$$\frac{E_{wye}}{I_{wye} + KI_{residual}}$$ which is again X_p.

This arrangement is the cheapest for complete line protection with accurate distance measurement. The distance relay operation is delayed by the small period taken by the selector relays to operate. This is the same for any type of fault.

In order that the distance relays may not operate normally when their potential circuits are deënergized, they must be controlled by a directional starting unit or else back contacts must be provided on the initiating relays to deënergize the operating current coils of the distance relays.

In very many cases the variations in system set-up do not affect the distance measurement on ground faults sufficiently to warrant zero sequence compensation. On the majority of lines it is sufficient to provide partial compensation by putting an impedance in series with the neutral of the distance relay potential circuits as shown in Fig. 10. This impedance can be a resistor in the case of relays having potential circuits which are of unity power factor or which can be made unity power factor by a parallel condenser. Its magnitude is such as to cause the relay to measure the same distance on single-phase-to-ground faults as with balanced 3-phase faults, i. e., to reduce the voltage on single-phase-to-ground faults in the same proportion as the current when the residual compensation is omitted.

Appendix A

Impedance of Line-to-Ground Faults

In a fault between phases the voltage between the faulty pair of conductors divided by the current flowing in them gives an impedance which is proportional to the distance from the fault because only the positive and negative phase sequence components are involved and they depend only upon the length of the line.

In a ground fault however this impedance is not always proportional to the distance from the fault on account of the fact that zero phase sequence component is included which is affected by changes in the location of the system grounding points, the mutual effect of the current returning in the ground and the other 2 conductors, which means that changes in generation and system connections will have an effect upon the value of $\frac{E}{I}$.

Compensation for the Effect of Mutual Inductance of Return Currents

With phase 1 grounded the phase-to-neutral voltage E_1 will be

$$E_1 = 1/3(I_1 + aI_2 + a^2I_3)X_p + (I_1 + a^2I_2 + aI_3)X_n + (I_1 + I_2 + I_3)X_z$$

where the currents are those flowing towards the fault in one direction, i. e., through the relay in question, and the reactances are measured on the same side of the fault, resistance being neglected. Z could have been written instead of X, but the latter was used in order to match with later equations.

Since $X_p = X_n$ for points along the line itself, we can put $X_p = X_n = X$ and $X_z = KX$ in the above equation. Therefore

$$E = \frac{1}{3}\left[(2I_1 + (a^2 + a)I_2 + (a + a^2)I_3)\right]X + (I_1 + I_2 + I_3)KX]$$

$$= \frac{X}{3}\left\{2I_1 - I_2 - I_3 + K(I_1 + I_2 + I_3)\right\}$$

$$= \frac{X}{3}\left\{3I_1 + (I_1 + I_2 + I_3)(K - 1)\right\}$$

$$= X\left\{I_1 + I_r \times \frac{K - 1}{3}\right\}$$

A distance relay for ground fault protection using wye voltage and the wye current in the same phase can therefore be set to operate on X_p (which is a direct measure of the length of line involved) if a component of the residual current be added to the line current in the current coils, in order to give correct operation under all ground fault conditions.

The relay in phase 1, in order to give a true indication of the proximity of the fault, must therefore measure $X = \dfrac{E_1}{I_1 + \dfrac{(K - 1)I_r}{3}}$

where I_r is the residual current of the 3 current transformers and where $K = \dfrac{X_z}{X_p}$.

Setting the Value of K

The amount of residual current which should be added to the phase current to compensate for the variations just discussed depends upon the ratio of the zero phase sequence reactance to the positive phase sequence reactance of the protected line, i. e., $K' = \dfrac{K - 1}{3}$.

Table V shows approximately how K' would vary with copper and steel ground wires and with no ground wires.

Table V—Values of K′

No. of Ground Wires	Kind of Wire	I_z in Ground Wire	I_z in Ground	$K = \frac{X_z}{X_p}$	$K' = \frac{K-1}{3}$
0		0%	100%	3.5	−4	0.83 to 1.0
1	Steel	5%	95%	3.5	−4	0.83 to 1.0
1	Copper	40–50%	60–50%	2.75–3	0.57 to 0.67
2	Copper	50–70%	50–30%	2	0.33
Perfect return path		100%		1	0

It is not always necessary to compensate for variations due to system set-ups. For instance it will be seen from the above tests that in some lines only $^1/_3$ of the residual current need be added to the phase current for full compensation. This does not mean that the variations in distance measurements will be 33 per cent without compensation because some of the departure from X_p is fixed and can be taken up by changing the distance setting on ground faults, which is easy if the relay setting is made by adjusting the potential circuit.

On some lines the location of grounding points is never changed and the layout of the system is such that the location of the fault does not appreciably affect the relation between the line-to-ground impedance $\frac{E_{wye}}{I_{phase}}$ and the distance to the fault.

In the following a formula is developed from which the actual variation in distance measurement can be calculated in a distance relay supplied with wye voltage and phase current. For simplicity impedances are considered instead of reactances. This method of analysis was taken from "Report on the Application of Impedance Relays for the Protection of Overhead Transmission Lines Against Ground Faults," by J. Fallou (see references at end of paper).

Effect of Changes in System Connections

In Fig. 11 is shown a section of 3-phase transmission line with power supplied at both ends and a ground fault on phase 1 at O. The following notations will be used:

Z = impedance O to A (including transformers and generators)
Z' = impedance O to B (including transformers and generators)
X = impedance O to M (The symbol X is used instead of Z to avoid confusion with the other Z terms)
$\underline{Z}$ = total impedance from fault to ends of line including both sets of transformers and generators, so that $\frac{1}{\underline{Z}} = \frac{1}{Z} + \frac{1}{Z}$

Similarly the total current in fault $J = I + I'$ flowing from A and B, respectively, in the lines shown in Fig. 11.

Also in phase 1 the total short-circuit current at O is

$$J_1 = J_p + J_n + J_z$$

also

$$J_p = J_n = J_z = \frac{E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_z}$$

where E is the Y voltage.

Since $\frac{1}{\underline{Z}_p} = \frac{1}{\underline{Z}_p} + \frac{1}{\underline{Z}_p}$, and the same for the other components

$$I = \frac{\underline{Z}_p}{\underline{Z}_p} Jp, \quad I_n = \frac{\underline{Z}_n}{\underline{Z}_n} \times J_n, \quad \text{and } I_z = \frac{\underline{Z}_z}{\underline{Z}_z} \times J_z, \text{ therefore}$$

$$I_1 = I_p + I_n + I_z = \frac{E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_z} \left\{ \frac{\underline{Z}_p}{\underline{Z}_p} + \frac{\underline{Z}_n}{\underline{Z}_n} + \frac{\underline{Z}_z}{\underline{Z}_z} \right\}$$

The star voltage V_1 at the relay M has components X_pI_p, X_nI_n, X_zI_z and its value is therefore

$$E_1 = \frac{E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_z} \left\{ X_p \frac{\underline{Z}_p}{\underline{Z}_p} + X_n \frac{\underline{Z}_n}{\underline{Z}_n} + X_z \frac{\underline{Z}_z}{\underline{Z}_z} \right\}$$

since voltage drops are produced only by components of current reacting with like components of impedance.

Then dividing by the expression for I_1 we have

$$\frac{E_1}{I_1} = \frac{X_p \cdot \frac{\underline{Z}_p}{\underline{Z}_p} + X_n \times \frac{\underline{Z}_n}{\underline{Z}_n} + X_z \cdot \frac{\underline{Z}_z}{\underline{Z}_z}}{\frac{\underline{Z}_p}{\underline{Z}_n} + \frac{\underline{Z}_n}{\underline{Z}_p} + \frac{\underline{Z}_z}{\underline{Z}_z}}$$

Let us make $\frac{\underline{Z}_p}{\underline{Z}_p} = A$; $\frac{\underline{Z}_n}{\underline{Z}_n} = B$; and $\frac{\underline{Z}_z}{\underline{Z}_z} = C$

Therefore

$$\frac{E_1}{I_1} = \frac{X_pA + X_nB + X_zC}{A + B + C}$$

$$= \frac{X_p(A + B) + X_zC}{A + B + C}, \text{ because } X_p = X_n \text{ for a transmission line}$$

$$= \frac{X_p(A + B + C) + (X_z - X_p)C}{A + B + C}$$

$$= X_p + \frac{X_z - X_p}{\frac{A + B + C}{C}}$$

$$= X_p + \frac{X_z - X_p}{1 + \frac{A + B}{C}}$$

$$= X_p + \frac{X_z - X_p}{\frac{1 + \frac{\underline{Z}_p}{\underline{Z}_p} + \frac{\underline{Z}_n}{\underline{Z}_n}}{\frac{\underline{Z}_z}{\underline{Z}_z}}}$$

In his previously mentioned article, Jean Fallou also works out an expression for the distance measurement of an uncompensated distance relay during double-ground faults. The expression is somewhat complicated and the reader is referred to the article for the analysis.

Variations in distance measurement during double-ground faults can be avoided by zero sequence compensation or by connecting the relay so as to consider a double-ground fault the same as a phase-to-phase fault, i. e., by eliminating the zero sequence components from both the potential and current circuits, either by using delta voltage and delta current or by using delta voltage and eliminating the zero sequence components from the wye current by means of a filter or a 4-winding transformer.

Distance Measurement With Zero Sequence Compensation

It can be shown quickly that by adding the proper amount of residual current the distance measurement depends only on the positive sequence reactance between the relay and the fault.

$$I_{ph} = I_p + I_n + I_z = \frac{E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_z}(A + B + C)$$

$$I_r = 3I_z = \frac{3E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_z} \cdot C$$

$$E_{ph} = \frac{E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_z}(AX_p + BX_n + CX_z)$$

Combining the above identities, we have

$$\frac{E_{ph}}{I_{ph} + \frac{K - 1}{3} \cdot I_r} = \frac{X_pA + X_nB + X_zC}{A + B + C + (K - 1)C}$$

$$= \frac{X_p(A + B) + X_zC}{A + B + KC} \text{ (assuming } X_p = X_n \text{ for a transmission line)}$$

$$= \frac{X_p(A + B + KC) + (X_z - KX_p)C}{A + B + KC}$$

$$= X_p + \frac{X_z - KX_p}{A + B + KC}$$

Since $K = \frac{X_z}{X_p}$ the second fraction will always be zero and the relay indication $\frac{E_{ph}}{I_{ph} - \frac{K - 1}{3} I_r} = X_p$ which is proportional to distance and not affected by variations in A, B, and C.

Appendix B

In Fig. 3 wye voltage was used with residual current. On single-phase-to-ground faults the distance measurement with this combination would be as follows:

$$E_{wye} = \frac{E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_z} \cdot \{AX_p + BX_n + CX_z\}$$

$$I_r = \frac{3E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_z} \cdot C$$

Therefore

$$\frac{E_{wye}}{I_{residual}} = \frac{AX_p + BX_n + CX_z}{3C}$$

$$= {}^1/_3 \left\{ X_z + \frac{A + B}{C} \cdot X_p \right\}$$

References

Patents

United States Letters Patent No. 1,573,622. J. Biermanns
United States Letters Patent No. 1,573,623. J. Biermanns
United States Letters Patent No. 1,573,624. J. Biermanns

Articles

Sur l'Emploi des Relais d'Impédance pour la Protection des Lignes Aériennes Contre les Misses à la Terre, Jean Fallou. *Bulletin de la Soc. Française des Electriciens*, Series 4, v. 10, No. 101, Jan. 1930, p. 82–94.

Fundamental Basis for Distance Relaying on Three-Phase Systems, W. A. Lewis and L. S. Tippet. Elec. Engg., June 1931, p. 420–2.

Die Distanzschutz-Schaltungen, Von M. Walter. *Elektrizitätswirtschaft*, April 30, 1932, p. 172–6, and May 15, 1932, p. 199–202.

A New High-Speed Reactance Relay, A. R. van C. Warrington. Elec. Engg., April 1933, p. 248–52.

Auditory Perspective —Transmission Lines

This paper continued from p. 32. The sixth and final paper in this symposium entitled "Auditory Perspective—System Adaptation" follows the remainder of this paper, beginning on p. 216.

stantially flat within a fraction of a decibel from 40 cps to 15,000 cps. The lower curves indicate successively what happens if the phase angle of the receiving carrier is adjusted different amounts from the optimum adjustment. It may be noted that for a 90-deg departure the transmission of a 40-cycle tone over the carrier channel would suffer more than 12 db in comparison with a 1,000-cycle tone.

Repeaters

As noted previously, the line circuit between Philadelphia and Washington included 5 intermediate repeater points. A schematic drawing of

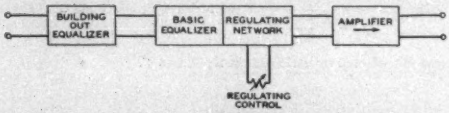


Fig. 8. Schematic diagram of repeater station apparatus

the apparatus installed at each point is shown in Fig. 8. The amplifiers at these points, as well as those used at the transmitting and receiving terminal, consisted of a new form of amplifier employing the principle of negative feed-back. The principal virtues of amplifiers of tihs type are their remarkable stability with battery and tube variations and great freedom from nonlinearity or modulation effects. Each amplifier is supplemented at its input by an equalizer designed to have its attenuation approximately complementary in loss to that of the line circuit in a single section. The amplifiers actually employed for the purpose were taken from a trial of a cable carrier system described in a recent A.I.E.E. paper by A. B. Clark and B. W. Kendall.[4]

The losses in the cable circuits do not, of course, remain absolutely constant with time, and slow variations due to change of temperature are compensated for by occasional adjustments of the variable equalizer arrangements provided. These adjustments were required only infrequently; approximately at weekly intervals because in an underground cable the temperature experiences only slow, seasonal variations.

As noted, new repeater stations were established at 2 points. The housing arrangements for one of these points, Abingdon, is shown in Fig. 9. The equipment at this repeater point also included relays remotely controlled from the nearest attended repeater station to permit the repeaters to be turned on and off at will and the power supply, which consisted of storage batteries, to be switched from the regular to the reserve battery or either battery put on charge if required.

Over-All Performance

While the system was set up specifically to provide transmission for the demonstration into Washington on April 27, 1933, it was operated over a period of several weeks and complete tests and measurements were carried out for the purpose of gathering information on cable carrier systems. The complete layout of apparatus and lines provided between Philadelphia and Washington is shown in Fig. 10.

The over-all frequency transmission characteristics of the 3 channels that were set up are shown in Fig. 11. These curves differ from those shown in Fig. 7, and include the complete high frequency line circuit with its 150 miles of cable, repeaters, equalizers, and other equipment. It may be seen that between the desired frequency limits the circuit is substantially flat in transmission performance to within ± 1 db. Various noise measurements made on the over-all circuit indicated that the circuits fully met the requirements that had been set up, and that the line and apparatus noise was inaudible in the auditorium at Washington even during the weakest music passages. The circuit also was found to be free from nonlinear distortion to a satisfactory degree. Harmonic components generated when single-frequency tones were applied to the channels at high volumes were found with one unimportant exception to be more than 40 db below the fundamental.

As a means of obtaining a further increase in volume range, which was not actually required for this demonstration, tests were made with a so-called predistortion-restoring technique. In this the higher frequency components of the music were transmitted over the carrier channels at a volume much higher than normal in relation to the volume of the lower frequencies. By this means any noise entering the carrier channels at frequencies equivalent to the higher music frequencies is greatly minimized in effect.

Fig. 9. Interior and exterior of special intermediate repeater station at Abingdon, Md.

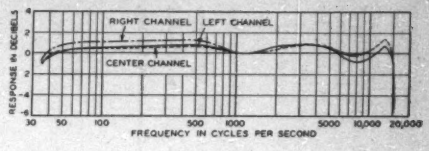


Fig. 11 (right). Frequency characteristics over carrier channels used between Philadelphia and Washington, D. C.

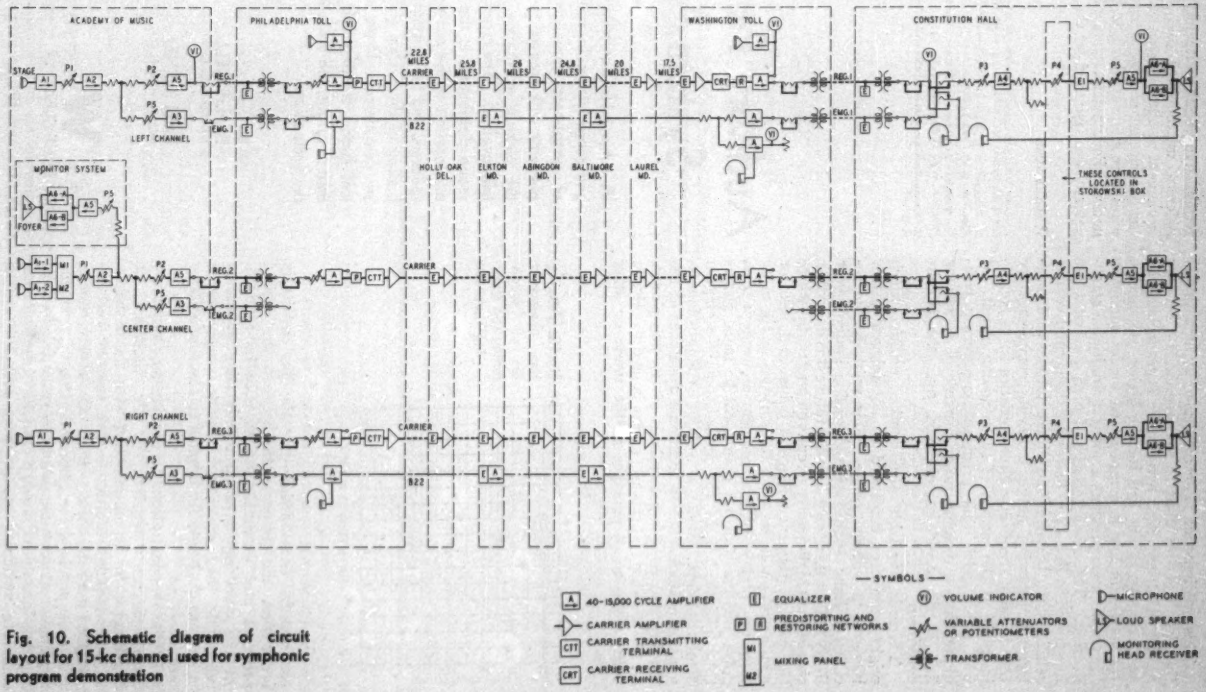


Fig. 10. Schematic diagram of circuit layout for 15-kc channel used for symphonic program demonstration

This predistortion is accomplished by including in the circuit at the input to the modulator a network having relatively high loss for the lower frequencies and tapering to low loss for the higher frequencies. Its maximum loss is compensated for by adding in the circuit an equivalent amount of additional amplification. The characteristics of such a network are illustrated in Fig. 12. To restore the normal volume relationships between the different tones and overtones a restoring network having complementary transmission frequency characteristics is, of course, included at the output of the receiving circuit. It was found with this predistortion-restoring technique that a volume range increase of something like 10 db could be obtained over the circuits described.

There is available also another method which might have been employed for obtaining a further increase in volume range. This method, the so-called volume compression-expansion system, very likely will be necessary if in the future it is desired to obtain such high quality circuits on long routes where the carrier frequency range is being used also for regular telephone message transmission or for other purposes, and where the problem of freedom from noise and crosstalk no doubt will be more serious than experienced in the Philadelphia-Washington demonstration. Such a volume compression-expansion system requires additional apparatus at the sending and receiving terminals of the line circuit. At the sending end this apparatus is used to raise in volume the weak passages of the music or other

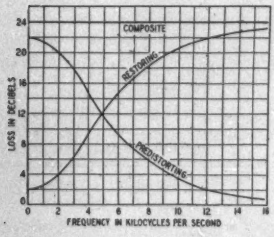


Fig. 12. Attenuation characteristics of "predistorting and restoring" networks

program for transmission over the line circuits in order that the proper ratio between the desired program and unwanted noises may be retained. At the receiving terminal coördinating apparatus reëxpands the compressed volume range to the volume range originally applied to the transmitting terminal.

In the demonstration, to provide supplementary control features required by Dr. Stokowski at Washington for communicating with the orchestra at Philadelphia, additional wire circuits were established between these points. Order wire circuits also were provided for communication between the terminals and repeater points to make possible the location troubles if any should arise. Rather elaborate switching means were included at the terminals to permit switching the carrier channels to different microphones and to different amplifier equipment at the loud speaker end. To take care of the contingency of a cable pair failure, spare pairs of wires were made available to be switched in at short notice. Fortunately, none of the reserve facilities actually were required for the demonstration.

References

1. Long Distance Cable Circuits for Program Transmission, A. B. Clark and C. W. Green. A.I.E.E. Trans., v. 49, 1930, p. 1514–23.

2. Thermal Agitation of Electricity in Conductors, J. B. Johnson. *Phys. Rev.*, v. 32, 1928, p. 97.

3. Thermal Agitation of Electric Charge in Conductors, H. Nyquist. *Phys. Rev.*, v. 32, 1928, p. 110.

4. Carrier in Cable, A. B. Clark and B. W. Kendall. Elec. Engg., July 1933, p. 477–81.

Auditory Perspective —System Adaptation

A communication system for the pick-up and reproduction in auditory perspective of symphonic music must be designed properly with respect to the acoustics of the pick-up auditorium and the concert hall involved. The reverberation times and sound distribution in the two auditoriums, the location of the microphones and loud speakers, and the response-frequency calibration of the system and its equalization are considered. These and other important factors entering into the problem are treated in this, the sixth and final paper of the symposium.

By

E. H. BEDELL
MEMBER ACOUS. SOC. OF AMERICA
Bell Tel. Labs., Inc., New York, N. Y.

IDEN KERNEY
MEMBER ACOUS. SOC. OF AMERICA
Am. Tel. and Tel. Co. New York, N. Y.

WHEN THE EFFECT of music or the intelligibility of speech is spoiled by bad acoustics in an auditorium, the audience is well aware that acoustics do play a most important part

in the appreciation of the program. One may not be conscious of this fact when the acoustical conditions are good, but a simple illustration will show that the effect still is present. Thus, of the sound energy reaching a member of the audience as much as 90 per cent may have been reflected one or more times from the various surfaces of the room, and only 10 per cent received directly from the source of the sound.

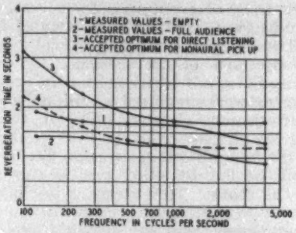


Fig. 1. Reverberation characteristics of Academy of Music, Philadelphia, Pa.

In listening to reproduced sound in an auditorium or concert hall, the effect of the room acoustics is perhaps even more important, for in this case the audience does not see any one on the stage and must rely entirely upon the auditory effect to create the illusion of the presence there of an individual or a group. Imperfections in the reproduced sound that are caused by defects in the acoustics of the auditorium may destroy the illusion and be ascribed improperly to the reproducing system itself.

In some types of reproduced sound, radio broadcast for example, where the reproduction normally takes place in a small room, the attempt is made to create the illusion that the listener is present at the source.[1,2] In the case considered here, however, where symphonic music is reproduced in a large auditorium, the ideal is to create the illusion that the orchestra is present in the auditorium with the audience. Since the orchestra is playing in one large room and the music is heard in another, the acoustical conditions prevailing in both must be considered.

Pick-Up Conditions

The source room is the auditorium of the American Academy of Music in Philadelphia. This room has a volume of approximately 700,000 cu ft, and a seating capacity of 3,000. Measured reverberation time curves for this auditorium, and preferred values[3,4] for a room of this volume, are given in Fig. 1. It may be seen that with a full audience this room might be considered somewhat dead, but would be considered generally satisfactory for pick-up either with or without an audience. A floor plan of the Academy auditorium and stage, showing the location of the 3 microphones used, is given in Fig. 2. The microphone positions were selected after judgment tests using several locations and are much nearer the orchestra than they would be for single channel pick-up.[2] The use of the microphones near the orchestra results in picking up a high ratio of direct to reverberant sound and thus reduces the effect of reverberation in the source room upon the reproduced music. A high ratio of direct sound is desirable in the present case also because of the use of 3 channels. The perspective effect obtained with 3 channels depends to a considerable extent upon the relative loudness at the 3 microphones, and since the change in loudness with increasing distance from the source is marked for the direct sound only, and not for the reverberant, there would be a definite loss in perspective effect if the microphones were placed at a greater distance from the orchestra. This effect is discussed more fully in another paper of this symposium.

With the microphones located close to the orchestra their response-frequency characteristics will be essentially those given by the normal field calibration, since relatively little energy is received from the sides and back. For a distant microphone position it would be necessary to use the random incidence

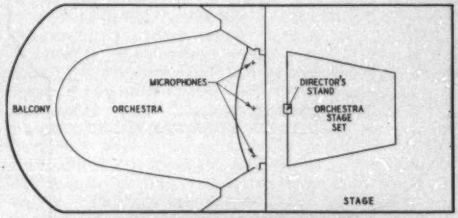


Fig. 2. Floor plan of Academy of Music, showing location of microphones

response characteristic, which differs from the normal because of the variation in directional selectivity of the microphones as the frequency varies. This difference in response characteristic depends upon the size of the microphone and may amount to as much as 10 db at 10,000 cps. It may be pointed out here that this difference in response is one factor frequently overlooked in the placement of microphones.

In addition to the 3 microphones regularly used, a fourth was provided to pick up the voice when a soloist accompanied the orchestra. In this case only the 2 side channels were used for the orchestra, the voice being transmitted and reproduced over the center channel. The solo microphone was so shielded by a directional baffle that it responded mainly to energy received from a rather small, solid angle. This arrangement permitted independent volume and quality control for the vocal and orchestral music.

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 31, 1933; released for publication Dec. 4, 1933. *Not published in pamphlet form.*

The Concert Hall

The music was reproduced before the audience in Constitution Hall in Washington, D. C. This hall has a volume of nearly 1,000,000 cu ft, and a seating capacity of about 4,000. A floor plan of the auditorium showing the location of the loud speakers and of the control equipment is given in Fig. 3. The loud speakers are placed so that each of the 3 sets radiates into a solid angle including as nearly as possible all the seats of the auditorium. Figure 4 shows the reverberation-frequency characteristics of Constitution Hall. The values given by the curve for the empty hall were measured through the use of the 3 regular loud speakers and several microphone positions in the room. The values for the hall with

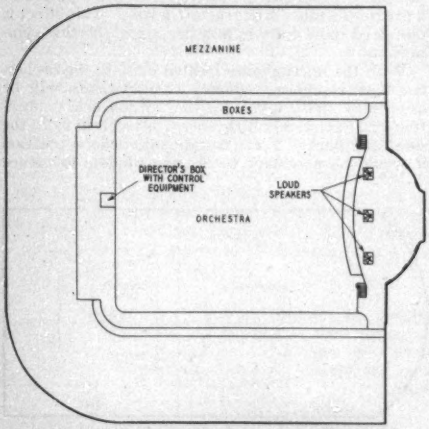


Fig. 3. Floor plan of Constitution Hall, Washington, D. C., showing locations of loud speakers

an audience present were calculated from known absorption data for an audience, and the optimum values are taken from accepted data for an auditorium of the volume of this one.[2] The reverberation times were considered satisfactory and no attempt was made to change them for this demonstration. The reverberation time measurements for both Constitution Hall and the Academy of Music were made with the high speed level recorder.[5] This instrument measures and plots on a moving paper chart a curve the ordinate of which is proportional to the logarithm of the electrical input furnished to it. When used in connection with a microphone for reverberation time measurements, curves are obtained showing the intensity of sound at the microphone during the period of sound decay. The rates of decay, and hence the reverberation times, are obtainable immediately from the slopes of these recorded curves and the speed of the paper chart.

Calibration of the System

In calibrating the system, a heterodyne oscillator connected to the loud speakers through the amplifiers was used. The oscillator was equipped with a motor drive to change the frequency, and as the frequency was varied through the range from 35 to 15,000 cps the sound was picked up with a microphone connected to the level recorder. Continuous curves of microphone response as a function of frequency thus were obtained for several positions in the auditorium, and for each channel independently. These response curves provided a check on a uniform coverage of the audience by each loud speaker, and also provided data for the design of the equalizing networks required to give an over-all flat response-frequency characteristic. If the system, including the air path from the loud speakers to one position in the auditorium, is made flat, it will not, in general, be flat for other positions or for other paths in the room. This variation in characteristic is due partly to the variation in the ratio of direct to reverberant sound, and partly to the fact that the sounds of higher frequency are absorbed more rapidly by the air during transmission.[6,7] This latter effect is of considerable importance; it depends upon the humidity and temperature of the air, and may cause a loss of more than 10 db in the high frequencies at the more distant positions in a large auditorium. Some compromise in the amount of equalization employed therefore is necessary. Probably the most straightforward procedure would be to design the networks according to the response curves obtained with the microphones near the loud speakers. This would insure that for both the response measurements and the pick-up the microphone characteristics would be the same, and any deviation from a uniform response in the microphones would be corrected for in this way, along with variations in the loud speaker output. This procedure was modified somewhat for the case under discussion,

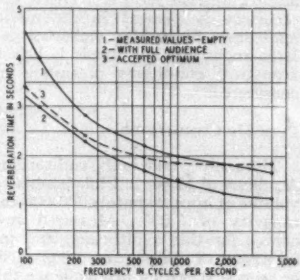


Fig. 4. Reverberation characteristics of Constitution Hall

however, because by far the greater portion of the audience was at a distance from the stage such that they received a relatively large ratio of reverberant sound, and it was believed that a better effect would

be achieved by equalizing the system characteristic in accordance with response measurements taken at some distance from the loud speakers.

Control Equipment

In addition to the equalizing circuits used to obtain a uniform response characteristic, 2 sets of quality control networks which could be switched in or out of the 3 channels simultaneously were employed. One set modified the low frequencies as shown at *A*, *B*, and *C* of Fig. 5, while the other gave high frequency characteristics as shown at *D*, *E*, *F*, and *G*. These latter networks permitted the director to take advantage of the fact that the electrical transmission and reproduction of music permits the introduction of control of volume and quality which can be superimposed on the orchestral variations. Quality of sound can be divorced from loudness to a greater degree than is possible in the actual playing of instruments, and the quality can be varied while the loudness range is increased or decreased. Electrical transmission therefore not only enlarges the audience of the orchestra, but also enlarges the *capacity* of the orchestra for creating musical effects.

The quality control networks and their associated switches were mounted in a cabinet (Fig. 6) at the right side of the director's position. Continuously variable volume controls for the 3 channels were mounted on a common shaft and housed in the center cabinet of Fig. 6. A separate control for the center channel was provided when that was used for

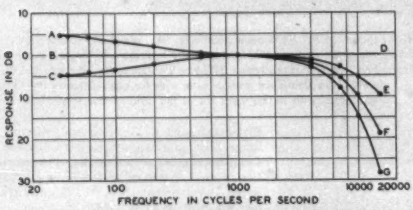


Fig. 5. Transmission characteristics of quality control networks used in the Philadelphia-Washington experiment

the soloist. In addition to the high quality channels certain auxiliary circuits were supplied to aid the smoothness of performance. Supplementing the order wire connecting all technical operators, a monitor circuit was provided in the reverse direction. The microphone was located on the cabinet before the director, and loud speakers were connected in the control rooms and on the stage with the orchestra, enabling the control operator to hear what went on in the auditorium and allowing the director to speak to the orchestra. Two useful signal circuits were employed; one giving the orchestra a "play" or "listen" signal, and at the same time connecting either the auditorium or the orchestra's loud speakers, respectively; the other being a "tempo" signal to the assistant director leading the orchestra that could be operated during the rendition of the music. The switches for the auxiliary circuits and the order wire subset are shown at the control operator's position at the left in Fig. 6.

That a reproducing system may have quite different characteristics in different auditoriums is well illustrated in the case of the 2 halls considered here. From Fig. 3 it may be seen that in Constitution Hall the stage is built into the auditorium itself, and that

Fig. 6. Cabinets housing quality control networks and providing communication facilities for operation

there is no back stage space. The Academy of Music, however, has a large volume back stage. When the orchestra plays in the Academy the reflecting shell shown in Fig. 2 is used to concentrate the radiated sound energy toward the audience. When the reproducing system was set up in the Academy the shell could not be used because of the stage and lighting effects desired, and a large part of the energy radiated by the loud speakers at the low frequencies was lost back stage. The loss of low frequency energy is attributable partly to the fact that the loud speakers cannot well be made as directional for the very low frequencies as for the higher. The loss amounts to about 10 db at 35 cps, and becomes inappreciable at 300 cps or more, as measured in comparable locations in the 2 auditoriums. This difference in characteristics emphasizes the fact that for perfect reproduction the acoustics of the auditorium must be considered as a part of the system, and that in general the equalizing networks must have different characteristics for different auditoriums.

References

1. Acoustics of Broadcasting and Recording Studios, G. T. Stanton and F. C. Schmid. *Jl.* Acous. Soc. Am., v. 4, No. 1, part 1, July 1932, p. 44.

2. Acoustic Pick-Up for Philadelphia Orchestra Broadcasts, J. P. Maxfield. *Jl.* Acous. Soc. Am., v. 4, No. 2, Oct. 1932, p. 122.

3. Optimum Reverberation Time for Auditoriums, W. C. MacNair. *Jl.* Acous. Soc. Am., v. 1, No. 2, part 1, Jan. 1930, p. 242.

4. Acoustic Control of Recording for Talking Motion Pictures, J. P. Maxfield. *Jl.* S.M.P.E., v. 14, No. 1, Jan. 1930, p. 85.

5. A High Speed Level Recorder for Acoustic Measurements, E. C. Wente, E. H. Bedell, K. D. Swartzel, Jr. Unpublished paper presented before the Acous. Soc. Am., May 1, 1933.

6. The Effect of Humidity Upon the Absorption of Sound in a Room, and a Determination of the Coefficients of Absorption of Sound in Air, V. O. Knudson. *Jl.* Acous. Soc. Am., v. 3, No. 1, July 1931, p. 126.

7. Absorption of Sound in Air, in Oxygen, and in Nitrogen—Effects of Humidity and Temperature, V. O. Knudson. *Jl.* Acous. Soc. Am., v. 5, No. 2, Oct. 1933, p. 112.

News
Of Institute and Related Activities

Winter Convention Program Provides Attractive Technical and Social Activities

A SCHEDULE of events which has been coördinated to provide a good balance between both business and social activities has been arranged for the winter convention of the A.I.E.E. to be held during the 4 days of January 23–26, 1934, in the Engineering Societies Building, 33 West 39th Street, New York, N. Y. Eleven technical sessions to be held during the mornings and afternoons of the first 3 days will present some of the most recent developments in electrical engineering. In the evenings a smoker, the Edison Medal presentation, a demonstration of transmission and reproduction of music, and the dinner-dance will be held. Special entertainment also is being arranged by the ladies entertainment committee, and will include a luncheon-bridge. Friday, the last day of the convention, will be devoted entirely to inspection trips; in addition, arrangements have been made to visit points of interest at other times. Altogether, the convention, which begins on Tuesday and ends on Friday, will be crowded with activity. In addition to this program, there will be a meeting of the board of directors at Institute headquarters on Monday, January 22, at 2:15 p.m., the day preceding the opening of the convention.

The New Brunswick, N. J., station of R.C.A. Communications, Inc., which is included on an inspection trip to be held Friday, January 26, 1934, during the Institute's forthcoming annual winter convention. Shown here are 2 Alexanderson 200-kw 27,000-cycle alternators. Behind the units, at the left, are the radio frequency transformers, with the compensating rheostats at the rear. Water pumps, not shown in this view are at the right of the alternators

Schedule of Events

A summarized schedule of events follows. Capital letters A, B, etc., denote technical sessions.

Tuesday, January 23

9:00 a.m.	Registration
10:00 a.m.	Opening of convention
10:30 a.m.	A—Protective devices B—Transportation
2:00 p.m.	C—Symposium on electric power switching
6:00 p.m.	Smoker

Wednesday, January 24

10:00 a.m.	D—Power transmission E—Education Meeting of committee on education and committee on Student Branches
1:00 p.m.	Ladies luncheon and bridge
2:00 p.m.	F—Communication; symposium on transmission and reproduction of speech and music in auditory perspective G—Symposium on electric furnaces
8:15 p.m.	Edison Medal presentation Transmission and reproduction of speech and music in auditory perspective

Thursday, January 25

10:00 a.m.	H—Power distribution I—Electrical machinery
2:00 p.m.	J—Electrical machinery K—Electrical measurements
7:00 p.m.	Dinner-dance
9:00 p.m.	Dance and buffet supper

Friday, January 26

All day	Inspection trips

Technical Sessions

The tentative technical program as announced in Electrical Engineering for December 1933, p. 928–30 is complete except for the following additional session and papers:

On Wednesday, January 24, at 10:00 a.m., a session on education will be held combined with a joint meeting of the committee on education and the committee on student branches. At this session it is expected to have Dean Doherty say a few words regarding the special series of articles on post college education now scheduled for month-by-month publication in Electrical Engineering. A brief abstract of the present activities of the committee on education and the committee on Student Branches will be presented by L. A. Doggett, chairman of both committees. Then a paper will be presented on "The University of Pittsburgh-Westinghouse Graduate Program" by H. E. Dyche, University of Pittsburgh, and R. E. Hellmund, Westinghouse Elec. and Manufacturing Company. Dean Barker will review to date the activities of the Engineers' Council for Professional Development (E. C. P. D.) and the meeting will conclude with discussion of the Dyche-Hellmund paper, other items referred to above, and any new business.

The symposium on electrical power switching to be held on Tuesday, 2:00 p.m., will be opened with an introduction prepared by A. H. Lovell, University of Michigan.

At the communication session to be held on Wednesday, 2:00 p. m., the symposium on long distance transmission and reproduction in auditory perspective of symphonic music will be preceded by the presentation of a paper entitled "Stabilized Feedback Amplifiers" by H. S. Black, Bell Telephone Laboratories, Inc. The following paper has been added to the above-mentioned symposium: "Loud Speakers and Microphones" by E. C. Wente and A. L. Thuras, Bell Telephone Laboratories, Inc.

The symposium on electric furnaces will also include an additional paper entitled "Iron and Its Production in the Cupola

and the Electric Furnace" by M. V. Healey, General Electric Co.

As all of the papers for the winter convention program will have been published in advance of the convention, it is expected that exceptionally valuable discussions will take place at the meetings. Winter convention papers published in this issue and the 2 issues immediately preceding it have been designated by a star before the title in the table of contents. The only paper not published in these issues is the one entitled "Power Limit of a Transmission System" by W. S. Peterson which appeared in ELECTRICAL ENGINEERING for August 1933, p. 569–72.

EDISON MEDAL PRESENTATION

The Edison Medal will be presented to Dr. Arthur E. Kennelly in the engineering auditorium on the evening of Wednesday, January 24, at 8:15 p.m. The medal has been awarded to Dr. Kennelly "for meritorious achievements in electrical science, electrical engineering, and the electrical arts as exemplified by his contributions to the theory of electrical transmission and to the development of international electrical standards." Further details of this award are included in a "personal" item on p. 232 of this issue. In view of the limited seating capacity, admission this year will be by ticket only.

TRANSMISSION AND REPRODUCTION OF SPEECH AND MUSIC IN AUDITORY PERSPECTIVE

The following statements prepared by Bell Telephone Laboratories, Inc., give the highlights of the convention's most striking demonstration:

"The technical features of this accomplishment in telephonic communication are to be presented in a symposium of papers by Bell System engineers at the midwinter convention of the American Institute of Electrical Engineers on the afternoon of January 24, 1934. On the evening of that day, as part of the convention program, there will be a demonstration of this new communication system in the auditorium of the Engineering Societies Building, 29 West 39th Street, New York. This demonstration, in charge of Dr. Harvey Fletcher, physical research director, Bell Telephone Laboratories, will illustrate the character and range of the effects that can be produced with this system.

"During the course of this demonstration Dr. Fletcher will describe the essential apparatus of the system and demonstrate its applicability to reproducing, with complete illusion of reality, a variety of sounds including speech and orchestral music.

"This system of electrical communication was briefly reported upon to the National Academy of Sciences in April 1933, in a paper by Dr. F. B. Jewett, vice-president of the American Telephone and Telegraph Company and president of Bell Telephone Laboratories. At that time a public demonstration of the new equipment was given in which a program of the Philadelphia Orchestra was transmitted from Philadelphia and reproduced with exact auditory perspective upon the stage of Constitution Hall in Washington. The physical characteristics of the system also, were at that time briefly described by Dr. Fletcher and demonstrated through a few experiments.

"The forthcoming symposium of papers will be the definitive presentation of the technical features of this accomplishment; and Dr. Fletcher's program of demonstration, an equally complete illustration of the remarkable range and unique psychological effects of the system.

"During the week following the A.I.E.E. convention similar demonstrations will be given through the courtesy of Dr. Fletcher and the Bell Laboratories to the following societies: Institute of Radio Engineers, Society of Motion Picture Engineers, Acoustical Society of America, and the New York Electrical Society."

Because the seating capacity of the auditorium is limited and a large demand is anticipated for seats, admission will be by ticket only. These may be obtained without charge, at the convention registration desk. The demonstration will be held immediately after the Edison Medal presentation.

ENTERTAINMENT AND SOCIAL ACTIVITIES

The smoker will be held in the Engineering Societies Building on Tuesday evening, January 23, at 6:00 p.m. In addition to a buffet dinner there will be movies and an excellent show in the auditorium. Tickets will be $2.75 per person and cover all events.

ANNUAL DINNER-DANCE PRESENTS NOVEL FEATURES THIS YEAR

The annual A.I.E.E. dinner-dance will be held Thursday, January 25, at the Waldorf Astoria Hotel, Park Avenue at 50th Street. As an innovation, it is to be a combination dinner-dance and dance-buffet supper. All the pleasurable features of previous years associated with the A.I.E.E. dinner-dances will be retained, but for those members and their guests who prefer to omit the formal dinner, the dance-buffet is offered. Music is by George Ellner's Orchestra. Following are the costs of tickets:

Dinner and dance reservation at $5.
Dance and buffet supper at $3.
For dinner-dancers an additional $1 to include the buffet-supper

The program is as follows:

7:00 p.m. Reception to President Whitehead—Basildon Room
7:30 p.m. Annual dinner—Astor Gallery
9:00 p.m.–2 a.m. Dancing—Jade Room
Buffet-supper service from midnight to 2:00 a.m.—Astor Gallery

The Basildon and Jade Rooms, together with the Astor Gallery, all fine examples of architectural art, are so equipped as to afford an excellent setting for this occasion. A most tempting dinner menu has been prepared and Oscar has assured us that he will make the most of this first opportunity

Fairchild Aerial Surveys Inc., Photo

An airplane view of lower Manhattan, looking across the East River, and with the Hudson Avenue generating station of the Brooklyn Edison Company in the foreground. New York City, which presents not only many striking scenes, but also many points of considerable engineering interest, is as usual the setting for the annual winter convention of the Institute, to be held this year, January 23–26. Back of the Hudson Avenue station and slightly to the left may be seen the older Gold Street station of the Brooklyn Edison Company, and beyond that, first, Manhattan Bridge, and then Brooklyn Bridge, with the Burling Slip station of the New York Steam Corporation just visible across the tops of the bridges, and almost shadowed by the tall buildings behind it

to "sell" us on the Waldorf. Transportation by subway is convenient and parking facilities will be provided by the Waldorf for a moderate fee.

Tables will be laid for 8 or 10 places. Send requests for tickets to the A.I.E.E. dinner-dance committee, 33 West 39th Street, New York City, and make checks payable to H. H. Henline, national secretary. Every effort will be made to comply with requests for the seating arrangements of members and their guests. To assist the committee in making arrangements, please purchase tickets early.

Inspection Trips

The inspection trips committee will endeavor to make available to the membership opportunities to visit a number of points of interest, some of which have been chosen because of their relationship to subjects covered in the technical program. It is planned to arrange for privileges to visit the following points on one or more days:

1. Electrical switch galleries, Hudson Avenue generating station, Brooklyn Edison Company
2. Roseland switching station, Public Service Electric and Gas Company, N. J.
3. 132-kv transformer substation, Pennsylvania Railroad
4. A-C calculating board, Pennsylvania Station, New York
5. Electric locomotive, Pennsylvania Railroad
6. Carrier current protective relays, Dunwoodie substation, 132-kv connection between generating stations in New York City with Niagara Hudson System
7. Electrical Testing Laboratories
8. Operating rooms of commercial telegraph companies
9. Electrical Research Products, Inc.
10. Electrical Institute of the Electrical Association of New York, Inc.
11. New York Museum of Science and Industry

Tentative plans are in progress for the arrangement of a special all-day motor bus trip to be made on Friday, January 26, over a route covering a large area in the northern part of the State of New Jersey, stopping for inspection of commercial long-wave and short-wave radio communication stations. The route will be chosen so as to include several points of historic and scenic interest as well. Some of the features of the trip are: Holland vehicular tunnel; elevated express highway; New Brunswick long-wave radio telegraph station of RCA Communications, Inc., where Alexanderson induction alternators may be seen; campus of Rutgers University; campus of Princeton University; Lawrenceville short-wave radio telephone transmitting station of the A. T. & T. Co.; Washington Crossing State Park; Netcong short-wave radio receiving station of the A. T. & T. Co.; Morristown; and Newark. The cost of this trip and further information will be available at the inspection trips desk during the convention. Please make your reservations promptly upon arrival at the convention so that the committee may complete arrangements.

Register in Advance

Fill in and post promptly the mail registration card which was included with the mailed announcement of the winter convention sent to members in nearby Districts. This will permit the committee to have badges ready and prevent congestion at the registration desk upon arrival. There will be a registration fee of $2 for nonmembers with the exception of Enrolled Students of the Institute, and the wives and children of members.

Reservations for hotel accommodations should be made by writing directly to the hotel preferred.

Reduced Railroad Rates

Fare and one-third for the round trip over the same route will be available to members and guests, provided 100 certificates are validated at the registration desk. Consult your local ticket agent regarding the territory and dates applicable as all passenger associations have not granted reduced rates. Obtain your certificate authorized by the railroad passenger associations.

Bring Your E.E.'s to the Convention

In accordance with the provisions of the Institute's new publication policy, all papers scheduled for discussion at the winter convention have been published in Electrical Engineering and thus circulated to the entire membership. Inasmuch as pamphlet copies of these papers will not be available, members attending the convention may wish to bring with them their August, November, and December 1933, and January 1934 issues.

A.I.E.E. Executive Committee Meets

In accordance with action of the board of directors, in October 1933, a meeting of the executive committee of the American Institute of Electrical Engineers was held at Institute headquarters, New York, N. Y., December 8, 1933, in place of the regular December meeting of the board of directors.

Present were: John B. Whitehead, chairman; H. P. Charlesworth, J. Allen Johnson, Everett S. Lee, E. B. Meyer, C. E. Skinner, and W. I. Slichter, of the executive committee; A. E. Knowlton and R. W. Sorensen, members of the board of directors; and H. H. Henline, national secretary.

In memory of Past-President Calvert Townley, the committee adopted a resolution, which is published elsewhere in this issue.

A report of a meeting of the board of examiners held on November 15, 1933, was presented and approved. Upon the recommendation of the board of examiners, the following actions were taken upon pending applications: 1 applicant was elected and 4 were transferred to the grade of Fellow; 11 applicants were elected and 15 were transferred to the grade of Member; 45 applicants were elected to the grade of Associate; 767 Students were enrolled.

The finance committee reported disbursements amounting to $18,740.83 for the month of November. Report approved.

Upon the recommendation of the Sections committee, approval was given to a petition for authority to organize a New Orleans Section of the Institute, with a territory embracing the entire state of Louisiana.

Professor W. I. Slichter was reappointed a representative of the Institute on the library board of the United Engineering Trustees, Inc., for the 4-year term beginning January 1, 1934.

The following were appointed as representatives of the Institute upon the assembly of American Engineering Council for the year 1934: C. O. Bickelhaupt, F. J. Chesterman, William McClellan, C. E. Stephens, John B. Whitehead, and H. H. Henline, alternate.

It was decided that the January meeting of the board of directors will be held on Monday afternoon, January 22, 1934.

Other matters were discussed, reference to which may be found in this and future issues of Electrical Engineering.

Nominating Committee Announces Candidates

A complete official ticket of candidates for the Institute offices that will become vacant August 1, 1934, was selected by the national nominating committee at its meeting held at Institute headquarters, New York, N. Y., December 7, 1933. This committee, in accordance with the constitution and by-laws, consists of 15 members, one selected by the executive committee of each of the 10 Geographical Districts and the remaining 5 selected by the board of directors from its own membership.

The following members of the committee were present: C. R. Beardsley, Brooklyn, N. Y.; H. P. Charlesworth, New York, N. Y.; A. F. Darland, Tacoma, Wash.; O. J. Ferguson, Lincoln, Neb.; P. S. Harkins, Philadelphia, Pa.; A. H. Hull, Toronto, Ont.; G. A. Kositzky, Cleveland, Ohio; F. H. Lane, Chicago, Ill.; Everett S. Lee, Schenectady, N. Y.; W. E. Mitchell, Atlanta, Ga.; L. W. W. Morrow, New York, N. Y.; G. H. Quermann, St. Louis, Mo.; R. W. Sorensen, Pasadena, Calif.; A. C. Stevens, Schenectady, N. Y.; H. R. Woodrow, Brooklyn, N. Y.

Following is a list of the official candidates selected by the committee:

For President

J. Allen Johnson, chief electrical engineer, Buffalo, Niagara & Eastern Power Corporation, Buffalo, N. Y.

For Vice-Presidents

North Eastern District (No. 1): W. H. Timbie, professor of electrical engineering and industrial practice, Massachusetts Institute of Technology, Cambridge, Mass.

New York City District (No. 3): R. H. Tapscott, vice-president, New York Edison Company, New York, N. Y.

Great Lakes District (No. 5): G. G. Post, vice-president, Milwaukee Electric Railway & Light Company, Milwaukee, Wis.

South West District (No. 7): F. J. Meyer, vice-president in charge of operation, Oklahoma Gas &

Electric Company, Oklahoma City, Okla.

North West District (No. 9): F. O. McMillan, research professor of electrical engineering, Oregon State College, Corvallis, Ore.

FOR DIRECTORS

F. M. Farmer, vice-president and chief engineer, Electrical Testing Laboratories, New York, N. Y.

N. E. Funk, vice-president in charge of engineering, Philadelphia Electric Company, Philadelphia, Pa.

H. B. Gear, assistant to the vice-president, Commonwealth Edison Company, Chicago, Ill.

FOR NATIONAL TREASURER

W. I. Slichter, professor of electrical engineering, Columbia University, New York, N. Y.

The constitution and by-laws of the Institute provide that the nominations made by the national nominating committee shall be published in the January issue of ELECTRICAL ENGINEERING. Provision is made for independent nominations as indicated in the following excerpts from the constitution and by-laws:

CONSTITUTION

SEC. 31. Independent nominations may be made by a petition of twenty-five (25) or more members sent to the national secretary when and as provided in the by-laws; such petitions for the nomination of vice-presidents shall be signed only by members within the District concerned.

BY-LAWS

SEC. 23. Petitions proposing the names of candidates as independent nominations for the various offices to be filled at the ensuing election, in accordance with Article VI, Section 31 (Constitution), must be received by the secretary of the national nominating committee not later than February 15 of each year, to be placed before that committee for the inclusion in the ballot of such candidates as are eligible.

On the ballot prepared by the national nominating committee in accordance with Article VI of the Constitution and sent by the national secretary to all qualified voters during the first week in March of each year, the names of the candidates shall be grouped alphabetically under the name of the office for which each is a candidate.

(*Signed*) National Nominating Committee
by H. H. HENLINE,
Secretary

BIOGRAPHIES OF NOMINEES

That those not personally acquainted with the nominees may know something of them and their qualifications for the Institute offices for which they have been recommended, brief biographical sketches are given on p. 230–2 of this issue.

Engineers Urged to Greater Activity in Local Affairs

Under the thought-provoking title of "Help Yourselves!" the following editorial prepared by the Professional Engineers' Committee on Unemployment, serving the metropolitan area of New York, N. Y., was released by the P.E.C.U. to the engineering societies:

"In a radio address, delivered on Sunday, October 15, 1933, our great leader of American thought in time of stress, the President, declared strongly against the policy of passing the relief-work 'buck' to the Federal Government. He declared that the community, the village, town, city, state—the ultimate unit in our social and economic scheme—must do its share and call upon Washington only as a last resort.

"To this pronouncement, the Professional Engineers' Committee on Unemployment, organized in 1931 to cope with problems of unemployment in the engineering profession, can cordially subscribe.

"It is not by a 3-billion-dollar public works program that enough people, especially professional engineers and trained technical men can be provided with employment.

"What kind of men will a program of road building, bridges, tunnels, public buildings, naval construction, employ? The vast majority will comprise laborers, sand-hogs, steel erectors, concrete-men and some building trade mechanics. The equipment required has been rusting in the yards for 4 years. It will probably be brought out, dusted off, oiled, and put to work. There will be little enough demand for new equipment, so that the effect upon factory production will not be conspicuously marked.

"But if each community will look around and see what work it can undertake, that will be another matter. There is hardly a village in the country which has not some neglected project or crying need for improvement ready to be undertaken at once. Water works, sewage disposal, street widening, transportation systems, airports, municipal buildings, paving, new equipment for police, fire, sanitary, hospital departments, bridges, docks, freight terminals, parks; slum clearance in which private capital is willing enough to interest itself with reasonable encouragment—all

In Memoriam

CALVERT TOWNLEY

ON November 27, 1933 there was removed from our ranks, Calvert Townley, thirty-second president of the American Institute of Electrical Engineers.

From the earliest days of his professional career, when on graduating from Sheffield Scientific School he entered the employ of the Brush Electric Light Company, down through his connections with the Boston subways, the N. Y., N. H., & H. electrification and his many years of affiliation with the Westinghouse Electric and Manufacturing Company, Calvert Townley exhibited an unusual ability to grasp quickly the technical details of the problems which confronted him, particularly as those details affected the managerial phases for which he was so often responsible. So also in his years of service devoted to the Institute and to the welfare of the profession which he had chosen, he exhibited the same quick grasp of detail and thorough understanding of problems as a whole. Entering the Institute in 1901 he became a Fellow in 1912. His executive ability soon brought him election as manager in 1905, vice-president in 1908 and president in 1919. He gave much of his time to the questions coming before the public policy committee serving as chairman for over 5 years. Recognition of his thorough understanding of the needs of the profession was indicated in his selection as chairman of the Committee on Development of the Institute and, likewise, his election to trusteeship in the United Engineering Society and the Engineering Foundation board.

Throughout his professional life, both before and since his presidency, he was constant in his active interest in the affairs of the Institute, especially in those questions pertaining to the dignity and elevation of the profession of engineering. At the time of his death he was giving freely of his counsel and time in important Institute activities of this type in the Coordination Committee of Engineering Societies. It would be difficult to overstate the value of his services to both Institute and profession. His loss is all the more serious at this time of agitation and uncertainty.

It is therefore with a keen sense of inability to evaluate in words the part which Calvert Townley has played in our ranks and the loss which the profession sustained when he passed on that we order this minute be spread upon the records, and that it be transmitted to his family and associates as an expression of appreciation and admiration from those who were privileged to work with him in the American Institute of Electrical Engineers.

—A.I.E.E. Executive Committee, Dec. 8, 1933

these are desperately needed in every community in the country, having now been neglected for years.

"And they would all employ engineers, not only in the work itself but in making the material and equipment necessary to carry it out. If all this were to be undertaken it would involve many more than 3 billions of expenditure. The normal building construction program amounts to 6 billions as does the steel industry and the automobile industry. In fact, our total years business added up to 88 billions of dollars in 1928.

"But, how to get this vast program under way? The answer is to bring pressure to bear in the individual community. And the engineer can do his share there, too, as a citizen as well as a technically trained, and, therefore, super-useful member of the community.

"The engineer is all too prone to sit back and watch the self-appointed governors of his home town, the local druggist, doctor, lawyer, banker, run the place, while he patiently awaits the result of their decisions. They elect themselves to the local board of supervisions, the State legislature, Congress, and settle, in their own political way, the engineering improvements which are to be made.

"Engineers! Wake up! Take a hand in your local government, the activities in your community. You know far more about the engineering needs of a town and how to execute it than the local politicians. Take the lead and get some of the local projects going. Organize the opinion of the substantial citizens. Get your newspaper interested. Take the side of good government. Towns can raise capital when individuals cannot.

"It is only by such capital investments that you and all engineers can live."

E.C.P.D. Committee on Professional Recognition

Commented Upon by C. N. Lauer and Dean Barker

THE committee on professional recognition, one of the 4 working committees of the newly organized Engineers' Council for Professional Development, has already actively undertaken its duties and has accomplished tangible results. These are summarized in the following article prepared by Conrad N. Lauer, chairman of the committee, and J. W. Barker, the representative of the A.I.E.E. upon this committee. This article was prepared for ELECTRICAL ENGINEERING by Mr. Lauer and Dean Barker, at the request of L. A. Doggett (A'13, M'16), chairman of the Institute's committees on Student Branches and on education. The article by Mr. Lauer and Dean Barker follows:

E.C.P.D. Brings Engineering Groups Together

For the first time in the history of the engineering profession in the United States there has been organized a joint activity dedicated to the principle of assisting the individual engineer in his personal professional development. This organization is known as the Engineers' Council for Professional Development and brings together the 5 principal engineering societies—the American Society of Civil Engineers, the American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, the American Institute of Electrical Engineers, the American Institute of Chemical Engineers—together with the national society of engineering educators, the Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners. This is not a super-engineering society nor does it parallel or interfere with any of the existing established agencies. It is purely a coöperative project and operates only to recommend to its constituent bodies joint action leading toward the ideal of enhancing the professional development of the engineer. It operates only through recommendations to the member bodies, first as to policies and when such policies have been approved by the member bodies acting individually then the Engineers' Council again comes into play in recommending procedures to carry out these approved policies. It is highly important that every member of our American Institute of Electrical Engineers shall thoroughly understand these principles of action, particularly in considering the reports of the Engineers' Council for Professional Development and its various committees. The policies outlined in committee reports when approved by the Engineers' Council for Professional Development still do not become effective until the individual member bodies have severally taken favorable action upon the recommendations.

Scope of the E.C.P.D.

The Engineers' Council for Professional Development considers that its problem covers the period in the engineer's life running from the first evidence of his inclination to become an engineer to the time when he finally attains full recognition by the professional societies, the engineering educational institutions and the state as a full-fledged engineer competent to take responsible charge of engineering work in his particular field. To cover this range the Engineers' Council has set up 4 main committees on student selection and guidance, on engineering schools, on professional training, and on professional recognition.

Committee on Professional Recognition

This article is concerned primarily with the committee on professional recognition which is composed of the following members:

Conrad N. Lauer, chairman (Representing The A.S.M.E.). President, Philadelphia Gas Works; past-president, A.S.M.E.; former chairman A.S.M.E. committee on economic status of mechanical engineers.

Joseph W. Barker (M'26, F'30) (Representing the A.I.E.E.). Dean, school of engineering, Columbia University; chairman of committee on university relations, engineering division, National Research Council; chairman of committee on degrees of engineering schools of New York State.

Frederick M. Becket (Representing the A.I.M.E.). President, A.I.M.E.; president, Union Carbide and Carbon Research Corporation; vice-president, Electro Metallurgical Corporation.

Frederick L. Bishop (Representing the S.P.E.E.). Secretary, S.P.E.E.; professor of physics, University of Pittsburgh.

H. C. Parmelee (Representing the A.I.Ch.E.). Vice-president, McGraw-Hill Publishing Company; former chairman, A.I.Ch.E. committee on engineering education.

J. P. H. Perry (Representing the A.S.C.E.). Member of board of direction of American Society of Civil Engineers; vice-president, Turner Construction Company.

David B. Steinman (Representing the N.C.S.B.E.E.) President, New York State Society of Professional Engineers; former president National Council of State Boards of Engineering Examiners; consulting engineer of the firm of Robinson and Steinman.

This committee on professional recognition is concerned with recommending through the Engineers' Council for Professional Development to the member bodies for approval standards for entrance to the profession and the methods of establishing and maintaining them. If the profession is to improve the minimum professional and intellectual background of those servants of the public to be called engineers it must itself establish high standards for those qualifications which will render the engineer a valuable member of society. This involves emphasis on social, economic, and general cultural training as well as the maintenance of high technical standards of education and practice.

While such a procedure will also improve the status of the engineering profession in the eyes of those who use engineering services and in the view of other professions and the public, the primary purpose of all the activities of this committee is and should be directed toward improving the services which the qualified engineer can and must render to the public service.

Policy Adopted

To guide the committee in fulfilling its purpose the following policy has been adopted by the Engineers' Council for Professional Development:

"The profession should establish as the goal of attainment a series of qualifications for which the young man, whether graduate or non-graduate, may successfully strive continuously from the time he enters upon an engineering career. This goal of attainment, embodied in a certificate,[1] equivalent to the professional degree and having a value recognizable as adequate to entitle the holder to licensing or registration in a state, should be based upon the following features:

a. Certification should be earned, and not granted as a mark of honor.

1. When the recommendations stated later in this article have been approved by each of the member bodies the committee on professional recognition will be concerned with setting up a joint coöperative examining board, which may be the committee itself, or a subcommittee thereof, or an agency independent of the committee, to examine and certify to the profession those candidates who meet the minimum definition of an "Engineer," as later outlined in this article.

b. The code of educational qualifications should be more advanced than graduation from college, yet attainable by both college and noncollege men.

c. The attainments should be tested individually by examination (written and oral) or the equivalent and not gauged by personal estimates and testimonials alone.

d. Educational qualifications should comprise scientific, technical, economic, and civic knowledge of a mature order.

e. The code of experience qualifications should normally make the age of certification fall between 25 and 30.

f. The ultimate certification into the profession should be the objective to which both the colleges and the professional societies should exert their influence. To this end the colleges should be encouraged to aid by granting the professional degree only to those who have been thus certified.

g. The certificate into the profession should be the means by which the state registration boards would with confidence recognize those essentials which they observe as requisite for the registration of engineers.

h. And, similarly, the certificate into the profession should be *prima facie* evidence of technical proficiency for admission into the corporate membership of the societies.

"By such a progressive educational program involving selection of proper material, its supervised education, intimate contact with the profession during the apprenticeship state and the attainment of definite specified educational requirements with concurrent recognition by professional societies, educational institutions, and state laws, it is believed that an identity would be attained by which those who have not developed experience and maturity of engineering judgment would be recognized as assistants in the engineering field and those who have attained engineering maturity would have an identity universally recognized by the profession itself and the public at large. It is believed that this definition of the engineering profession will be of immeasurable benefit."

Policy as Affecting Colleges, State Boards, and Societies

It should be noted in this policy the Committee has suggested placing the question of professional recognition on a more scientific basis. It recommends dispensing with testimonial opinion alone and substituting therefor fact as determined by actual examination. This policy furthermore attempts to avoid duplication either of examination by the engineer or by the bodies concerned with his professional training. As an example, under (*f*) above it does not require that the engineering Alma Mater shall be required to grant the professional degree to engineers who have been thus certified but suggests that those engineering colleges desiring to grant professional degrees to their graduates shall coöperate in the general program by not granting the professional degree prior to the attainment of this certification. Many of our engineering schools at the present time grant professional degrees to such of their graduates as have been in the practice of engineering for a certain number of years and who submit to the engineering faculty concerned a suitable thesis on some phase of their professional activity. It is quite probable that when the policies of the committee on professional recognition have been approved by the member bodies and this committee turns its attention to the modus operandi of certification it will require as a part of the final examination for professional recognition a thesis or similar work covering the most important phase of the candidate's professional activity. Such a thesis could be submitted simultaneously to the engineering faculty concerned as well as to the certifying board and if the candidate is granted certification the engineering school could, if it so desired, then grant the professional degree.

Similarly under (*g*) above the various state licensing and registration boards could also recognize this certificate and the examination leading up to the certificate as covering those essentials which they are required to observe as requisite for the state registration of engineers. This would again avoid duplication of work both by the candidate and by the responsible body. It should also be noted that there is nothing in this policy which requires the candidate to become licensed by any state unless the type of work in which he is then or later becomes engaged requires such registration.

As another example under (*h*) above there is nothing which requires a candidate to assume corporate membership in his professional society when he secures the certificate. It simply means that the certificate is recommended for adoption by each of the professional societies as a necessary and prima facie evidence of proficiency for admission to the corporate membership grade.

Minimum Qualifications for an "Engineer"

The committee on professional recognition reviewed in great detail the present requirements for recognition embodied in the grades of membership of the participating societies, in the "model" law for registration and licensing of engineers and in the practice of awarding professional degrees. Lack of uniformity seemed prevalent in all of these requirements and the need was apparent that a united profession must have a minimum definition of an engineer. Based upon this study the following was adopted by the committee, by the Engineers' Council for Professional Development, and to be recommended to the participating societies as the minimum qualification for an engineer:

a. Graduation from an approved course in engineering of 4 years or more in an approved school or college; a specific record of an additional 4 years or more of active practice in engineering work of a character satisfactory to the examining body (the examining body, in its discretion may give credit for graduate study in counting years of active practice); and the successful passing of a written and oral examination covering technical, economic, and cultural subjects and designed to establish the applicant's ability to be placed in responsible charge of engineering work and to render him a valuable member of society:

or alternatively

b. Eight years or more of active practice in engineering work of a character satisfactory to the

May Be Visited During the Winter Convention

ABOVE is shown the 132-kv Elmsford substation of the Westchester (N. Y.) Lighting Company, which incorporates an unusual design of 132-kv structure. In the picture at the side is shown carrier current equipment at the Dunwoodie station of the Yonkers (N. Y.) Electric Light and Power Company; this is part of the 132-kv Niagara-Hudson interconnection. Both of these stations may be visited by those attending the Institute's winter convention, January 23–26, 1934.

examining body and the passing of written and oral examinations designed to show knowledge and skill approximating that attained through graduation from an approved engineering course and also examinations written and oral covering technical, economic, and cultural subjects designed to establish the applicant's ability to be placed in responsible charge of engineering work and to render him a valuable member of society.

Society Membership Grades

It should be noted that there is no attempt on the part of the committee to recommend for adoption one solitary road to recognition as an engineer but the committee recognizes that competent engineers may be trained either in the formal processes in our educational institutions or in the school of practice. It should also be noted that the committee recommends that formal education alone or practice alone cannot produce a competent engineer. The combination of study and practice is necessary. In this connection the committee feels that there are a minimum of 3 large groups of persons in the engineering field who may be roughly separated as follows. A student who is a person matriculated in an approved engineering school or one who is engaged in practice and is pursuing on his own initiative studies comparable with those given in an engineering school. It is anticipated that the committee on professional training of the Engineers' Council for Professional Development will so organize its work as to provide possibilities to the young apprentice who has not gone to an engineering school to carry out these fundamental engineering studies on his own initiative. These 2 groups constitute our student class and consequently the committee on professional recognition has recommended that the professional societies concerned should seriously consider amending their student membership rules and specifications to bring these groups into the societies as "student members." After graduation from an approved engineering school or after the noncollege student has passed equivalent written and oral examinations he becomes in essence an engineer in training or a junior engineer. Consequently the committee has recommended that the participating societies seriously consider amending their membership rules and specifications to provide for "junior members" for this class of persons. This "junior membership" would cover the minimum period until the person has met the minimum qualifications of an engineer as outlined above, whereupon he should become eligible for the "member" grade.

Uniformity in the grades of membership in the various societies and in conformity with the above suggested grades and designations are both logical and highly desirable. At the present time there is little uniformity between our various societies and great confusion exists in the minds of the public at large as to the meaning of our various society membership designations. A simple, rational, logical, and uniform nomenclature and specification has therefore been recommended and it is hoped that the societies may adopt this as a logical ideal toward which to work. It should be appreciated, of course, that nothing completely revolutionary to the present set-up should be attempted. With this in mind the Engineers' Council did not approve any recommendation for "fellow" grade, as being outside the purview of the council. Secondly, the Engineers' Council made the following statement: "These recommendations, however, are not intended to exclude the affiliations of other persons with any constituent society in a capacity other than the grades of membership indicated." Third, the Engineers' Council recommended that these specifications for "student member," "junior member," and "member" be regarded as "minimum."

Further Action to Be Taken

In accord with the policy first outlined in this article the grade of membership, the license, and the professional degree should be in substantial agreement with the minimum definition of an engineer. The committee urges that steps be taken to place this view before the faculties of engineering schools for consideration so that in time the grades of professional recognition when granted may be uniform. In this connection the committee on professional recognition and the Engineers' Council for Professional Development recommended through the Society for the Promotion of Engineering Education that the faculties of engineering schools give consideration to the bestowal of professional degrees only to those who have attained the minimum standard, the actual vote of the Engineers' Council being as follows: "That when the recommendations for minimum definition and standard grades of membership are approved by the participating bodies, then E.C.P.D. make the suggestion through S.P.E.E. that the professional degree be granted only to those who meet the minimum definitions."

Throughout this article the phrase "approved school" has been used with the knowledge that the committee on engineering schools has this matter under consideration and that a scheme for accrediting schools will be forthcoming which would result in a list of approved schools. The phrase therefore should be viewed in the light of a possible report from the committee on engineering schools which was made at the meeting of the Engineers' Council by the committee on engineering schools and was adopted for recommendation to the participating bodies. It is beside the point whether accrediting is desired or not. It is a fact which must be met that various of the state laws require the setting up of a list of approved schools and it is highly desirable that such a list be uniform throughout the country.

The committee on professional recognition is fully cognizant of the fact that acceptance by the participating bodies of these various recommendations including the minimum definition of an engineer will not of themselves raise the standard of the profession. The committee is therefore bending its efforts to a consideration of the mechanism, scope, and content of examinations and other procedures for measuring the achievement of standards for recognition by the individual in order that it may be ready when the participating bodies have approved the policy and recommendations to make additional recommendations for the modus operandi. The committee again stresses the fact that these recommendations are recommendations and are not compul-

Great Britain's First Streamlined Rail Car

According to The Travel and Industrial Development Association of Great Britain and Ireland, the first streamlined rail car to be used in Great Britain was placed in service in a "press" run December 1, 1933. It is used by the Great Western Railway on one of its suburban services. The journey of 36 miles between London and Reading was covered in this run in 39 min 52 sec and in 42 min 24 sec, for each of 2 nonstop runs; the maximum speed obtained was 62 mph. The car, of unique design, is the outcome of exhaustive tunnel tests to reduce wind resistance, which at normal speed requires more power to overcome than the driving of the car along the rails. The car, shown above, is 62 ft long, and 11 ft 4 in. high. It weighs 20 tons and has been designed for a maximum speed of 60 mph. Seating capacity is for 69 passengers, the leather covered seats being arranged in pairs, permanently placed back-to-back. The sides of the car extend to within one foot of the track, so that practically the whole of the car, including wheels, is enclosed in a streamlined case. Everything possible has been enclosed, even to the head and tail lamps, controlled from the driver's seat, which are fitted flush with the case. It is stated that the effect of this streamlining has been to reduce wind resistance to $^1/_4$ of that encountered by a similar square-ended car.

sory upon any organization until they have been adopted by the proper body of that organization. Coöperation between all our various engineering bodies looking to the ideal of enhancing the professional development of each and every engineer in this country is the keynote of all the work of the Engineers' Council for Professional Development and the work of the committee on professional recognition with which this article is concerned. To establish a guild or union is not the concept which motivates anybody concerned with this movement. Before we can convince the public that the engineer is truly a professional man we must coöperate in developing a professional status and in this coöperation it is desirable that every member of the profession shall be cognizant of and in sympathy with the ideals for which we are striving.

Primary Considerations Relating to Steam, Electric, and Diesel-Electric Traction. Identified as being based upon actual operating conditions on British railways, an article carrying the foregoing title and published in *World Power* for November 1933, p. 247–55, surveys the technical and financial positions of the 3 forms of railroad traction. The paper originally was presented before the "British" Institution of Civil Engineers. The article presents perhaps the most detailed study of its kind that has appeared, and the tables and illustrations contain a mass of essential information on railway conditions. The figures are, however, based upon estimates and applied to British conditions.

San Francisco Section Stimulates Student Participation

Student participation in the activities of the Institute's San Francisco, Calif., Section undoubtedly will be broadened and stimulated by policies announced by Section Chairman W. C. Smith at the September 29, 1933, meeting of the Section. The plan is that at each meeting a Student will present a 5-min biography of one of the pioneers in electrical development. At the September 29 meeting, the plan was inaugurated by a 5-min biographical sketch of Ampere, presented by a Student.

Further to stimulate the attendance of Enrolled Students at Section meetings, the Section has inaugurated the policy of absorbing for all students attending, half the price of the regular dinner that precedes Section meetings.

Chemistry Industry Medal Awarded to J. G. Vail. The Chemical Industry Medal of the American Section of the Society of Chemical Industry was presented to J. G. Vail, of the Philadelphia Quartz Company, at a meeting held in New York, N. Y., November 3, 1933. The meeting was held jointly with the American Chemical Society, the Electrochemical Society and the Société de Chimie Industrielle. This is the first award of what is called the "Chemical Industry Medal" which takes the place of the Grasselli Medal awarded annually for several years by this society. The new medal is awarded Mr. Vail in recognition of his work on sodium silicates in industry. He joined the chemical department of the Philadelphia Quartz Company in 1905, and is now a vice-president and chemical director.

High Voltage X Ray Tubes Are Compared

A comparison has been made at the U.S. Bureau of Standards of the X ray output as a function of the applied voltage for different types of high voltage tubes. The complete results of this work are contained in research paper No. 595, published in the September 1933 number of the "Bureau of Standards Journal of Research."

The comparison was made for 2 thin glass X ray tubes, 5 thick glass tubes, and 1 metal-centered tube on several generators of different voltage wave form. Thin glass tubes show about 15 per cent greater output than thick glass tubes on constant potential, while the metal-centered tube gave about 15 per cent less output. At any given effective (rms) voltage, the outputs of all glass tubes or all generators were nearly the same, and equal to the output on a constant potential of the same value. Likewise, at a given effective voltage, the quality (full absorption curve) was the same for all tubes on all generators.

Outputs of all tubes at a given peak voltage varied over a range of 25 per cent between tubes and between different generators. The metal-centered tube output varied widely between half and full wave rectification at equal peak voltages. The same tube, however, gave the same output at any given effective voltage supplied by any generator.

Development of Mines and Men Traced in "Porphyry Coppers"

Whether or not all electrical engineers will agree with John Hays Hammond, in his foreword to Parson's "Porphyry Coppers," that major developments in the electrical industry have come about through the assurances of large supplies of copper is not known. However, the mining engineer feels assured that his professional colleagues in the electrical industry at least will admit that the enormous tonnages of copper that became available in the decade commencing with 1910 have had a marked influence upon electrical developments as well as on the face of nature in the western mountains.

Mr. Parsons, now secretary of the American Institute of Mining & Metallurgical Engineers, is singularly well equipped for the task he has undertaken—the writing of a chronicle of engineering in the 2 Americas. Educated in Utah, Mr. Parsons has spent much of his professional career among the men who were actively engaged on these enterprises. His clear and attractive style, polished by service on the editorial staffs of the *Mining and Scientific Press* and the *Engineering and Mining Journal*, has humanized the history and technology of the big copper mines treated in the pages of "The Porphyry Coppers."

In his book the author points out through numerous examples that the entire success of these mining projects was due to engineering principles, correctly applied and amplified by the ingenuity and steadfast courage of a large number of American engineers. Backed by capital, mainly American and British, these engineers "have converted huge ore deposits in many countries into the big metal mines of the world." Throughout the pages names of men still active in mining and financial circles appear in settings markedly different from their earlier surroundings where they are so vividly depicted as eager searchers for ore. Although the book is primarily a story of and for the mining engineer, it has much of interest to anyone who ever has felt the call of far away places or the desire to get rich in a hurry by buying stocks in some mining enterprise with a flowery name.

Mining engineers realize that the author in selecting his title has chosen the term "The Porphyry Coppers" judiciously. Presumably only a geologist or a mining engineer will be particularly interested in the fact that not all the great mines that are discussed are in porphyritic deposits. The author himself points out that there are other copper deposits, some of which have been exploited profitably, that are not included. The author confines the term to those mines having enormous tonnages of low grade ore, in which the minerals occur disseminated over large areas. From these deposits, considered of doubtless economic value 30 years ago, copper has been won by large scale production methods.

It is interesting to note that the porphyry deposits, which have yielded more than 17 billion pounds of copper and have reserves of more than 100 billion pounds of copper in unmined ore, all had been worked prior to 1900. The Chino mine in New Mexico may have been the scene of the first mining activity in the Western hemisphere. At Chuquicamata, Chile, copper had been mined by the Incas in the 16th century. However, it was not until Jackling had pioneered the porphyry coppers with Utah Copper in Bingham Canyon, Utah, that the potential extent of the various porphyry coppers came to be realized.

The subject matter of the book includes the stories of 12 remarkable mines, 9 in North America and 3 in South America. Considerably more than half the book is devoted to historical summaries of the development of these great mines from their humble beginnings as prospects to their fruition as profitable enterprises. The technology of mining, including exploration, ore extraction, and treatment processes, so markedly advanced by engineers connected with those various companies, is treated most adequately in several chapters. Throughout the discussion the author emphasizes the effect these vast enterprises have had upon the social and economic development of the Western states—Utah, Nevada, Arizona, and New Mexico—and upon Chile, sister republic in South America. Their effect upon the "Building of the West" has been unquestioned for the past 2 decades and this marked influence will continue for many years to come.

The title of the first chapter—"An

Achievement of Engineers"—would serve admirably as a subtitle of the book as a whole. The author has stated that "Whatever Power is reponsible for the Universe made ore deposits; but mines are made by the genius of men." He might have added the corollary which his book so clearly indicates—mines make men.

"The Porphyry Coppers" by A. B. Parsons is the first of the Rocky Mountain Fund Monographs to be published (1933) by the American Institute of Mining and Metallurgical Engineers, 29 West 39th Street, New York, N. Y. The book is cloth bound, 6 x 9 in. in size; its 581 pages are well illustrated, and its price is $5.—H. M. Lawrence.

Electrically Controlled Wind Tunnel Completed at Case. A large wind tunnel for testing wind pressures and their effects on airplane structures, buildings, etc., has recently been completed at the Worcester Reed Warner Laboratories, Case School of Applied Science, Cleveland, Ohio. The tunnel, which is built of heavy sheet metal reinforced with angle-iron, is approximately 30 ft long. Its cross-sectional area is 81 x 81 in. at the largest part, and tapers down to 3 by 3 ft at the semi-open section where the test models or objects are placed. A sensitive counterbalance system of suspension wires permits accurate measurement of the force or "drag" exerted by the wind upon the object and a draft gage connected to a "pitot tube" enables the velocity of the airstream to be determined readily. To assure a wide range of steady non-pulsating airflow at all velocities from that of a gentle breeze to the equivalent of a destructive tornado, special adjustable voltage equipment was designed by the Electric Generator and Motor Company. A 75-hp 3-phase squirrel-cage induction motor direct coupled to a 50-kw d-c generator was installed. The generator is separately excited from a small machine which also supplies the separately excited fields of the fan-motor in the wind tunnel. The main generator armature is arranged to feed the armature of the fan motor. In this way, the required speed variation of the fan is obtained without any tendency toward instability of control at low speeds.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Slide Rule Calculation of $\sqrt{a^2 + b^2}$

To the Editor:

The method here set forth makes use of the well-known expansion of $\sqrt{a^2 + b^2}$ in terms of the descending continued fraction; viz:

$$\sqrt{a^2 + b^2} = a + \frac{b^2}{2a+}\,\frac{b^2}{2a+}\,\frac{b^2}{2a+}\cdots$$

Divide b^2 by $2a$ and add the quotient to $2a$ to form a new divisor, and repeat until a constant quotient is attained. Add this quotient to a to secure the final answer.

Even when a and b are equal 4 movements of the cursor are all that are required. For rapid convergence b is taken to be the smaller of the 2 numbers but that is not essential.

The method gives more accurate results than the direct method of squaring and adding and extracting the root and is faster.

Example:

$$\sqrt{2^2 + 1^2} = 2 + \frac{1}{4+}\,\frac{1}{4+}\,\frac{1}{4+}\cdots$$

(1) $\frac{1}{4} = 0.25$

(2) $\frac{1}{4.25} = 0.235$

(3) $\frac{1}{4.235} = 0.236$

Hence $\sqrt{2^2 + 1^2} = 2.236$ by slide rule, with the last figure definite. From a table $\sqrt{5} = 2.2361$.

Very truly yours,
V. G. SMITH (A'26)
(Asst. Prof. of Elec. Engg.
Univ. of Toronto, Ontario, Can.)

A New Method of Calculating Circuits

To the Editor:

The object of this paper is to attempt to show, and in a somewhat different way perhaps than that contemplated by W. B. Kouwenhoven and M. W. Pullen in their article "A New Method of Calculating Circuits" (see ELECTRICAL ENGINEERING for November 1933, p. 776–9), the exact foundation upon which this method rests.

In a general theory, it is not necessary to emphasize one section of circuit over another. The load impedance may therefore be looked upon as simply one of the parallel generator branches.

In Fig. 1, consider the points A, B and its n branches. By Kirchoff's laws:

(*a*) The algebraic sum of the voltage drops along all paths connecting the same 2 points are equal.

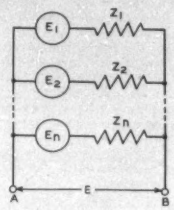


Fig. 1

(*b*) Every impedance Z through which a current I passes exerts an equivalent back-voltage E equal in value to IZ.

(*c*) The algebraic sum of the currents at any point is zero.

From the diagram, and by (*a*), (*b*)

$$E_S - I_S Z_S = E \geq 0;\ S = 1, 2, \ldots, n \quad (1)$$

Let the currents I_S have 2 components. Then

$$I_S = I_{S0} - I_{S1};\ S = 1, 2, \ldots, n \quad (2)$$

Substituting eq 2 in eq 1, and dividing by $Z_S \neq 0$

$$\left(\frac{E_S}{Z_S} - I_{S0}\right) + I_{S1} = \frac{E}{Z_S} \quad (3)$$

and hence

$$\sum\left(\frac{E_S}{Z_S} - I_{S0}\right) + \sum I_{S1} = E\sum\frac{1}{Z_S} \quad (4)$$

By (*c*) and eq 2

$$\Sigma I_{S0} - \Sigma I_{S1} = \Sigma I_S = 0 \quad (5)$$

Substituting eq 5 in eq 4

$$\sum\left(\frac{E_S}{Z_S} - I_{S0}\right) + \sum I_{S0} = E\sum\frac{1}{Z_S} \quad (6)$$

As I_{S0} is arbitrary, simplification of eq 6 will result if

$$\sum\left(\frac{E_S}{Z_S} - I_{S0}\right) = 0;\ \text{or}$$

$$\frac{E_S}{Z_S} - I_{S0} \equiv 0 \quad (7)$$

The first of these appears sterile. The second leads to direct physical interpretation, and is that adopted by the authors. From another point of view, eq 6 represents a "mean-value theorem" with 2 mutually cancelling terms arbitrarily added; and when used without them, completely dispenses with the fiction of short-circuit currents.

Very truly yours,
I. H. BARKEY (A'29)
(Technical Consultant,
2020 52nd St., Brooklyn, N. Y.)

To the Editor:

The paper "A New Method of Calculating Circuits" by W. B. Kouwenhoven and M. W. Pullen in ELECTRICAL ENGINEERING for November 1933, p. 776–9, describes the application of the so-called "short-circuit current solution" in the determination of the currents and voltages in a network consisting of any number of sources of electromotive force operating in parallel and delivering energy to a load (see Fig. 1). By the use of the fictitious short-circuit

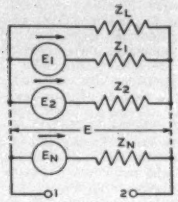


Fig. 1.

current of each generator and a fictitious impedance of the network, it is shown in the paper how to calculate readily the common complex voltage E of the system, the determination of which evidently supplies the key to the solution of all the currents of the network.

The common voltage E across the terminals 1–2 can also be determined by the use of the following obvious alternative form of Thévenin's Theorem (see "Sur un Nouveau Théorème d'Électricité Dynamique," by L. Thévenin, *Comptes Rendus*, v. 97, 1883, p. 159–61): "The voltage between any 2 points in a circuit is equal to the product of the current which would flow through an impedanceless conductor were the latter connected to these 2 points, and the impedance which would exist across these 2 points were all sources of electromotive force removed." The application of this theorem to the circuit shown in Fig. 1 is as follows: The complex current which will flow through an impedanceless conductor connected to terminals 1–2 is evidently

$$\frac{E_1}{Z_1} + \frac{E_2}{Z_2} + \ldots + \frac{E_N}{Z_N},$$

i. e., the sum of the short-circuit current of each generator. The complex impedance between the terminals 1–2 when the voltages E_1, E_2, . . ., E_N are removed is

$$\frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2} + \ldots + \frac{1}{Z_N} + \frac{1}{Z_L}}.$$

Therefore

$$E = \frac{\frac{E_1}{Z_1} + \frac{E_2}{Z_2} + \ldots + \frac{E_N}{Z_N}}{\frac{1}{Z_1} + \frac{1}{Z_2} + \ldots + \frac{1}{Z_N} + \frac{1}{Z_L}}.$$

This equation is identical with eq 8 of the paper which is being discussed here.

The foregoing discussion shows that the "short-circuit current" method makes use of the same fictitious short-circuit current of each generator and the same fictitious impedance which are used in a direct application to the circuit under consideration of the alternative form of Thévenin's Theorem given above. It is evident, therefore, that in the treatment of this particular network the use of the "short-circuit current" method is not characterized by advantages superior to those already obtainable by the use of one of the existing artifices of circuit theory. It is probable, however, that the "short-circuit current" method may be advantageously used in solving other types of circuits.

Very truly yours,
MICHAEL J. DI TORO (A'32)
(Electrical Engineer, 1378 West 7th Street, Brooklyn, N. Y.)

To the Editor:

Since the publication of "A New Method of Calculating Circuits" by W. B. Kouwenhoven and M. W. Pullen, in the November 1933 issue of ELECTRICAL ENGINEERING, p. 776–9, the attention of the authors has been called to the fact that the method is also applicable in unbalanced polyphase systems. The treatment for this case is to be found in "Experimental Electrical Engineering," by V. Karapetoff, v. 2, p. 110.

Very truly yours,
W. B. KOUWENHOVEN (A'06, M'22)
(Professor of Electrical Engineering and Assistant Dean, Johns Hopkins University, Baltimore, Md.)

Theory of Probability

To the Editor:

It is to be hoped that the excellent article by Professor Bennett on "Theory of Probability" published in the November 1933 issue of ELECTRICAL ENGINEERING, p. 752–7, will stimulate attempts on the part of engineers to bring the theory into use in a number of fields where it has not yet been generally applied.

That there should be important applications in power system design, to mention one such field, is suggested by the problem of determining the proper number of spare generators, transformers, cables, etc., to insure a satisfactory degree of service reliability. Spare capacity is now too frequently determined by arbitrary rules having little or no logical basis. For example, reserve generating capacity is often taken as a certain percentage of the capacity required for peak load without due regard to the number and size of units. It should almost be self-evident that 6/20,000-kva generating units installed for a peak load of 100,000 kva give less assurance of dependable service than 12 similar units installed for a peak of 200,000 kva, even though in each case the spare capacity is 20 per cent.

To illustrate the fact that as the number of units increases the percentage spare can be materially reduced without sacrificing reliability, the curve, Fig. 1, for generating units has been calculated. To simplify the problem all units are assumed to have the same capacity, and each is assumed to be subject to emergency outage time to the extent of 3 per cent of its service hours. The curve shows the number of spare units required to be running at the time of the peak, plotted against units needed to carry the peak, in order that the probability of load interruption at the time of the peak shall be $\frac{1}{1{,}000}$. For example, it is shown that when one machine is required for load one additional machine, or 100 per cent spare, must be run to insure the desired degree of service reliability. If the system has 5 units for the peak, 2 reserve units or 40 per cent must be run. Twenty units need 4 spares, or 20 per cent. If 2 systems, each having load for 20 units, interconnect to form in effect a 40-unit system, the reserve need be but 6 units instead of 4 each when operating separately. If 5 such systems pool their generating resources the reserve can be reduced to 10 units, or 10 per cent spare, as against 20 per cent before pooling.

The above results are of course based upon hypothetical considerations. Space does not permit more than brief mention

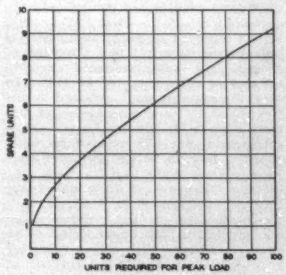


Fig. 1.

of some of the practical considerations that must enter into the solution of an actual problem. For example, account must be taken of the variety of sizes of generating units usually present in an existing system, and of possible short-time overload capacities. It usually will be necessary to calculate probabilities of load outage not only at the time of the peak load but also at loads just under the peak. Again it may be necessary to determine probabilities at times when scheduled turbine, generator, or condenser maintenance temporarily reduces the system capacity, even though at these times the load may be considerably below the peak.

A good method of computing probabilities in a problem such as this consists simply of expanding the binomial $(p + q)^n$, where p is the probability that a generating unit will be unavailable (in the case cited $\frac{0.03}{1 + 0.03}$), q the probability that it will be available $\left(\frac{1}{1 + 0.03}\right)$, and n the total number of machines running. The expansion results in $n + 1$ terms, the first of which

is the probability that n machines will be simultaneously unavailable, the second the probability that $n - 1$ will be simultaneously unavailable, and so on to the last term which gives the probability that no units will be unavailable. (Compare second paragraph in second column on p. 754 of Professor Bennett's article.) This method presupposes that all available machines are actually running and subject to outage. When certain machines are available but idle and therefore not liable to breakdown the problem is somewhat altered. Other methods are available for dealing with this condition.

Very truly yours,
S. A. Smith, Jr. (A'24, M'31)
80 Park Place, Newark, N. J.

Personal Items

J. Allen Johnson Nominated for Presidency

Joseph Allen Johnson (A'07, F'27) chief electrical engineer of the Buffalo, Niagara and Eastern Power Corporation, Buffalo, N. Y., has been nominated for the presidency of the A.I.E.E. for the 1934–35 term. He was born at Northboro, Mass., June 21, 1882. In 1905 he graduated from the Worcester Polytechnic Institute with the degree of B.S. in E.E. From 1905 to 1912, he was employed in electrical engineering work by the Ontario Power Company of Niagara Falls, being appointed electrical engineer of that company in 1912. In 1917, this company was purchased by the Hydro-Electric Power Commission of Ontario, of which Mr. Johnson became assistant engineer, but still retained his other position. In 1918, he was appointed electrical engineer of the Cliff Electrical Distributing Company and Hydraulic Power Company of Niagara Falls, N. Y., and with the consolidation of these companies and the old Niagara Falls Power Company to form The Niagara Falls Power Company in 1918, he became electrical engineer of the enlarged company. In this capacity he was responsible for many important features of the electrical design of the Niagara developments during the period of their rapid growth from 1918 to 1924. In 1929, he was appointed chief electrical engineer of the Buffalo, Niagara and Eastern Power Corporation, which position he now holds. During his career Mr. Johnson has taken a prominent part in the development of the art of power generation and transmission. Perhaps the most important of such developments was that of the system of generator voltage control by individual regulators, which he originated and pioneered in the plant of the Ontario Power Company about 1910, and which he described in a contribution to the technical press shortly thereafter. His contributions to the art of generator testing by means of the retardation method are also well known. Mr. Johnson has contributed to the Institute several important papers on such subjects as reactors in hydroelectric stations, the retardation method of determining losses in hydroelectric generating units, fire protection in a-c generators, and operating aspects of reactive power. As joint author he has also made contributions on power developments at Niagara Falls, lightning protection for transformers, and fundamentals of design of electric energy delivery systems, the latter to be presented at the coming winter convention. He has served the Institute as a member of the electrochemistry and electrometallurgy, electrical machinery, instruments and measurements, protective devices, and research committees. He became a director of the Institute in 1928, served as chairman of the membership committee for the 2 years 1929–31, and is at present chairman of the national committee on transfers, as well as of a special committee to consider the dues of Associates and related matters. He is also a member of the Edison medal committee and the executive committee, and vice president of the North Eastern District (No. 1). He was organizer and first chairman of the Niagara Frontier Section, and served in that capacity from the date of its organization, February 10, 1925, to July 31, 1926. It is also of interest that he was the first chairman of the Worcester Polytechnic Institute Branch of the A.I.E.E. in 1905. Besides his Institute activities, Mr. Johnson served the former National Electric Light Association as chairman of its electrical apparatus committee, as a member of its power systems engineering committee, and is at present chairman of the electrical equipment committee of the Edison Electric Institute. He is also a member of the American Association for the Advancement of Science, and a member of the Electrical Standards Committee of the American Standards Association.

Vice Presidential Nominees are McMillan, Meyer, Post, Tapscott, and Timbie

Fred Orville McMillan (A'14, M'26, F'33), research professor of electrical engineering, Oregon State College, Corvallis, has been nominated to serve the Institute as vice-president representing the Northwest District (No. 9). He was born at Albia, Iowa, May 12, 1890. In 1912 he received the degree of B.S in E.E. from Oregon State College and that of M.S. in E.E. from Union College, Schenectady, N. Y., in 1919. In 1912 he entered the student engineering course of the General Electric Company at Schenectady, and was transferred to the engineering department of that company in 1914. He was engaged in experimental and designing engineering work at the Schenectady works until 1920. He was appointed assistant professor of electrical engineering at Oregon State College in 1920, associate professor in 1923, and to his present position of research professor in 1930. He is a registered professional engineer in the state of Oregon, and in addition to academic work has acted as consulting electrical engineer for a number of public utilities, the Port of Portland, Ore., in 1925, and the United States Bureau of Fisheries from 1929 to 1933. Mr. McMillan has served the Institute as counselor for the Oregon State College Branch, 1926–32, and 1933–34; chairman of the Northwest District committee on Student activities, 1927–28; and a member of the national committee on student Branches, 1931–34. He also has presented a number of technical papers and discussions before the Institute, several of these having to do with radio interference from high voltage insulators. Mr. McMillan is a member of the Society for the Promotion of Engineering Education and of the Northwest Electric Light and Power Association. He also is a member of the following scholastic honor societies: Phi Kappa Phi, Sigma Xi, Tau Beta Pi, Eta Kappa Nu, and Sigma Tau.

Frank J. Meyer (A'13, M'17) vice-president in charge of operation for the Oklahoma Gas and Electric Company, Oklahoma City, has been nominated to serve the Institute as vice-president representing the Southwest District (No. 7). He was born in Grant City, Mo., July 12, 1884. In 1891 he moved with his parents to Oklahoma territory where his father, a Presbyterian minister, did missionary work among the Creek and Seminole Indians. Between 1901 and 1904, he was meter man for the Oklahoma Gas and Electric Company, and between 1904 and 1906 attended Pratt Institute, Brooklyn, N. Y., where he graduated with the 1906 class in applied electricity. Following graduation, he spent 18 months in Porto Rico as assistant electrician for the Guanica Centrale Sugar Company. He returned to Oklahoma in the fall of 1907 and entered the services of the Oklahoma Gas and Electric Company at Oklahoma City, as chief electrician. In 1920 he was made general superintendent of the company and in 1924 became assistant to general manager in charge of operations. In May 1931 he was appointed to his present position of vice-president in charge of operation for the Oklahoma Gas and Electric Company, a subsidiary of the Standard Gas and Electric Company. Mr. Meyer has been quite active in A.I.E.E. work in the Southwest.

George Gilbert Post (A'11, F'33) vice-president in charge of power for The Milwaukee Electric Railway and Light Company, Milwaukee, Wis., and also vice-president and director of the Wisconsin Electric Power Company, has been nominated to serve the Institute as vice-president representing the Great Lakes District (No. 5). He was born near Madison, Wis., in 1881. In 1904 he graduated from the

University of Wisconsin, Madison, with the degree of B.S. in E.E. The 2 years following graduation were spent as an inspector in the electrical engineering laboratory of the University of Wisconsin. In June 1906 he entered the service of The Milwaukee Electric Railway and Light Company as an assistant in the lighting department where he worked as draftsman, material clerk, and statistician; in 1909 he became superintendent of electrical testing for this company, and in 1910 became electrical engineer of the lighting department. When there was a change of management in 1911, he was made head of the electric distribution department, and held this position until late in 1929 when he was appointed to his present position as vice-president in charge of power. Mr. Post has served the Institute as a member of the committee on power transmission and distribution 1922–26, and the committee on power generation 1932–34. He also has been active on technical committees of the Association of Edison Illuminating Companies, and the Edison Electric Institute. For the former National Electric Light Association, he was chairman of the underground systems committee 1922–23, and vice-chairman of the engineering national section 1932. He also has been active in local engineering circles in Milwaukee and Wisconsin, and is a director of the Milwaukee Engineers' Society.

Ralph Henry Tapscott (A'18, F'29) vice-president of the New York Edison Company and of the United Electric Light and Power Company, New York, N. Y., has been nominated to serve the Institute as vice-president representing the New York City District (No. 3). He was born in Brooklyn, N. Y., August 31, 1885. In 1909 he graduated from Union College, Schenectady, N. Y., with the degree of B.S. in E.E. He then joined the testing department of the General Electric Company at Schenectady, transferring shortly afterward to the lighting engineering department where his duties largely involved work with the New York group of utilities. In 1917 Mr. Tapscott became assistant chief electrical engineer of the New York Edison Company, and in 1925 was made electrical engineer of that company. In 1932 he was appointed to his present positions as vice-president of the New York Edison Company and of the United Electric Light and Power Company. Mr. Tapscott has served the Institute as a member of the standards, electrical machinery, power transmission and distribution, headquarters, Edison medal, and finance committees, and the board of examiners. He also has served the New York Section as secretary and as chairman. In 1930 he was elected a director of the Institute for the term expiring July 31, 1934. Among other societies, he has been chairman of the electrical apparatus committee of the former National Electric Light Association, and later a member of its engineering national committee. At present he is chairman of the light and power group of representatives on the Electrical Standards Committee of the American Standards Association. He also is a vice-president of the General Electric Test Alumni Association.

William Henry Timbie (A'10, M'12, F'24) professor of electrical engineering and industrial practice at Massachusetts Institute of Technology, Cambridge, has been nominated to serve the Institute as vice-president representing the North Eastern District (No. 1). He was born at Pittsfield, Mass., August 20, 1877. In 1901 he graduated from Williams College with the degree of bachelor of arts. From 1901 to 1902 he taught at Westerleigh Collegiate Institute, New Brighton, L. I., N. Y. Between 1902 and 1911 he was instructor of industrial electricity at Pratt Institute, Brooklyn, N. Y., spending the summers from 1904 to 1907 as tester in the works of the General Electric Company, Pittsfield, Mass. From 1911 to 1918 he was head of the department of applied science at Wentworth Institute, Boston, Mass., and from 1918 to 1919 was editor-in-chief of the committee on education and special training of the U. S. War Department. He has been at M. I. T. since 1919, his principal duties being the organizing and conducting of the course in coöperative electrical engineering. Professor Timbie is the author of the following books: "Elements of Electricity," 1910; "Essentials of Electricity" 1913; "Alternating Current Electricity" (*with H. H. Higbie*) 1914; "Essentials of Alternating Currents" (*with H. H. Higbie*) 1919; "Principles of Electrical Engineering" (*with V. Bush*) 1922; "Industrial Electricity" 1924. In 1925 he contributed a paper to the Institute on "The Cooperative Method of Education." He has served the Institute as a member of the Section committee 1929–34, committee on Student Branches 1925–28 and 1929–34, having been chairman of this committee 1929–33. He also has served as a member of the committee on education 1929–33, and committee on general power applications 1924–30. He has been a member of the executive committee of the Institute's Boston Section for many years and at present is chairman of this Section. He has for many years also been counselor of the Student Branch at M. I. T., and for one year was chairman of the Branch counselors committee of District No. 1. He is a member of the following national honorary fraternities: Phi Beta Kappa (scholastic), and Pi Gamma Mu (social science). He also is a member of Kappa Eta Kappa, national social fraternity, and of the Williams Club, New York, N. Y., and Albemarle Club, Boston, Mass.

Farmer, Funk, and Gear Nominated for Institute Directorships

Frank Malcolm Farmer (A'02, M'12, F'13) vice-president and chief engineer of the Electrical Testing Laboratories, New York, N. Y., has been nominated to serve the Institute as a member of its board of directors. He was born in Ilion, N. Y., March 28, 1877. In 1899 he graduated from Cornell University, Ithaca, N. Y., and has since been identified with inspection and testing activities in the electrical field. Following about one year in the test department of the General Electric Company of Schenectady, N. Y., and about 2½ years in the inspection division of the U. S. Navy, Brooklyn Navy Yard, he joined the staff of Electrical Testing Laboratories (then the Lamp Testing Bureau) in 1903. In 1906 he was given the title of "engineer" and in 1912 became chief engineer. He has had an extensive experience in research, testing, and inspection in connection with electrical engineering materials and apparatus. Subjects to which he has given special attention are electrical measurements, electrical insulating materials, and electric power cables. He has been active on committees of technical societies dealing with these subjects, has contributed numerous papers to the technical literature, and is the author of "Electrical Measurments in Practice," an associate editor of the "American Civil Engineers Handbook," an author of the "Standard Handbook for Electrical Engineers," etc. He has been interested in welding matters since his association with the research work of the welding committee of the Emergency Fleet Corporation of the World War days. Mr. Farmer has served the Institute as a member of the board of examiners 1923–28, and has been a member of the following committees: standards 1919–22 and 1923–34; technical program 1933–34; award of Institute prizes 1933–34; electric welding 1927–28 and 1930–31; power transmission and distribution 1920–34; and research 1929–34. He was chairman of the research committee 1933–34. Mr. Farmer is a fellow of the American Association for the Advancement of Science, a member of the American Society for Testing Materials (past-president), American Welding Society (past-president), Institution of Electrical Engineers (British), The American Society of Mechanical Engineers, and other engineering organizations. For the American Standards Association he is vice-chairman of the standards council, and chairman of its board of examination, the sectional committee on insulated wires and cables, and the sectional committee on electric welding apparatus.

Nevin Elwell Funk (A'07, M'13) vice-president in charge of engineering of the Philadelphia Electric Company, Philadelphia, Pa., has been nominated to serve the Institute as a member of its board of directors. He was born in Bloomsburg, Pa., November 4, 1883. In 1905 he received the degree of electrical engineer from Lehigh University, Bethlehem, Pa. Mr. Funk served as an apprentice in the Westinghouse Electric and Manufacturing Company, E. Pittsburgh, Pa., in 1905 and 1906. He then worked as subforeman in the employ of the New York Central Railroad Company, Berwick, Pa., during part of 1906, and from 1906 to 1907, served as associate professor of electrical machine design and mathematics at the Georgia School of Technology, Atlanta, Ga. From 1912 to 1913, he was in the employ of the Sterling Switch Board Company in Camden, N. J. From 1907 to 1912, and from 1914 to the present time Mr. Funk has been with the Philadelphia Electric Company occupying the following posts: foreman, station electric construction department; assistant superintendent of Schuylkill station; combustion engineer, Schuylkill No. 1 and No. 2 stations; assistant operating

engineer; operating engineer; assistant chief engineer; chief engineer; assistant general manager; and finally, vice-president in charge of engineering. Mr. Funk is also vice-president of the Conowingo Power Company, the Electric Realty Corporation, Philadelphia Electric Power Company, Southern Pennsylvania Power Company, The Susquehanna Electric Company, The Susquehanna Power Company, and The Susquehanna Utilities Company; he is vice-president and director of the Deepwater Light and Power Company, Philadelphia Hydro-Electric Company, and the Philadelphia Steam Company. Mr. Funk is the author of many technical papers. He has served the Institute as a member of the committee on power generation 1924–33. For the Association of Edison Illuminating Companies, he is chairman of the committee on power generation and is a member of the power generation committee of the Edison Electric Institute. He also is a member of The American Society of Mechanical Engineers, the Franklin Institute, the United States Chamber of Commerce, the Philadelphia Chamber of Commerce, the Philadelphia Board of Trade, and the American Committee of the World Power Conference. Mr. Funk is president of the Engineers' Club of Philadelphia, and is a member of the University Club, Lehigh University Club, the Penn Athletic Club, the Philadelphia Country Club, and the Union League, all of Philadelphia.

Harry Barnes Gear (A'01, M'13, F'20) assistant to the vice-president in charge of engineering, construction, and operation of the Commonwealth Edison Company, Chicago, Ill., has been nominated to serve the Institute as a member of its board of directors. He was born in Marietta, Ohio, March 6, 1872. In 1892 he graduated from Marietta College with the degree of bachelor of arts, in 1895 received the degree of M.E. in E.E. from Cornell University, Ithaca, N. Y. Mr. Gear entered the service of the Chicago Edison Company, predecessor of the Commonwealth Edison Company, in 1895. Among the earlier tasks assigned him was the merging of the distribution plants of 4 utility systems, erected in a competitive race for the World's Fair business of 1893, and embodying an assorted lot of voltages, frequencies, and systems. These were merged into the first 2,300/4,000-volt 4-wire 3-phase distribution system to be used in any large city in the United States; it went into service in 1899. In 1911, Mr. Gear was appointed engineer of distribution of the Commonwealth Edison Company, serving in this capacity until 1921. While in this position he was in charge of the design of the power transmission and distribution system of the company. In 1921 he was appointed to his present position, in which his attention has been given to the wide range of problems arising from the conducting of a great utility system in a period of unprecedented growth. While engineer of distribution for the company, Mr. Gear gathered data for a paper on "Diversity Factors" which appeared in the A.I.E.E. Transactions in 1910; this is believed to be the first paper presented before any engineering body on this important subject. During the same year he published jointly with P. F. Williams "Electric Central Station Distribution Systems," a pioneer treatment of this subject and now in its third edition. Papers on various phases of electrical distribution have been presented by him at other times before the Institute. He was a member of the group which met with the representatives of the U. S. Bureau of Standards in 1915 to formulate the first edition of the National Electric Safety Code. For 33 years the incandescent lamp service to retail customers of the company in Chicago has been under his supervision, and he is a member of the lamp subcommittee of the Association of Edison Illuminating Companies. For the Institute, Mr. Gear has been a member of the following committees, safety codes 1914–34 (chairman 1921–24), standards 1923–27, Lamme medal 1932–35, technical program 1932–34, and Edison medal 1932–34. He also has been representative of the Institute on the electrical committee of the National Fire Protection Association 1921–24, and of the National Fire Waste Council 1923–24. In 1910 he received a Chanute Medal award of the Western Society of Engineers (Chicago). He has been a trustee of the University of Chicago and of the Morgan Park Military Academy since 1924, and is a member of the American Association for the Advancement of Science and the Chicago Art Institute. He also is a member of the Union League and South Shore Country Clubs, Chicago.

W. I. Slichter Renominated as Institute Treasurer

Walter Irvine Slichter (A'00, M'03, F'12) professor of electrical engineering at Columbia University, New York, N. Y., has been nominated to succeed himself as treasurer of the Institute. He was born at St. Paul, Minn., May 7, 1873, and graduated from Columbia University, in 1896, with the degree of electrical engineer. Since 1914 Professor Slichter has been an active member of 18 Institute committees and has represented the Institute on 6 joint bodies; he is now a member of 7 committees and a representative on 5 bodies. A full biographical outline of Professor Slichter's career was published on p. 56 of Electrical Engineering for January 1931.

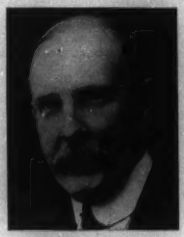
A. E. Kennelly to Receive Edison Medal

Arthur Edwin Kennelly (A'88, M'99, F'13, HM'33, life member and past-president) professor emeritus of electrical engineering, Harvard University and the Massachusetts Institute of Technology, Cambridge, has been awarded the A.I.E.E. Edison Medal for 1933 "for meritorious achievements in electrical science, electrical engineering, and the electrical arts exemplified by his contribution to the theory of electrical transmission and to the development of international electrical standards." Actual presentation of the medal will take place during the forthcoming A.I.E.E. winter convention to be held in New York, N. Y., January 23–26, 1934.

The Edison Medal was founded by associates and friends of Thomas A. Edison, and is awarded annually for "meritorious achievement in electrical science, electrical engineering, or the electrical arts" by a committee consisting of 24 members of the Institute.

Since its establishment in 1904, the medal has been awarded to the following eminent engineers and scientists: Elihu Thomson, Frank J. Sprague, George Westinghouse, William Stanley, Charles F. Brush, Alexander Graham Bell, Nikola Tesla, John J. Carty, Benjamin G. Lamme, W. L. R. Emmet, Michael I. Pupin, Cummings C. Chesney, Robert A. Millikan, John W. Lieb, John White Howell, Harris J. Ryan, William D. Coolidge, Frank B. Jewett, Charles F. Scott, Frank Conrad, Edwin W. Rice, Jr., and Bancroft Gherardi.

In connection with Doctor Kennelly's election as an Honorary Member of the Institute, the highest grade of membership available, a detailed biographical sketch of



A. E. KENNELLY

his career was given in Electrical Engineering for July 1933, p. 512. His marked scientific ability, great versatility in the application of complex theory to practical purposes, continuous contributions to the development of definitions and standards in electrical engineering, and his charming personality has given him an outstanding international reputation.

Frank Conrad (A'02) assistant chief engineer of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been awarded the John Scott Medal by the city of Philadelphia, Pa. This medal, of bronze, was awarded for scientific achievements. It was established in 1816 by John Scott, a chemist of Edinburgh, Scotland, who bequeathed a sum of money to the city of Philadelphia for the maintenance of these awards. Since that time one or more awards have been made annually. Doctor Conrad was awarded the 1930 Edison Medal of the A.I.E.E. "for his contribution to radio broadcasting and short wave radio transmission," as announced in Electrical Engineering for January 1931, p. 60–1, and March 1931, p. 216–8.

H. A. Johnson (M'17) general manager for the receivers of the Chicago (Ill.) Rapid Transit Company, has been appointed director of research of the Ameri-

can Railway Association with the title of chairman. Mr. Johnson has been in charge of extensive testing and research work on air brakes conducted by the Steam Railroad Association. He will head a new committee of the mechanical division which will be devoted to investigations and reports on research problems that may require attention in the opinion of the division.

C. W. Koiner (A'04, F'12) district manager, Southern California Edison Company, Ltd., Redondo Beach, Calif., has been appointed city manager of Pasadena, Calif. Mr. Koiner previously served the city in that same capacity from 1921 to 1925, and for many years prior to that was manager of the municipal light and power department of Pasadena.

Lazare Gelin (A'28), formerly connected with Schneider-Westinghouse in France, has been appointed manager of the foreign division of Kellogg and Tree, an industrial sales promotion company located at New York, N. Y. This firm is engaged in creating a coördinated marketing organization throughout the United States and the leading foreign countries.

H. A. Martin (A'20, M'26) formerly chief engineer of the Peoples Light and Power Company, New York, N. Y., has been appointed division manager of the West Coast Power Company with headquarters in Portland, Ore. He is in charge of the Washington and Oregon properties of the company.

Bryant White (M'20) manager of the electric department of the Delaware Electric Power Company, Wilmington, was recently appointed president of the Kentucky Utilities Company. Mr. White has been an executive of the American Gas and Electric Company since 1920.

J. P. Barton (A'30) has recently been appointed sales engineer in the electrical sheet division of the Empire Sheet and Tin Plate Company, Mansfield, Ohio. Mr. Barton previously was section engineer for the General Motors Radio Corp., Dayton, Ohio.

H. W. Hitchcock (A'15, F'27) chief engineer, Southern California Telephone Company, Los Angeles, has been elected second vice-president of the Engineers' Club of Los Angeles for the year 1933–34.

E. R. Stauffacher (A'15, M'26) electrical protection engineer, Southern California Edison Company, Los Angeles, has been elected secretary of the Engineers' Club of Los Angeles for the year 1933–34.

W. R. Clifford (A'29) chief engineer, Layne and Bowler Pump Corporation, Los Angeles, Calif., has been elected treasurer of the Engineers' Club of Los Angeles for the year 1933–34.

H. V. Schreiber (A'03, M'13) Capital Traction Company, Washington, D. C., has been elected secretary of the electric railway section of the National Safety Council.

Obituary

Calvert Townley (A'01, M'07, F'12, and past-president) a former vice-president of the Westinghouse Electric and Manufacturing Company, died November 27, 1933, at New York, N. Y. He was born October 18, 1864, at Cincinnati, Ohio. In 1886 he graduated from the Sheffield Scientific School of Yale University with the degree of bachelor of philosophy, receiving the degree of M.E. in 1888. In 1887 he was with the Brush Electric Light Company in Cincinnati. Between 1887 and 1904 he spent the first of 2 periods with the Westinghouse Electric and Manufacturing Company. He was erecting engineer for the company in 1887, and for the following year was in charge of the design of electric lighting distribution systems. From 1888 to 1895 he was engaged in commercial and executive work for the Westinghouse company in various capacities. From 1895 to 1897 and from 1898 to 1900 he was manager of the Boston, Mass., office of the company. From 1901 to 1904 he was general agent for the Westinghouse company with headquarters in New York, N. Y., in charge of relations with large transportation interests there. In 1904, he became acting fourth vice-president of the New York, New Haven, and Hartford Railroad Company in charge of all electrical work of that system whether transportation, transmission, lighting, or power. At this time he also was assistant to the president of the Consolidated Railway Company in charge of the engineering, construction, and operation of that company's electrical division. In 1905 he became first vice-president of the Consolidated Railway Company and consulting engineer for the N. Y., N. H. & H. Railroad Company on their electrical work. During this period he also was in charge of the electrical engineering of transportation, power, and lighting systems in a number of cities. During this period he was vice-president of the Connecticut Company and about 30 subsidiaries, in charge of trolley, light, gas, and water companies owned by the New Haven railroad. In 1911 he returned to the Westinghouse company as vice-president and assistant to the president, with headquarters in New York. He held these positions until his retirement in 1931. He was also vice-president of the Westinghouse Electric International Company, trustee of the Westinghouse Company, and director in the Westinghouse X Ray Company, and the Regina Corporation. He was president and director of the Servap Company. During the War he superintended the erection of a turbine factory near Philadelphia, the output being very largely used for the federal government merchant and naval vessel. Mr. Townley served the Institute as a member of the following committees: Edison Medal 1918–23, executive 1919–22, and public policy 1914–19, 1921–22, 1923–24. At the time of his death he was a member of the Coördination Committee of Engineering Societies. He had been a member of the Pan-American engineering committee, the John Fritz Medal board of award, and the American Engineering Council, of which he had served as chairman of the organizing conference. He had served as vice-president and trustee of the United Engineering Trustees, Inc., and on the board of The Engineering Foundation. He was a delegate and member of the executive committee of the engineering delegation to the World Power Conference in London in 1924, and a member of the American Industrial Mission to Mexico that same year. He was elected manager of the Institute in 1905, vice-president in 1908 and president in 1919. He has contributed many papers to technical societies, mostly dealing with power and traction problems. He was a former president of the Yale Engineering Association and a member of the following clubs: Engineers, Yale, Railroad, Bankers (all of New York), New Haven Country, Graduate (New Haven) and Cragston Yacht and Country.

Kempster Blanchard Miller (A'98, M'07, F'27) consulting engineer, Pasadena, Calif., died November 22, 1933. He was born August 14, 1870, at Boston, Mass. In 1893 he graduated from Cornell University, Ithaca, N. Y., with the degree of mechanical engineer. He then entered the U. S. patent office as assistant examiner and was given charge of inventions relating to telephony, continuing at this work until 1896. He then entered the employ of the Westinghouse Electric and Manufacturing Company at East Pittsburgh, Pa. A few months later he became chief electrician of the Western Telephone Construction Company, Chicago, Ill., his particular duties being the designing and superintending of the manufacture of telephone apparatus. In 1898 he engaged in writing text books on telephony and telegraphy and doing other editorial work for the International Correspondence Schools at Scranton, Pa. In 1899 he became electrical engineer of the Kellogg Switchboard and Supply Company in Chicago, Ill., and shortly thereafter took charge of the experimental shop and laboratory of this company. At a somewhat later date he took complete charge of the entire manufacturing plant. During this period he was actively engaged in engineering work on design of new apparatus and systems and made a number of inventions which went into wide commercial use. In 1904 he began practice as a consulting engineer in partnership with S. G. McMeen. He continued in this position until 1919, when he became general manager for the North Electric Manufacturing Company, developing and making machine switching telephone exchange equipments. Since 1922 he has been consulting engineer, specializing in telephony. In connection with his work on telephone systems, he has served as arbitrator and expert witness in telephone litigation. In addition to his telephone work he has designed and constructed hydroelectric plants in Oregon and southern California. He had served as director and general manager in several manufacturing companies and public utility companies. He was the author of "American Telephone Practice," a work of about 900 pages published in 1904, and considered a standard treatise on telephony. He also was the author of numerous technical papers. He had served the Institute as a

member of the safety codes committee 1914–15, and committee on telegraphy and telephony 1914–19. He was for some years chairman of the Institute's Chicago Section. He was a past first vice-president of the Western Society of Engineers (Chicago).

JOHN FRANKLIN STEVENS (A'94, M'01, F'13, member for life and past vice-president) consulting engineer, Philadelphia, Pa., died December 11, 1933. He was born in Philadelphia, Pa., in 1870. In 1890 he graduated from the University of Pennsylvania with the degree of bachelor of arts, and in 1891 received the degree of M.E. from the same institution on the completion of graduate work in mechanical and electrical engineering. From 1891 to 1893 he was mechanical and electrical engineer for the firm of John F. Stevens and Sons of Philadelphia, manufacturers of industrial iron and steel. From 1893 and 1895 he was in charge of accounting and factory production for the LaRoche Electric Works, serving as secretary and treasurer. In 1894 he undertook the manufacture of measuring instruments as a partner in the Keystone Electrical Instrument Company, becoming owner, designer, chief engineer, and general executive of this firm. He maintained this connection until 1911. Concurrently he was vice-president and consulting engineer for the American Electric Heater Company from 1898 to 1900, and from 1902 to 1913 was general executive and member of the firm in charge of finances for Steward and Stevens Iron Works. In 1911 he entered upon his practice as a consulting engineer. During the War he was vice-chairman of the conservation board and district chairman for southeastern Pennsylvania of the power and conservation division of the Federal Fuel Administration. He was a frequent lecturer and contributor to engineering publications, and was the holder of 6 patents on electrical measuring instruments. He served the Institute as manager 1912–13, and vice-president 1915–17. He also was a member of the following A.I.E.E. committees: Edison Medal 1913–18, executive 1915–17, finance 1913–17 (chairman 1913–17), headquarters 1916–17, membership 1918–19, sections 1912–14, and standards 1911–13. He was a former president of the Engineers' Club of Philadelphia and was a member of the American Electrochemical Society. He was also a member of the Engineers' Club of New York, and the Union League and University Clubs of Philadelphia.

T. HERBERT CLEGG (A'16, M'21) an electrical engineer for the Tennessee Valley Authority, Knoxville, Tenn., and an assistant to Llewellyn Evans, electrical engineer in charge of operations at Muscle Shoals, died November 20, 1933. He was born at Primos, Delaware County, Pa., in 1887. In 1909 he completed the course in surveying at Temple University, Philadelphia, and in 1911 completed the course in hydraulic engineering conducted by the Scranton Correspondence School. In 1914 he completed the evening course in electrical engineering at Drexel Institute of Philadelphia. In 1906 he served as a switchboard operator for the Philadelphia Rapid Transit Company. From 1910 to 1917 he was engineering assistant to the assistant electrical engineer of the Philadelphia Rapid Transit Company, being engaged on analysis of power plant statistics and economics and assisting in the supervision of power system operation. In 1918 he became superintendent of a steam generating plant of the Atlantic Refining Company of Philadelphia, later in the same year becoming superintendent of power for the Northern Virginia Power Company, Winchester, Va. In 1919 he became assistant to O. M. Rau, power specialist, engaged on investigation work in connection with power plants. He later became special engineer for the Philadelphia Rapid Transit Company and the International Railway Company (Buffalo, N. Y.), retaining these positions for several years. Mr. Clegg was a member of The American Society of Mechanical Engineers, the American Electric Railway Association, and the former National Electric Light Association. He has served the Engineers' Club of Philadelphia as director and as chairman of the finance committee.

THORBURN REID (A'90, M'98 and member for life) a retired consulting electrical engineer, died November 10, 1933. He was born May 1, 1864, at London, England. He was a graduate of Hampden-Sydney College, Va., and studied at the University of Virginia and Stevens Institute. During his early career he was for a while professor of mechanical engineering at South Carolina State University. He was then in the testing department of the United States Electric Manufacturing Company, Newark, N. J., and was assistant in the laboratory of William Stanley, Jr., for a few months. After a few months as consulting electrical engineer in New York, N. Y., he spent one year with the Edison General Electric Company at Schenectady. He then spent 6 years with the General Electric Company at Lynn, Mass., and in Schenectady, followed by several months with the British Thomson Houston Company in London, England. In 1897 he undertook private practice as a consulting electrical engineer in New York and was active in this capacity for many years until his retirement.

VEATOR DAVID MENDENHALL (A'31) designing engineer, General Electric Company, Philadelphia, Pa., died October 31, 1933. He was born at Yadkin College, N. C., in 1892. He studied at Moravian College for 2 years. From 1913 to 1917 he was marine engineer in the U. S. Navy, and for 16 months of this period was in responsible charge of operation of all power equipment of a 10,000-ton vessel. From 1919 to 1922 he was designer for the R. J. Reynolds Tobacco Company, being engaged on the detailed design of automatic machinery. From 1922 to 1924 he was designer for the General Electric Company, engaged on detail design of electrical switching equipment. In 1924 he became designing engineer of the General Electric Company, and being responsible for the design of considerable outdoor switching equipment.

WILLIAM FENNER LAMME (A'04) who had been representative of electrical machinery manufacturers and who maintained offices at San Francisco, Calif., died September 16, 1933.

Membership

Recommended for Transfer

The board of examiners, at its meeting of December 20, 1933, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Brooks, Josiah A., asst. E.E., N. Y. & Queens Elec. Lt. & Pwr. Co., Flushing, N. Y.
Fleming, Arthur P., director of research and education, Metropolitan Vickers Elec. Co. Ltd., Manchester, England.
Hickernell, Latimer F., chief engr., Anaconda Wire & Cable Co., Hastings-on-Hudson, N. Y.
McCurdy, Ralph G., noise prevention engr., Am. Tel. & Tel. Co., New York.

To Grade of Member

Albert, John C., asst. E.E. in charge of testing labs., Bureau of Pwr. & Lt., Los Angeles, Calif.
Beveridge, Harold H., chief research engr., RCA Communications, Inc., New York.
Blume, Louis F., E.E., Gen. Elec. Co., Pittsfield, Mass.
Borden, Douglas C., managing engr., Elec. Constr. Co., Toronto, Ont. Can.
Canfield, Charles E., mech. engr., Gen. Elec. Co., Pittsfield, Mass.
Danner, Ronald F., gen. supt., Okla. Gas & Elec. Co., Oklahoma City, Okla.
Darrow, Leo H., engr. of bldgs. and equip., N. J. Bell Tel. Co., Newark, N. J.
Findley, Paul B., managing editor "Bell Laboratories Record," New York.
Green, Stanley, secy. and chief engr., Duncan Elec. Mfg. Co., Lafayette, Ind.
Hutton, William S., E.E., Canadian Fire Underwriters Association, Toronto, Ont. Can.
Jennings, Earl B., foreign wire relations engr., Southwestern Bell Tel. Co., Oklahoma City, Okla.
Little, John J., gen. mgr., Northern B. C. Pwr. Co., Ltd., Prince Rupert, B. C. Can.
Plumb, Harold J., transmission line supervisor, Consumers Pwr. Co., Jackson, Mich.
Ports, Earl George, chief engr., Federal Telegraph Co., Newark, N. J.
Putnam, Russell C., asst. prof. of E.E., Case Sch. of Ap. Sci., Cleveland, O.
Siskind, Charles S., instructor, Purdue Univ., Lafayette, Ind.
Sultzer, Morton, protection devpmt. serv. engr., Am. Tel. & Tel. Co., New York.
Taylor, Hamilton D., designing engr., Gen. Elec. Co., West Lynn, Mass.
Webb, Earl B., bldg. and equip. engr., Indiana Bell Tel. Co., Indianapolis, Ind.
Wilson, Stanley M., gen. supt. of equip., Western Elec. Co., Kearny, N. J.

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before January 31, 1934, or March 31, 1934, if the applicant resides outside of the United States or Canada.

Armstrong, C. J., Oklahoma Gas & Elec. Co., Drumright, Okla.
Avery, F. (Member), Southern Bell Tel. & Tel. Co., Atlanta, Ga.
Bain, D. S., Michigan Alkali Co., Wyandotte.
Brown, J. J., 253 Jamesville Ave., Syracuse, N. Y.
Brown, P. F., Indiana Bell Tel. Co., Indianapolis.
Burnett, C. E., RCA Radiotron Co., Inc., Harrison, N. J.
Chambers, H. J., Toronto Hydro-Elec. System, Toronto, Ont., Can.

Cropper, R. E., Canadian Nat. Carbon Co. Ltd., Toronto, Ont., Can.
Danielsson, C. E. J., Empresa de Telefonos Ericsson, S. A. Mexico, D. F., Mexico.
Davis, J. M., Indiana Bell Tel. Co., Indianapolis.
Diehl, A. C. V., Brooklyn (N. Y.) Edison Co., Inc.
Durand, A. G. (Member), New York (N. Y.) Edison Co., Inc.
Ericsson, E. R., Empresa de Telefonos Ericsson, S. A. Mexico, D. F., Mexico.
Foster, S. P., c/o Jenson Bowen & Farrell, Ann Arbor, Mich.
Freedman, E. A., 787 Lexington Ave., New York City.
Fries, P., Jr., 374 E. 141 St., New York City.
Hammond, E. M., Bell Telephone Co. of Pa., Phila.
Hooker, T. (Member), Delaware Pwr. & Lt. Co., Wilmington.
Hull, H. N., Municipal Lt. & Pwr. Plant, Columbus, Ind.
Kiefer, J. F., Delaware Pwr. & Lt. Co., Wilmington.
Kleinau, C. S., So. Calif. Tel. Co., Los Angeles.
Kotraschek, L. C., K. & B. Elec. Equip. Co., Inc., New York City.
LeFever, E. A. (Member), Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Lips, J. G., Louisville Gas & Elec. Co., Louisville, Ky.
Ludwig, A., Western Elec Co., Kearney, N. J.
Marks, A. M., Elec. Dvpmt. Corp., New York City.
McAdam, R. E., 31 Brunswick Ave., Troy, N. Y.
Megeath, S. A., Jr., 110 Seaman Ave., New York City.
Menger, F. B., Gen. Elec. Co., Schenectady, N. Y.
Metzger, L., 581 Columbus Ave., New York City.
Miller, R. F. (Member), Pocono Pines, Pa.
Millermaster, R. A. (Member), Cutler Hammer Inc., Milwaukee, Wis.
Millikan, J. E., 83 N. 20 St., Columbus, Ohio.
Musson, C. E., H. E. Musson & Co., Oklahoma City, Okla.
Pettengill, H. C., 39 E. Westfield Ave., Roselle Park, N. J.
Point, C. L., Virginia Elec. & Pwr. Co., Richmond, Va.
Potter, E. A., Am. Tel. & Tel. Co., New York City.
Prosser, W. H., The Lincoln Elec. Co., Cleveland, Ohio.
Ramsey, W. H., Oscar D. & Herbert V. Dike, New York City.
Ranney, H. W., Buffalo Tech. High School, Buffalo, N. Y.
Settles, O. P., Mountain States Tel. & Tel. Co., Denver, Colo.
School, R. A., Pub. Serv. Co. of Indiana, Connersville.
Shepherd, J. O'D., Southern Bell Tel. & Tel. Co., Atlanta, Ga.
Simpson, C. N. (Member), Gatineau Pwr. Co., Ottawa, Ont., Can.
Stanley, Foster L., Indiana Bell Tel. Co., Indianapolis.
Thomas, E. J., Gen. Elec. Co., Ft. Wayne, Ind.
Thorn, C. S. (Member), Birmingham Elec. Co., Birmingham, Ala.
Thrush, G. H., Jr., Elec. Stor. Batt. Co., Pittsburgh, Pa.
Wallsten, S. E., Empresa de Telefonos Ericsson, S. A. Mexico, D. F., Mexico.
Wantland, S. S., Oklahoma Gas & Elec. Co., Oklahoma City.
Warren, W. J., Univ. of Ill., Urbana.
Wilhelm, H. A., Square D Co., Milwaukee, Wis.

52 Domestic

Foreign

Basu, M., E. Marelli & Co., Milano, Italy.
Bhavnani, K. J., Messrs. Callender's Cable & Constr. Co., Ltd., Bombay, India.
Bongale, R. M., Tata Hydro Elec. Pwr. Supply Co., Ltd., Parel, Bombay, India.
Gates, B. G., The British Electrical & Allied Industries Research Assn., London, Eng.
Ghosh, K. C., E. Marelli & Co., Milano, Italy.
Hayes, W. F. (Member), Luton Corporation Electricity Sta., Luton, Bedfordshire, Eng.
Mill, A., Aces Elec. Ltd., Wellington, New Zealand.
Mortlock, J. R., The British Thomson Houston Co., Ltd., London, Eng.
Preston, G. W. (Member), Copper Devpmt. Assoc., London, S. W. 1, Eng.
Roberts, E. L., Metropolitan-Vickers Elec. Co., Ltd., Manchester, Eng.
Winterbottom, J. G., Lancashire Cotton Corp., Ltd., Manchester, Eng.

11 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Black, H. M., 425 South Ave., Wilkinsburg, Pa.
Blackhall, Harold J., Postlagernd, Essen, Germany.
Bolcourt, Frank R., Rockwell City, Iowa.
Bugnion, Frank E., 14 Clinton St., Cambridge, Mass.
Code, F. L., 6061 Trafalgar St., Vancouver, B. C., Can.
Dean, George H., Corrie, Old Shoreham Road, Shoreham-by-Sea, Eng.
Ghamat, S. B., School of Engg. of Mil., Milwaukee, Wis.
Hamby, H. M., 708 F St., N.E., Washington, D. C.
Hirsch, Chas. J., Level Club Hotel, 253 W. 73rd St., New York City.
How, John H., 42 Wai Oi Road East, Canton, China.
Kahale, N. A., Box 434, W. Lafayette, Ind.
Lober, Charles, K. C. P. & L. Co., 1330 Baltimore Ave., Kansas City, Mo.
Shitrin, Leonard I., c/o Tanenbaum, 12 Pinehurst Ave., New York City.
Soskin, Samuel B., 1225 S. Calif. Ave., Chicago, Ill.
Strommer, E. N., 7229 Penn Ave., Pittsburgh, Pa.
Talbot, H. L., 55 Pine Ave., E., Montreal, Que., Can.
Weber, George A., 537 Addison Ave., Palo Alto, Calif.

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, during November are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface or text of the book in question.

INDUSTRIAL HEAT TRANSFER. By A. Schack, trans. from the German by H. Goldschmidt and E. P. Partridge. N. Y., John Wiley & Sons, 1933. 371 p., illus., 9x6 in., cloth, $5.00. Supplies simple formulas or graphs which will enable the engineer to deal with problems of furnaces and heat exchangers. Based upon the author's 7-yr. experience as investigator of heat-transfer problems. Converted all equations to English units. A useful bibliography is included.

PROCEDURE HANDBOOK of ARC WELDING DESIGN and PRACTICE. By Lincoln Elec. Co. Cleveland, Ohio, Lincoln Elec. Co., 1933. 434 p., illus., 9x6 in., cloth, $1.50. *Contents:* Welding methods and equipment; technique of welding; procedures, speeds, and costs for welding mild steel; weldability of metals; designing for arc-welded and construction of machinery; designing for arc-welded structures; and typical applications of arc welding in manufacturing, construction and maintenance.

STAHLHOCHBAUTEN, ihre Theorie, Berechnung und bauliche Gestaltung, vol. 2. By F. Bleich. Berlin, J. Springer, 1933. 934 p., illus., 11x8 in., cloth, 46.50 rm. The 3 main sections of this volume treat of mill buildings, roofs, and masts and towers for electric lines and radio. Fifty pages are given to masts and towers. Gives an excellent view of German practice in the design of steel structures.

STEAM and GAS ENGINEERING. By T. E. Butterfield, B. H. Jennings, and A. W. Luce. 2 ed. N. Y., D. Van Nostrand Co., 1933. 488 p., illus., 9x6 in., cloth, $4.50. An introduction to the development of heat and power from fuels, which emphasizes steam equipment somewhat more than internal-combustion engines. The material is based on thermodynamics, the construction, and operation of a variety of apparatus being used as a background. The new edition has been thoroughly revised.

The UNIVERSE of LIGHT. By Sir William Bragg. N. Y., Macmillan Co., 1933. 283 p., illus., 9x6 in., cloth, $3.50. For the general reader interested in the new physics. Taking as the thread of his story the old rivalry between the corpuscular and wave theories of light, Sir William writes of the early researches in light from which present physical concepts have arisen. The work is a masterly popular account of the evolution of physical science.

VOCATIONAL GUIDANCE IN ENGINEERING LINES. Edit. by Am. Assn. of Engrs.; Editorial Committee—J. A. L. Waddell, *Chairman*, Frank W. Skinner, Harold E. Wessman. Pub. 1933 by Mack Printing Co., Easton, Pa. 521 p., illus., 9x6 in., cloth, $2.50. The aim of this book is stated to be "a simple, practical yardstick by which those young men who aspire to be engineers can measure their natural fitness for the tasks imposed by the profession, their ability to content themselves with its probable rewards, and the intensity of their own desires to join the ranks of the Sons of Martha." Some 60 chapters, each by a well known practitioner in some important branch or specialty of engineering, give an unusually broad picture of the whole field. In addition, such general subjects as engineering ethics, idealism in engineering, vocational guidance, and aptitude tests, are discussed.

HOW to do PUBLICITY. By Raymond C. Mayer. N. Y. and Lond., Harper & Bros., 1933. 258 p., 9x6 in. cloth, $3.00. Discussion of practical methods of conducting publicity including newspaper, magazine, trade paper, radio, etc., as well as publicity found useful by corporations, trade associations, charitable, scientific and professional societies. (A.I.E.E.)

AUTOMOBILE ELECTRICAL EQUIPMENT. By A. P. Young and L. Griffiths. Lond., Iliffe & Sons, Ltd., 1933. 336 p., illus., 9x6 in., cloth, 18s. Covers the electrical equipment used with the internal-combustion engine on land and sea, and in the air. The principal types of British machines are described and illustrated.

BOOK of STAINLESS STEELS, Corrosion Resisting and Heat Resisting Chromium Alloys. Ed. by E. E. Thum. Cleveland, Ohio, Am. Soc. for Steel Treating, 1933. 631 p., illus. 9x6 in., cloth, $5.00. The manufacture, properties, and uses of corrosion and heat resistant chromium alloys are discussed. The properties of the typical alloys are presented, and the requirements of a large number of consuming industries are explained. A useful classified list of trade names is included.

ELECTRICAL CIRCUITS and MACHINERY. Vol. 2, ALTERNATING CURRENTS. By J. H. Morecroft and F. W. Hehre. 3 ed. N. Y., John Wiley & Sons, 1933. 582 p., illus., 9x6 in., cloth, $4.50. A presentation of the fundamental principles of alternating currents, for use in elementary undergraduate courses by any students except those specializing in electrical machinery. In this edition new material has been added and the book thoroughly revised.

ELECTRICAL ENGINEERING PRACTICE. a Practical Treatise for Electrical, Civil and Mechanical Engineers, v. 3. By J. W. Meares and R. E. Neale. 4 ed. Lond., Chapman & Hall, 1933. 920 p., illus., 9x6 in., cloth, 30s. Designed to provide students and engineers with a survey of the whole field of electrical engineering. The 3 volumes cover the generation, distribution, and uses of electricity in a practical way. In volume 3 electrical motors and their control, and the applications of electrical energy in industrial operations and processes, in traction and marine propulsion, and in agriculture are fully described. Specifications, testing and rules and regulations are also considered.

ELEKTRISCHE SCHALTVORGÄNGE und verwandte Störungserscheinungen in Starkstromanlagen. By R. Rüdenberg. 3 ed. Berlin, Julius Springer, 1933. 634 p., illus., 10x7 in., cloth, 42 rm. A detailed presentation of the transient phenomena that occur in electric installations as a result of switching, short circuits, and other break-downs. The third edition is revised and enlarged.

Engineering Societies Library

29 West 39th Street, New York, N.Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written applications, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

The Louis Allis Co. Appoints Charles F. Norton.—According to a recent announcement, Charles F. Norton, formerly vice-president and general manager of the Howell Electric Motors Co., who recently became associated with The Louis Allis Co. of Milwaukee, has been appointed general sales director of the latter organization.

Canadian Bristol Co. Organized.—The Bristol Company, Waterbury, Conn., announces that in order to serve the Canadian market still better and to expand and consolidate its present Canadian service laboratory of 12 years' standing so as to include sales, service and manufacturing, a separate company, The Bristol Company of Canada, Ltd., has been incorporated. Factory and general headquarters will be located at 64 Princess St., Toronto, Ont., where Bristol recording, indicating and control instruments will be made. J. S. Mayberry, for 10 years with the parent company, has been appointed manager.

New Insulation Tester.—The Sound Engineering Corp., 416 Leavitt St., Chicago, announces a new instrument for testing the dielectric strength of sheet materials, such as paper, rubber, mica, etc. Means are also provided for testing complete units such as transformers, motors, insulated wire, etc. The testing equipment is completely self-contained in an all metal case, measuring 16 by $18^1/_2$ by $8^1/_4$ inches and weighes 65 pounds. Among the features emphasized by the manufacturer are absolute safety to the operator, accuracy, smooth and convenient control of voltage from 200 to 10,000 volts, and definite pressure and even distribution of the electrical field over the test sample. A Weston vane type meter using a 10 milliampere field coil is employed in conjunction with 2 sets of resistors to measure the voltage across the test sample. The meter is calibrated in 3 ranges, 0–1,000, 0–5,000, and 0–10,000 volts. The secondary circuit is so designed that the instant a breakdown in the test sample occurs the voltage indicated on the meter drops to approximately zero, thus providing a direct, accurate means for reading the actual potential at insulation failure.

Westinghouse Reports Central Station Trends in 1933.—In its annual engineering review for 1933 the Westinghouse Electric & Mfg. Co. notes that the 165,000 kw unit for the Richmond Station of the Philadelphia Electric Co. is now under construction, comprising a tandem compound turbine with a single generator of 183,334 kva capacity. In the hydroelectric field the station of the New Kanawha Power Company, consisting of 4 units of 30,000 kva each, was the only one of any importance to be built. During the year the Westinghouse Company received an order for 2 of the Boulder Dam generators each of 82,500 kva.

In the transmission and distribution field, continued progress is reported in the study of lightning phenomena in the laboratory and in field experiments. These studies indicate that apparatus may be designed with proper protective measures to withstand surges actually encountered in service. This, however, involves an increase in cost of the equipment and there is, therefore, an economic limit to how far the improvement can be carried. An example of built-in protection is a surge-proof distribution transformer.

During the year a number of voltage regulators for feeders of the higher voltages were sold, operating on the principle of the tap-changing transformer. These regulators are intended to supplement the line of induction regulators. Considerable advance has been made in high voltage fuses. Deion power fuses of 7,500, 15,000, and 23,000 volts were developed, with interrupting ability of 325,000, 500,000, and 600,000 kva, respectively. In these fuses a tube lined with boric acid provides the source of deionization of the arc stream created by the rupture of the fuse element.

A great improvement has been made in the current type of telemeter, in which a small direct current proportional to the quantity to be measured is transmitted to distant receivers. The earlier forms were inherently sluggish in response due to the necessarily large devices used to modify the value of the transmitted current. These could not be speeded up without introducing hunting.

G-E Progress Review.—Among the developments in the General Electric Company's review of engineering progress during 1933, the modernization of industrial plants is reported as an important factor in the developmental work of the year, and improvements were made in the design, construction, or operating characteristics of practically every class of apparatus for industrial service. A new element was added last year by an increased modernization demand for central-station switching and distribution equipment, stimulated by the rising curve of kilowatt-hour consumption. The modernization in this case included the replacement of windings of transformers to provide higher ratings and improved protection, and the replacement of parts of oil switches by oil-blast mechanisms to increase their rupturing capacity—in some instances as much as 300 per cent.

The maximum rating of waterwheel generators was increased to 82,500 kva for two machines of this type for the Boulder Dam development; previous maximum rating being those of the 77,500 kva units installed at Dnieprostroy, Russia.

Unusual activity prevailed in the development of motors and a new type of variable-speed alternating-current machine, utilizing Thyratron tubes, was built and tested. A supersynchronous motor of record capacity was constructed and additional ratings were provided in machines intended for operation in gaseous atmospheres or other hazardous conditions. A complete redesign of fractional-horsepower motors was effected which established common mounting dimensions for all types of these motors of a given output rating. For many applications, they were provided with ingenious elastic supports to insure quiet operation.

Transformers embodying revolutionary changes in design were made possible by the adoption of Pyranol, the new non-inflammable synthetic insulating and cooling medium for use in place of the conventional transformer oil. A reduction of about one-half was secured in the physical dimensions of these transformers. Pyranol was used also as a treating medium for capacitors, thereby effecting a reduction in volume of about one-third as compared with previous designs.

Research work was continued actively through the year. Lightning investigations were made both in the field and the laboratory to improve the continuity of electric service, and a 2,000,000-volt lightning generator was utilized for the commercial impulse testing of transformers. The chemical and physical characteristics of magnetic sheet steels were improved, and permanent magnet alloys of greatly increased strength were developed which made it possible to obtain new information in regard to the nature of magnetic phenomena.

Trade Literature

Motors.—Catalog 33, 24 pp. Describes Marble-Card motors, generators, motor generator sets and rotary convertors. Marble-Card Electric Co., Gladstone, Mich.

CO_2 Meters.—Folder. Describes CO_2 recording meters for measuring combustion efficiency. The Brown Instrument Co., Wayne Ave., Philadelphia, Pa.

Pyrometers.—Bulletin. Describes indicating, thermoelectric type pyrometers for panel or wall mounting, portable use, and multiple point installations. Mishawaka Industrial Instrument Mfg. Laboratory, Mishawaka, Ind.

Diesel Generating Sets.—Bulletin 812-A, 4 pp. Describes Buda, full Diesel generating sets ranging in size from 10 to 90 kw. The high speed, light weight Diesel engine is manufactured under a German license. The Buda Co., Harvey, Ill.

Blowers.—Catalog 833, 40 pp. Describes various types of blowers; illustrates applications and includes comprehensive tables giving detailed information. Ilg Electric Ventilating Co., 2850 N. Crawford Ave., Chicago, Ill.

Capacitors.—Bulletin 710, 16 pp. Describes box type and rack type capacitors for power factor correction. Contains complete details of construction as well as dimensions and weights, also tables for determining the proper size capacitor required for correction of low power factor conditions in practically any plant. Ideal Electric & Mfg. Co., Mansfield, O.

Published Monthly by

American Institute of Electrical Engineers

(Founded May 13, 1884)

Electrical Engineering

Registered U. S. Patent Office

February 1934
Volume 53
No. 2

The Official Monthly Journal and Transactions of the A.I.E.E.

J. B. Whitehead, President
H. H. Henline, National Secretary

Publication Committee
E. B. Meyer, Chairman
R. N. Conwell — H. H. Henline
W. S. Gorsuch — H. R. Woodrow

Publication Staff
G. Ross Henninger, Editor
C. A. Graef, Advertising Manager

PUBLICATION OFFICE, 20th and Northampton Streets, Easton, Pa.

EDITORIAL AND ADVERTISING OFFICES, 33 West 39th Street, New York, N. Y.

ENTERED as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918.

SUBSCRIPTION RATES—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii and the Philippine Islands, Central America, South America, Haiti, Spain and Spanish Colonies; $13 to Canada; $14 to all other countries. Single copy $1.50.

CHANGE OF ADDRESS—requests must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered due to incorrect address cannot be replaced without charge. Be sure to specify both old and new addresses and any change in business affiliation.

ADVERTISING COPY—changes must be received by the fifteenth of the month to be effective for the issue of the month succeeding.

STATEMENTS and opinions given in articles appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters.

REPUBLICATION from "Electrical Engineering" of any Institute article or paper (unless otherwise specifically stated) is hereby authorized provided full credit be given.

COPYRIGHT 1934 by the American Institute of Electrical Engineers.

ELECTRICAL ENGINEERING is indexed in Industrial Arts Index and Engineering Index.

Printed in the United States of America. Number of copies this issue—

17,500

This Month—

Front Cover

New all-metal TWA airliner takes to the skies. For further description of this plane see p. 349.

Special Educational Series—3

Electric Discharges in Gases—Ionization and Excitation 239
By LEWI TONKS

Special Articles

External Impedance Vs. Short-Circuit Currents 252
By B. L. ROBERTSON and T. A. ROGERS

Measurement of Wetting of Dielectrics . 255
By D. A. McLEAN and G. T. KOHMAN

Locating Grounds by Distribution Ratio Method 258
By W. F. DUNKLE and J. S. DeSHAZO

Protective Relays on Pa. Locomotives . 261
By BENJAMIN LUTHER

Corona Loss Vs. Atmospheric Conditions 272
By L. HEGY and G. W. DUNLAP

Energy Consumption of Multiple Unit Cars 280
By F. A. COMPTON, JR.

Two Applications of Nonlinear Circuits 293
By T. M. AUSTIN and F. W. COOPER

A New High Speed Air Circuit Breaker 322
By A. O. KEEP

A.I.E.E. Papers

The Life of Impregnated Paper 244
By J. B. WHITEHEAD

Port Washington Power Plant Design . 264
By G. G. POST

Iron Shielding for Telephone Cables . . 274
By H. R. MOORE

Better Instrument Springs 282
By ROBERT W. CARSON

Stray Load Loss Test on Induction Machines 286
By THEODORE H. MORGAN and PAUL M. NARBUTOVSKIH

A Unique Oscillograph 290
By K. A. OPLINGER

Electrical Figures on Plates in Air . . . 300
By J. GIBSON PLEASANTS

Effect of Oil Pressure on Insulation Strength 308
By JOHN A. SCOTT

Theory of Primary Networks—Part I . . 310
By F. M. STARR

Silicon Steel With A-C and D-C Excitation 318
By R. F. EDGAR

Energy Consumption on Street Railways 326
By BENJAMIN F. THOMAS, JR.

Decrement Curves for Power Systems . . 331
By CHARLES F. DALZIEL

Reactance and Stray Losses of Power Transformers 338
By H. L. COLE

Irregular Windings in Wound Rotor Induction Motors 342
By R. E. HELLMUND and C. G. VEINOTT

Transformer Reactance and Losses With Nonuniform Windings 346
By H. O. STEPHENS

News of the Institute and Related Activities 350

A Science Series for Engineers

NOW appearing month-by-month in ELECTRICAL ENGINEERING is a series of articles written by some of the foremost authorities in several of the more important and rapidly advancing fields of science that are of special significance to electrical engineers. The original idea was suggested by Prof. Vladimir Karapetoff of Cornell University who urged the preparation and publication of "a series of short articles in ELECTRICAL ENGINEERING for the guidance of ambitious young engineers who wish to prepare themselves for the newer problems (to be met) after the recovery from the present depression." Taken under advisement by the A.I.E.E. committee on education this suggestion was developed through the active coöperation of many interested parties. The result of more than a year of thoughtful planning, development, and coördination, and presenting the generous contributions of some of the highest recognized authorities, this series of articles aptly has been called a post-college course in contemporary science.

The first article in the series was published in November 1933 issue of ELECTRICAL ENGINEERING; the second in the January 1934 issue; the third begins on the facing page. Each of the authors generously has promised his full coöperation in the preparation of subsequent manuscripts which will be fully up-to-date as published. The complete program is listed in the following tabulation, which includes the title of the paper and the actual or scheduled publication date, followed by a short biographical sketch of the author:

Theory of Probability — **Nov. 1933**

ALBERT ARNOLD BENNETT—Mathematician. Professor of mathematics at Brown Univ., Providence, R. I., since 1927; born Yokohoma, Japan, June 2, 1888; A.B. Brown Univ. 1910, A.M. and M.S. 1911; Ph.D. Princeton 1914; instructor in mathematics at Princeton 1914–16; adjunct professor Univ. of Texas 1916–18, associate professor 1918–25; professor and head of the department Lehigh Univ., 1925–27. Mathematician and dynamic expert ordnance dept., U.S. Army 1919–22. Member of Am. Math. Soc. and Math. Assoc. of Am.

Fundamental Properties of the Electron — **Jan. 1934**

ALAN TOWER WATERMAN—Physicist. Associate professor of physics at Yale Univ., New Haven, Conn., since 1930; born Cornwall-on-Hudson, N. Y., June 4, 1892; A.B. Princeton 1913; A.M. 1914, Ph.D. 1916; instructor in physics at Cincinnati 1916–17; lieutenant, meteorlogical section U. S. A. Signal Corps, 1917–19; instructor in physics Yale Univ. 1919–23; associate professor 1923–30; fellow Am. Phys. Soc.

Electric Discharges in Gases; Ionization and Excitation — **Feb. 1934**

LEWI TONKS—Physicist. Research physicist, General Elec. Co., Schenectady, N. Y.; born New York, N. Y., Dec. 13, 1897; B.S. Columbia Univ. 1917, assistant in physics 1915–18; special government expert New London, Conn. 1918–19; Ph.D. Columbia Univ. 1924; member Am. Phys. Soc.

Electric Discharges in Gases; Scattering Drift and Diffusion of Ions — **March 1934**

KARL KELCHNER DARROW—Physicist. Member, technical staff, Bell Tel. Labs. Inc. since 1925; born Chicago, Ill., Nov. 26, 1891; B.S. Univ. of Chicago 1911, Ph.D. 1917; physicist Western Elec. Company 1917–24; summertime professor Stanford Univ. 1929, Univ. of Chicago 1931, Columbia Univ. 1932; member of Am. Phys. Soc., Optical Soc. of Am., Physik. Gesell., Soc. de Physique.

Electric Discharges in Gases; Arcs and Glows — **April 1934**

JOSEPH SLEPIAN—Physicist, Electrical Engineer. Consulting research engineer Westinghouse Elec. and Mfg. Co., since 1916; born Boston, Mass., Feb. 11, 1891; A.B. Harvard 1911, A.M. 1912, Ph.D. 1913; instructor Cornell Univ. 1914–15; Fellow A.I.E.E.

RURIC COIN MASON—Co-author with Doctor Slepian. Since 1924 with Westinghouse Elec. and Mfg. Co.; born Bentonville, Ark., Sept. 6, 1903; B.S. Univ. of Ark. 1924; Associate A.I.E.E.

Structure of Atoms and Molecules; Electronic Theory of Valence — **May 1934**

MAURICE LOYAL HUGGINS—Chemist. Associate, dept. of chemistry, The Johns Hopkins Univ.; born Berkeley, Calif., Sept. 19, 1897; A.B., B.S. Univ. of Calif. 1919, M.S. 1920, Ph.D. 1922; instructor in chemistry Stanford Univ. 1925–26, assistant professor 1926–33; member Am. Chem. Soc., fellow Am. Phys. Soc.

Thermionics — **July 1934**

SAUL DUSHMAN—Physical Chemist. Assistant director General Elec. research laboratory since 1928; born Rostov, Russia, July 12, 1883; A.B. Univ. of Toronto 1904, demonstrator in electrochemistry 1904–09, lecturer 1909–12, Ph.D. 1912; with the Gen. Elec. research lab. since 1912; member Am. Phys. Soc., Am. Chem. Soc., Optical Soc. of Am., associate A.I.E.E., naturalized citizen of the United States since 1917.

Photoelectricity — **Aug. 1934**

ARTHUR LLEWELYN HUGHES—Physicist. Head of the department of physics at Washington (St. Louis) Univ. since 1923; born Liverpool, Eng., December 18, 1893; Oliver Lodge fellow, Liverpool, B.S. 1906, D.Sc. 1912, A.B. Cambridge 1910; assistant demonstrator in physics in Cavendish Lab. (Cambridge), assistant professor of physics at Rice Inst., research professor at the Queens Univ. (Canada) 1919–23; member Am. Phys. Soc.

Recent Theories of Magnetism — **Sept. 1934**

FRANCIS BITTER—Electrical Engineer. Research engineer Westinghouse Elec. and Mfg. Co. since 1930; born Weehauken, N. J., July 22, 1902; A.B. Columbia Univ. 1924, Ph.D. 1928; National Research Council fellow Princeton Univ., and Calif. Inst. of Tech. 1928–30; member Am. Phys. Soc.

Operational Calculus — **Oct. 1934**

MURRAY FRANK GARDNER—Electrical Engineer. Assistant professor, electrical engineering, Mass. Inst. of Tech., since 1929; born Lansing, Mich., Dec. 17, 1897; B.S. Univ. of Mich. 1920, M.S. M. I. T. 1924; electrical engineer, cable works, Am. Steel and Wire Co., Worcester, Mass., 1922–23; instructor in electrical engineering in M. I. T. 1923–29; Associate A.I.E.E.

X Rays — **Nov. 1934**

GEORGE LINDENBERG CLARK—Chemist. Professor of chemistry, Univ. of Ill. since 1928; born Anderson, Ind., Sept. 6, 1892; A.B. DePauw Univ. 1914; M.S. Univ. of Chicago 1914, Ph.D. 1918; instructor in chemistry DePauw 1914–16; professor of physical chemistry, Vanderbilt, 1919–21; National Research Council fellow, Harvard Univ. 1921–24; assistant professor of applied chemical research, Mass. Inst. of Tech. 1924–27; associate professor of chemistry at the Univ. of Ill. 1927–28; member Am. Chem. Soc., fellow Am. Phys. Soc., fellow Royal Soc. of Arts, member Physik. Gesell.

Fundamental Electrical Properties of Mercury Vapor and Monatomic Gases — **Dec. 1934**

ALBERT WALLACE HULL—Physicist. Assistant director General Elec. research lab. since 1928; born Southington, Conn., April 19, 1880; A.B. Yale Univ. 1905, Ph.D. 1909; instructor in physics, Worcester Poly. Inst. 1909–12, assistant professor 1912–14; research physicist for the Gen. Elec. Co. since 1914; D.Sc. Union Col. (Schenectady) 1930; awarded Potts' medal by Franklin Inst. 1923 for work on X ray crystal analysis; Morris Liegmann prize 1930 for work on vacuum tubes; member Am. Phys. Soc.

Mapping of Fields — **Jan. 1935**

ERNST WEBER—Research Engineer. Research professor of electrical engineering at Poly. Inst. of Brooklyn, N. Y., since 1930; born Vienna, Austria, Sept. 6, 1901; Dipl. Ing. 1923 and Dr. of technical science 1927, Poly. Inst. of Vienna; Ph.D. 1925, Univ. of Vienna; research engineer Siemens-Schuckert Werke A.G., Vienna, 1924–29 and Berlin, 1929–30; associate professor Poly. Inst. of Berlin 1929–30; member Vienese Inst. of Elec. Engrs.; Berlin Inst. of Elec. Engrs.; Berlin Soc. for App. Math. and Mech.; Am. Phys. Soc.; Associate A.I.E.E.

Electric Discharges in Gases

Ionization and Excitation

By LEWI TONKS
FELLOW, AM. PHYS. SOC.

General Elec. Co.
Schenectady, N. Y.

ELECTRIC CHARGES free to move in a gas give rise in their wild state to some of nature's most splendid spectacles. Tamed, controlled, and harnessed in new and "unnatural" ways, these same entities have been put to work as part of man's host of inanimate servants. Untamed there are the ionized layers of the atmosphere, which, as the Heaviside Layer, were assumed in the first place to explain long distance radio transmission. There is lightning with its puzzling off-shoot, ball lightning, and there is the aurora borealis. The very air we breathe contains free electricity which has definite physiological effects. Tamed, we have mercury vapor and other similar lamps, mercury arc rectifiers, and certain protective devices against lightning. Only half tamed are the phenomena in circuit breakers of many kinds, commutator sparking, and corona. The widespread occurrence and technical importance of the various manifestations of free electricity in gases are evident.

The treatment of this subject lends itself to division into 3 parts. The first, which the present article will survey, is concerned with the nature of the free charges, how they arise from the normally uncharged atoms and molecules of a gas, and their relation to light radiation. The second division will deal with the laws governing the movement of the free charges through the gas, and the third will discuss known types of discharges in the light of the basic processes which by that time will have been set forth in this series of articles as published in ELECTRICAL ENGINEERING.

In view of the widespread occurrence and the current technical importance of the various manifestations of free electricity in gases, this article appropriately reviews current knowledge concerning the nature of such free charges, how they arise from the normally uncharged atoms and molecules of a gas, and their relation to light radiation. This is the third in a series of special articles developed under the sponsorship of the A.I.E.E. committee on education, and the first of three that will deal with the major divisions of the general subject of electric discharges in gases; the second will deal with the laws governing the movement of free charges through a gas, and the third will discuss known types of discharges in the light of the basic processes which by that time will have been set forth in these columns.—Editor

BASIC CONCEPTS

All matter is made up of atoms, and every atom has a positively charged nucleus at the core around which are grouped enough electrons to contribute an equal negative charge. Thus any disruption of an atom yields charged particles which can carry electricity under the influence of an electric field. The simplest of such particles is the electron. More complicated are atoms or molecules lacking one or more electrons. These constitute the simpler positive ions. Electrons can join neutral atoms or molecules to give simple negative ions. More complex are clusters of atoms and molecules held in union by the electron deficiency or excess of one of them. All these are ions, but, as experiment indicates that in technical applications up to the present only electrons and simple positive ions are important, the word ion will be used in this article to designate the latter, and ionization will refer to the corresponding atom-splitting or molecule-splitting process.

A fundamental fact about ionization is that to ionize a normal atom a definite characteristic amount of energy must be supplied to it. In what forms and by what agencies this is accomplished, and what other phenomena accompany the transfer we proceed to inquire.

When electrons of known and controllable speed are shot into the gas under investigation, no ions appear until a definite minimum value is exceeded. The elements of the experimental apparatus by which this value first was conclusively determined by Davis and Goucher in 1917 are shown in Fig. 1. Electrons from the hot filament C were accelerated by the electric field between it and the gauzes G (the potential distribution is indicated by the fine continuous line) so that when they passed into the GH space they had a kinetic energy eV, e being the electronic charge and V the potential increase between C and G. Parenthetically it may be noted that this voltage rather than the more orthodox energy units can serve as a measure of energy, and that it is so used under the designation *electron volt* or *equivalent volt*. Some of the electrons traversing the GH region collided with gas atoms there, the rest passed into the opposing field in HP (for the moment, suppose J to be absent) which is sufficient to turn them back. Thus P could receive no electron current, but ions, freed by

collisions between G and H, could flow to it and be registered by the galvanometer. It was recognized at the time that such experiments were first performed that radiation capable of ejecting electrons from the metallic electrodes might also arise in these collisions, and that such electrons originating at P would be indistinguishable from the ions reaching P. By inserting the additional gauze J Davis and Goucher were able definitely to separate the 2 effects. The ions were able to penetrate the adverse field between

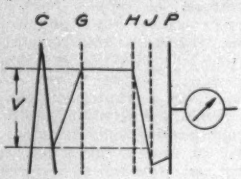


Fig. 1. Elements of apparatus for determining ionization potentials

J and P by virtue of the momentum acquired between H and J, but the photoelectrons from P had insufficient energy to overcome this same field and consequently they fell back to P again. Ionization was found to set in abruptly at a certain voltage. This is the ionization potential of the gas, and accordingly is its dissociation energy in electron volts. At other voltages radiation set in abruptly. Taken together, all these potentials are called *critical potentials*. Some values will be given later.

The *modus operandi* of this classical experiment is not always as simple as the foregoing description would indicate. Some of the complications are inherent in the design of the apparatus, some in the nature of the atom. Other methods have given results consistent with this early one, and have helped in disentangling the intricacies, particularly those connected with the light emission from impacted atoms. To understand the many interrelated phenomena one requires a working model of the atom. Quantum theory, devised originally by Planck to explain certain discrepancies in radiation theory, has been expanded fruitfully to cover atomic properties by the contributions of Bohr, de Broglie, Born, Schroedinger, Heisenberg, and Dirac—to mention only a few of the most outstanding. The fundamental principle of quantum theory is that light has a corpuscular as well as a wave aspect. Each corpuscle or photon carries a definite amount of energy E which is equal to the frequency ν of the wave multiplied by Planck's constant, $h = 6.55 \times 10^{-27}$ erg sec; that is,

$$E = h\nu \tag{1}$$

Bohr, in 1913, made the hypothesis that in each atom there was a finite number of possible energy levels which depended, in the main, upon the relation of individual electrons to the rest of the atom.

When transition between 2 of these levels was accompanied by either the absorption or emission of light, the energy difference was related to the light frequency by eq 1. In this way, the lines of the spectrum were directly connected with the structure of the atom. Later additions to the theory have had to do with the question of which transitions can occur spontaneously, and with the calculation of the energy levels. It is in the latter field that the methods and concepts of wave mechanics, originating with Schroedinger in 1926, have been applicable. Crudely stated, this theory allows the calculation of the standing-wave states of the atom when the wave nature of the electrons is taken into account. Beyond this we do not have to go, as it suffices for us to know the energy levels, whether they have been empirically or theoretically determined. Figure 2 is a diagram of the lower energy levels of the mercury atom showing the energy differences and the wave lengths corresponding to them. The table gives a few critical potentials for some of the gases most commonly used in electrical discharges.

Interactions of Electrons and Photons With Atoms

The lower energy absorptions of which an atom is capable excite it by raising the outermost electron to levels of potential energy higher than it possesses in the normal atom, and this sequence of states terminates with the complete removal of that electron. Through excitation succeeded by ionization, a normal atom can be ionized by 2 or more smaller energy doses. There is, of course, a least energy which a normal atom can absorb, and experiment shows that under *certain conditions* ions appear when the energy of the impinging electrons exceeds this value. This is one of the complications which might have made difficulties in the Davis and Goucher experiment, but in practice did not. The reason is that the electron density and gas densities were so low that the yield from 2- or multiple stage processes was undetectable, although at higher concentrations this yield might be greater than that from single impacts.

The efficiency of ionization by electrons as well as the conditions for ionization must be considered. Two kinds are of importance. First, an electron traveling at a known constant velocity traverses a gas at a standard density and frees a certain number of ions (and electrons, of course) per unit length of path. Second, an electron with a known velocity is projected into a gas and releases a certain total number of ions while dissipating its whole kinetic energy. Each of these efficiencies is appropriate to special portions or types of actual discharges.

The former can be expressed in terms of an area, the effective cross section of the atom for single impact ionization. Suppose a slab of gas (thickness x) of not-too-great concentration (N atoms per unit volume), each atom of which has a vulnerable cross section σ, to be placed across a beam of electrons. The gas presents a target area for ionizing impact of σNx per unit area of slab. $N\sigma$ is, then, the number of ions freed per electron per unit length of path, and σ is the atomic property defining the yield. Below the ionizing voltage σ is zero; its course above begins with a steep rise to a broad maximum between 100 and 500 volts and then a steady decline as far as experiments have been carried—some 25,000 volts.

The curves for several gases are reproduced in Fig. 3. The ordinate is $N\sigma$, and N is roughly 3.27 $\times 10^{14}$. The maximum values of σ are less than half the ordinary kinetic theory values based upon viscosity, equation of state, etc.

All the encounters do not result in singly charged ions. The increasing electron energies available are able to eject not only the most loosely bound electron, but also, successively, those held more tightly. Mercury ions bearing up to 5 elementary charges have been observed by Bleakney below 150 volts. At this potential doubly charged ions carry $^1/_2$ while Hg^{3+} carry 12 per cent of the current carried by Hg^+.

The second kind of efficiency increases continually with increasing energy. In those cases that have been tested, the complicated processes involved produce a rather simple result: For energies well above the ionizing potential, the number of ion pairs formed is proportional to the electron energy, and the actual number formed lies between $^1/_3$ and $^4/_5$ (depending on the gas) of the number which would be created if only the ionization potential was absorbed for each pair.

In our theoretical discussion radiation effects in the atom were anticipated. In the Davis and Goucher experiment such effects were demonstrated. The emission of light by atoms in reverting to lower energy levels, and the raising of atoms in these states to the higher levels by photons of the same frequencies, are linked by the principle of detailed balancing which asserts that the existence of an elementary process always signifies the possibility of the reverse process. In particular, the lowest frequency which a normal atom can absorb is its *resonance radiation*, and is connected through eq 1 with one of the critical potentials, which accordingly is called the resonance potential.

In this way photons are able to act the rôle of electrons. Resonance photons are able to produce ionization in a gas under certain conditions just like electrons at the lowest critical potential, but 3 important differences between electron and photon behavior are to be noted.

First, in one respect electrons are much more effective exciting agents, for their probability of excitation extends to many volts above the critical potential itself, whereas photons must carry exactly the proper energy. For instance, a Doppler effect broadening of a spectrum line, which might escape the eye, renders the extreme frequencies in the line useless for excitation.

Second, the kinetic energy of an electron is, for all practical purposes, irrevocably lost as such at an excitation. After 10^{-7} to 10^{-8} sec the atom ejects this energy as a photon. However, the light itself may be reborn many times through absorption, excitation, and reëmission. This is particularly true of resonance radiation for which a plentiful supply of excitable atoms exists. This phenomenon has been called *imprisonment of radiation*. Photons of the 2,536 resonance line of mercury have a mean free path of 0.12 cm in mercury vapor saturated at a temperature of 60 deg C. On the average, a photon starting at the center of a bulb 5 cm in radius would excite $(5/0.12)^2 = 1{,}700$ times. A duration of a single excitation of 10^{-7} sec would lead to a total time of existence of the energy in the gas of 1.7×10^{-4} sec. Actually, collisions of the second kind, discussed in the following paragraphs, prolong this time still more.

Third, electrons can cause transitions that photons cannot cause. Electrons of 4.66 volts can excite mercury atoms but 2,536 corresponding to 4.86 volts is the lowest frequency light that the atom will absorb. The principle of detailed balancing tells that the emission of radiation corresponding to 4.66 volts does not occur. This transition therefore is shown as a broken line in Fig. 2. In a case like this, where the so-called forbidden line is for a transition ending in the normal state, the excitation energy is trapped, and the atom is said to be in a *metastable state*. Whether the atom ever can revert spontaneously is not known; what is known is that the atom remains in such a state possibly hundreds of thousands of times as long as in other excited states, and certainly long enough so that other agencies can release it. Both imprisonment of radiation and the formation of metastable states are properties which permit the accumulation of large numbers of

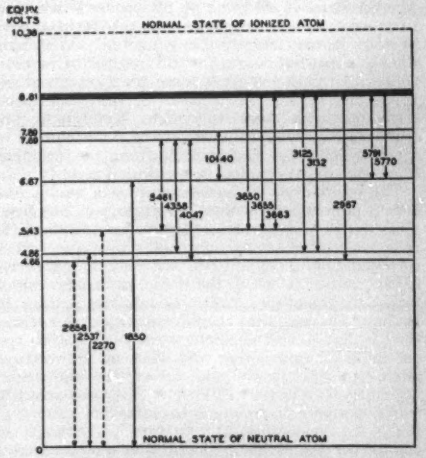


Fig. 2. Lower energy levels of the mercury atom

The numbers on the transition arrows give the wave length of the corresponding radiation in Angstrom units (10^{-8}cm)

excited atoms from which transitions to higher levels can occur.

Other Types of Energy Interchange

The energy of an excited atom can be transferred directly to other atoms by contact without the mediation of electrons or photons. The classical experiment was performed by Franck and Cario in 1922. There is no interaction between thallium

vapor and the 2,536 mercury line. An admixture of mercury vapor while 2,536 photons traversed the gas, resulted, however, in the emission of several lines of the thallium spectrum. The excited mercury atoms which collided with normal thallium transferred their pent-up energy, certainly leaving the thallium excited, and probably dividing the excess between the 2 atoms as kinetic energy. Contacts of this type, known as *collisions of the second kind*, have been observed in other cases and guessed at in many more.

A limiting case is that in which an ion and an atom of the same species interchange their charge, but not their kinetic energy. Actually, the immediate experimental evidence might as well indicate an exchange of kinetic energy and not of charge; but this view is inconsistent with an extrapolation from the known behavior where contact is between excited and normal atoms of the same species, or between ions and atoms of different species as the critical potentials approach equality. Actual proof probably is impossible, although theoretically an experiment with isotopes would be decisive.

The kinetic or radiation energy absorbed by a gas in the various processes that have been described is, of course, lost to the original energy beam, whether it be of electrons or photons. With electrons most of the energy goes into new forms; with photons it may merely be scattered. Watching what happens has been a fruitful method of investigation. Critical potentials have been observed by noting the decrease in electrons of full velocity as these potentials were exceeded. Resonance potentials are evidenced by the powerful absorption of the corresponding wave length from the incident beam and its reradiation in all directions.

The positive ion is another corpuscle which can have a profound effect upon an atom. It has been used to bombard gas atoms despite far greater difficulties attending experiments of this type and a corresponding uncertainty in the results. A series of experiments in which the noble gases were bombarded by ions of the alkalis prove that ionization by ion impact occurs, that roughly and with exceptions the ion that is most effective is the one next to the gas in the atomic series, and that in the voltage range studied—up to 800 volts—the ionization, beginning at from 100 to 300 volts, increases steadily with potential. In argon gas the efficiency of ionization of K^+ (potassium) at 700 volts lies between 50 and 100 per cent of that of electrons at their optimum velocity.

Just as excited atoms can transfer their excitation to others, it is possible for ions from atoms of higher ionization potential to ionize other kinds of atoms of lower ionization potential by contact, and the closer the ionization potentials lie, the more likely is the transfer. Helium and neon presumably are ionized in a definite relative proportion when a mixture is bombarded by electrons of fixed velocity. Harnwell tried increasing the opportunity for interchange of charge by simply raising the gas density. The Ne^+ increased relative to the He^+. The behavior of N_2^+ and N^+ has been found to be similar in other experiments, and the admixture of other gases has shown that the closer the ionization potentials of the contacting particles, the more likely is the interchange.

Neutral atoms of argon have been reported by Beeck as rather effective ionizing agents for argon. At the lowest velocity for which the design of his apparatus was suitable, about 50 volts, ions were generated in large numbers. Full details and further confirmation apparently have not yet been announced.

Fast electrons, such as beta rays, high frequency photons like X rays and gamma rays, high speed protons, alpha particles (He^{++}), and neutrons, originating in radioactivity or cosmicr adiation, all are ionizing agents. Their rôle is confined to the fortuitous or intentional initiation of an electrical discharge in certain cases where the voltages, pressures, etc., are adequate to maintain the current flow once it is started, but the first few free charges are lacking.

Finally, high temperature must be listed as a cause of ionization. In the ideal case of thermal equilibrium there exists a complete melange of kinetic energy, excited states, radiation, free ions, and free electrons, among which all the interchanges so far discussed are taking place equally in both directions. Saha has derived a relation between ionization potential, temperature, and the equilibrium constant for dissociation from thermodynamics that has been confirmed experimentally in many cases.

Charges Freed From Solids

The origin of free charges and radiation within the body of a gas is not, in general, the only source of electricity in a discharge. The glass or metallic

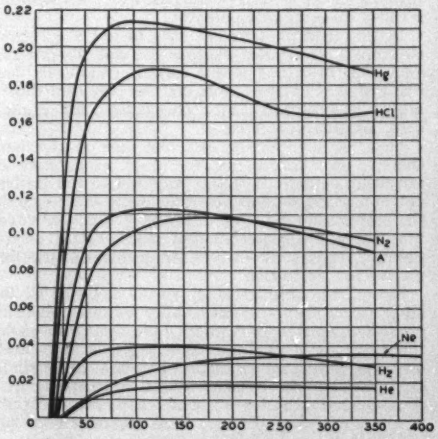


Fig. 3. Probability of ionization by electron impact

Number of elementary charges freed per centimeter of path at 1 mm pressure and room temperature plotted against the kinetic energy of the electrons in electron volts (Compton and Van Voorhis, "Phys. Rev.," v. 27, 1927, p. 724)

Table of Critical Potentials

Gas	Transition	Energy Difference—Volts
Mercury (Hg)	Metastable	4.66
	Resonance	4.86
	Ionization	10.36
	Hg^{+} to Hg^{++}	19.0
Helium (He)	Metastable	19.77
	Ionization	24.5
Neon (Ne)	Metastable / Resonance	16.4 -16.7
	Ionization	21.5
Argon (A)	Ionization	15.69
Sodium (Na)	Resonance	2.10
	Ionization	5.12
Nitrogen (N)	N to N^{+}	14.5
	N_2 to N_2^{+}	16.0

confining walls and the electrodes by which current enters and leaves the conducting space often are necessarily and sometimes disconcertingly active in producing new charges.

Thermionic emission either of electrons or of ions from hot metals and compounds is well known and will be discussed in a later article of this series.

Electrons can be drawn from cold conductors by strong electric fields of magnitudes exceeding 10^6 volts per cm. As surface contamination is eliminated, the necessary field strengths become greater. A very marked aging effect of clean surfaces indicates that the emission usually has occurred at minute, but possibly sharp, surface irregularities which caused local increases of field strength. To avoid this unknown and variable field amplification Beams recently has applied high fields to a clean liquid mercury surface. Enough electrons were extracted with 1.8×10^6 volts per cm to start a discharge in the low pressure mercury vapor. Either an unsuspected cause of local concentrations of field is present, or theory needs revision, for this field is only $^1/_{18}$ that which the wave mechanics formula derived by Fowler and Nordheim indicates as necessary.

All the agencies of gas ionization also free electrons from metals. Some of them are known or suspected to act similarly on certain nonconductors, but often it is impossible to devise experiments to test this. The condition of a metal surface, whether it contains gas either absorbed or adsorbed, and the presence of minute traces of other surface contamination, particularly atoms of the alkalis, markedly affects the phenomena.

Electrons with energies of the order of hundreds of volts are able not only largely to escape themselves from metal targets on which they impinge, but also to eject additional electrons from the metal itself. The onset of this phenomenon, known as *secondary electron emission*, has been observed down to less than one volt. At the optimum an actual reversal of current approximating the incident current in magnitude can occur. Alkaline earth contamination enhances the effect. Certain cases of the conduction of electron currents in good vacuum through long glass tubes can be explained only on the hypothesis that the walls became and remained positively charged by the emission of secondary electrons from the glass.

In order for a photon to eject an electron from a conductor, its energy must exceed the work function φ of the surface. The corresponding frequency is the long wave length limit for photoelectric emission. The energy of the photon in excess of that absorbed in leaving the surface may appear as kinetic energy of the photoelectron. The maximum energy E_m of the latter therefore is given by the equation

$$E_m = h\nu - e\varphi$$

which was proposed by Einstein in 1905. X rays or ultra-violet light impinging on an electrode often are used to initiate a discharge. Differences between the voltage equivalent of the photoelectric threshold and the thermionic work function arise from contamination which is the more serious in causing deviations from clean surface values in the photoelectric case because the high temperatures necessary for thermionic emission tend to keep the surface clean. A surface film of oxygen increases the work function; surface films of the alkalis lower it. Efficiencies of one electron per 14 incident *quanta* have been observed.

Emission of electrons attending the impact of metastable atoms of helium (19.7 volts) on molybdenum and magnesium has been detected by Oliphant. Some electrons were found to possess as kinetic energy the full excess of the excitation energy over the work function of the metal. Various effects in arcs in the noble gases have been attributed to the release by metastable atoms of electrons from the electrodes and the glass walls, but the photoelectric effect seems now to have been the chief factor in several of these cases.

The ejection of electrons by fast moving ions is indubitable, but the experimental difficulties are such that comparatively little definitive work has been done, and the results of different experimenters cannot be compared. A ratio greater than unity of electrons emitted to helium ions impinging on cold contaminated molybdenum has been reported by Oliphant when the energy was greater than 800 volts. A constant relative yield of 0.2 was found for clean molybdenum all the way from 600 down to 100 volts. A helium ion carries enough potential energy not only to free from the metal the electron needed for its own neutralization, but also to eject another besides, and perhaps it is an effect of this kind rather than one caused by the kinetic energy that is operative here. These yields are tremendous compared to the few per cent found in certain other cases of ion impact.

A brief survey such as the foregoing can give only a certain superficial acquaintance with the field. Greater experimental detail and fuller discussion is to be found in such books as K. K. Darrow's "Electrical Phenomena in Gases" (Published by Williams and Wilkins, Baltimore, Md.) or the 2 volumes on the "Conduction of Electricity Through Gases" by J. J. and G. P. Thomson (Published by University Press, Cambridge, England). In German the "Handbuch der Physik" (Published by Julius Springer, Berlin), Vol. 23, chapters 5 and 7, covers some of the ground. In these books will be found the references to the original papers upon which present knowledge ultimately rests.

The Life of Impregnated Paper

A series of accelerated life tests on 14 different oils as used for the impregnation of one grade of cable insulating paper is described herein. Complete absence of gaseous ionization was insured in these tests. It is shown that there is a definite relationship between the life of impregnated paper under stress, and the capillary constant of the oil. With oils of one definite type, the life of the paper increases with penetrative power. Between oils of different types, there may be differences in the relation of penetrative power to life. The influence of dielectric loss on life is negligible, and the values of power factor during life tests appear to have no relation to life.

By
J. B. WHITEHEAD
FELLOW A.I.E.E.

The Johns Hopkins Univ.
Baltimore, Md.

IT IS generally agreed that the most important factor limiting the life of the so-called solid type of impregnated paper insulated cable is internal ionization in voids or gas pockets, commonly due to expansion and contraction under temperature cycles, or less commonly, to impregnation originally imperfect. Gaseous ionization leads to well-known rapid heating and destructive action on both oil and paper. Under its influence the original sealing action of the oil is lost, and the original paper structure is destroyed, both in such mutually cumulative relation as to lead rapidly to breakdown.

Efforts to increase the life of such cables therefore have been of 2 general types: (1) the search for materials which will withstand gaseous ionization without injury; and (2) the suppression or elimination of ionization.

In the first type of effort an enormous amount of work and expenditure of money has been directed to studies of wax formation, ionic bombardment, and allied phenomena in oils and in oil mixtures, in search for a compound which is most nearly proof against the action of ionization. Apparently the point of view in these studies is that gaseous ionization is necessarily inherent in the solid cable and that it should be possible to discover materials which are not damaged thereby. It cannot be said that the results of this large amount of work have been very encouraging. Some knowledge has been acquired as to the probable causes of wax formation and some differences in the behavior of various oils have been found. No compound of outstanding resistance to ionization has been found, however, nor in view of the inherent chemical instability of oil and the susceptibility of paper fiber to oxidation can it reasonably be expected that a radical improvement will be found in this direction.

Far more promising, however, are the results attained in the suppression and elimination of internal gaseous ionization. The most obvious measures are the restriction of voltage stress and temperature elevation to such values as, based upon practice and experiment, are certain to limit the intensity of ionization to such values as will permit a reasonable life of the cable. These are the measures commonly adopted for solid cables and they have therefore imposed definite limitations upon their capacities and voltage ratings.

Next in order of importance as limiting ionization is the shielded or type *H* cable. This improvement is based upon sound principles since it limits the volume of insulation exposed to ionization without interference with the normal insulating function, and at small cost. It does not, however, attack the essential limitation of the solid cable, namely the occurrence of gas voids in the body of the insulation wall.

The most recent and most important improvement in the direction of the suppression of ionization is the so-called oil filled principle in which by the use of oil channels and thin oils, it is aimed to furnish a sufficient supply of oil at all times and at all places to prevent any tendency to the formation of gas voids resulting from temperature variation.

Of the relative value of the 2 classes of effort just described for the increase of the life of cables, there can be no question of the outstanding importance of the second group, and particularly of the oil filled principle. The remarkable improvements in ionization characteristics and the increases in current and voltage ratings of cables of the type *H* and oil filled types on the one hand, and the failure to find refractory materials or preventive measures in the solid type of cables on the other hand, clearly demonstrate the directions in which improved cable performance must be looked for. In this statement it will be understood that we are considering the possibilities offered by underlying physical principles only, and have not introduced consideration of the economic element of relative cost. The relatively lower cost of the solid cable and clear knowledge of its limitations will insure probably for always its wide use in the lower voltage ranges. But for increased current capacities, higher voltages, and higher temperatures, the oil filled cable is indicated clearly and probably will find wider use as its cost is reduced and its ultimate possibilities are explored more completely.

The dominant influence of internal ionization on the life of solid cables has overshadowed the question

Full text of "The Life of Impregnated Paper" (No. 33-72) presented at the A.I.E.E. summer convention, Chicago, Ill., June 26–30, 1933.

of a possible inherent influence of the impregnating oil itself on the life of impregnated paper. As a consequence, this question has received little or no experimental study. Specifications for a cable oil are limited usually to values of low-voltage d-c conductivity, power factor, dielectric strength, aging under temperature as measured by conductivity and power factor, and viscosity as related to the purchasers' or manufacturers' ideas of its bearing upon permanence of impregnation. By sufficient care in refinement, it is possible to meet these specifications with a very wide variety of oils and as a consequence this variety in fact extends itself in considerable measure to the cable oils now in use.

In the oil filled cables so far installed and operated, the oils employed have been limited to only 1 or 2 grades, and there is no knowledge as to the inherent properties which have given them their value, nor has any comparative study been made looking to a determination of important oil characteristics and the relative behavior of the large number of available oils. It is high time, therefore, that studies of this character be begun.

The Materials and Test Samples

This paper reports the results of a series of accelerated life tests on impregnated paper samples in which effort has been made to eliminate all variable factors and conditions except those pertaining to the oil. To this end a single paper has been used, and all test samples assembled, dried, evacuated, and impregnated as nearly as possible under identical conditions. The impregnation program adopted aimed at practically complete impregnation, so that gaseous ionization would be eliminated as an important factor in the life of the samples. This result seems to have been attained as will appear. With gaseous ionization either absent or reduced to very low terms, it is believed that the interesting differences which have been found in the behavior of the various oils are inherent either in the properties of the oils themselves or in the relation of these properties to the structure of the paper.

The Paper. The same grade of wood pulp paper tape as furnished to the cable trade by a well-known manufacturer was used in all the samples. It was not supercalendered and had the following characteristics at 25 deg C:

Thickness	0.004 in. (0.01016 cm)
Width	1 in. (2.54 cm)
Specific gravity	0.937
Gurley air resistance	640 sec
Effective capillary radius	8.2×10^{-4} cm
Conductivity (dry)	9.5×10^{-18} mhos per cu cm

The Oils. Fourteen different oils have been studied, as furnished by 4 manufacturers. Some description of the oils and their principal physical constants are given in Table I. The oils for the most part, are those offered to the cable trade. Exceptions are No. 104 and notably Nos. 109 to 113, these latter having been prepared by a well-known refiner as having special characteristics for these experiments. In connection with most of these oils it has not been possible to secure complete information either as to their origins, their programs of refinement, or their principal chemical characteristics. This applies particularly to those oils which now are sold to the cable trade. As may be seen, most of the oils are those commonly employed for solid core cables. Three, however, Nos. 104, 108, and 113, are thin oils such as used in oil filled cables. The differences in viscosity in these 2 groups are quite wide.

Most of the oils were shipped to us protected by an atmosphere of carbon dioxide or of nitrogen. This condition was maintained by us and at no time before completion of the impregnated sample was the oil exposed to the air. Before admission to the impregnating tank, the oil was sprayed into a vacuum equivalent to one millimeter of mercury, passing down over a series of cones to a heating tank where it was elevated to a temperature of 60 deg under vacuum, and thereafter drawn into the impregnating tank. The d-c conductivity and dielectric strength of the oil was measured both before and after this treatment. A substantial lowering of conductivity and an increase of dielectric strength was found in practically all cases. (See Table I.)

The Impregnated Samples. Each sample consisted of 16 layers of the 0.004-in. paper spiralled in cable fashion with butt joints and with $^1/_4$ width overlap,

Table I—Oil Properties

Oil No.	Base	Pour Point °C	Flash Point °C	Specific Gravity at 40° C	Viscosity Poises at 40° C	Surface Tension Dynes/Cm at 40° C	Penetrative Power $\times 10^{-3}$ (Kraft) at 40° C	Dielectric Strength Volts: Before Treatment	Dielectric Strength Volts: After Treatment	20-Min Conductivity Mhos/Cu Cm $\times 10^{-14}$ at 40° C: Before Treatment	20-Min Conductivity Mhos/Cu Cm $\times 10^{-14}$ at 40° C: After Treatment	P.F. of Impreg. Sample at at 40° C	Life at 400 Volts/Mil (Avg of 20-Min Sets) in Hours
100	"Undewaxed" paraffin	35.0	274	0.8788	7.5	51.8	5.57	20,175	27,960	105.0	34.2	0.00275	1,118
101	Paraffin	15.7	296	0.881	5.7	31.2	5.0	16,864	25,850	605.0	218.0	0.00353	974
102	Semi-refined naphthene	−7.0	288	0.9268	7.2	20.1	3.55	19,931	29,827	1,630.0	1,313.0	0.00483	2,948
103	Naphthene (phenol extract)	19.3	255	0.96				14,670	25,620	11,900.0	6,400.0	0.00872	20.8
104	Highly refined white oil	0.0		0.83	0.132	32.0	33.0	31,100	31,550	1.4	1.0	0.00264	12,882
105	"Dewaxed" paraffin	−7.0	282	0.8829	4.9	31.3	5.47	17,552	25,500	322.0	84.8	0.00276	1,599
106	75% No. 105, 25% rosin by weight	4.4		0.935	17.5	21.6	2.28	27,660	28,845	130.0	149.0	0.00282	1,096
107	Highly refined paraffin	4.4	263	0.903	4.07	38.3	6.52	27,837	28,820	7.34	5.75	0.00258	1,053
108	Refined light oil	−29.0	149	0.8805	0.1602	28.2	28.2	27,640	26,990	12.6	24.8	0.0027	9,081
109	Highly refined naphthene	−6.7	271	0.9015	2.46	33.0	7.67	18,410	27,790	32.4	22.0	0.00238	7,146
110	Refined naphthene	−7.0	294	0.903	4.82	32.8	5.48	21,600	31,710	47.1	23.8	0.00261	2,868
111	Paraffin blend	−4.0	202	0.8693	0.368	32.9	19.5	27,150	27,763	103.0	74.3	0.00376	6,510
112	Paraffin blend	−2.0	218	0.878	0.878	32.9	12.85	29,400	33,540	7.9	5.4	0.00309	1,929
113	Refined naphthene	−17.8	190	0.891	0.37	30.3	18.96	29,520	30,975	81.7	61.2	0.00289	14,304

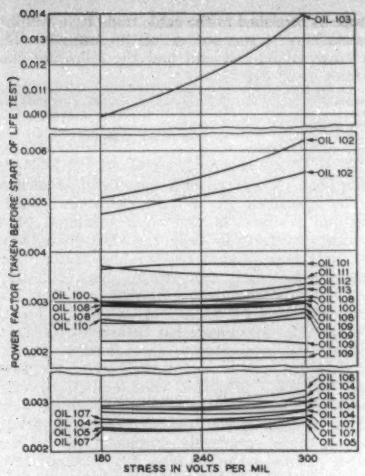


Fig. 1. Power factor-voltage curves

Kraft paper—various oils
Standard construction and treatment
40 deg C

on a 2.5-cm diameter smooth brass tube as high voltage electrode. The outer or measuring electrode (60.96 cm long) was of lead foil reënforced with thin sheet lead. This electrode was protected by guard rings and ends of reënforced insulation. Both high voltage and measuring electrodes were perforated at wide intervals with very small holes to facilitate impregnation. Drying, evacuation, and impregnation were carried out at 2-mm mercury pressure in the standard specimens for life test. After impregnation in the vacuum tank, the specimen was transferred to the high voltage test box containing 3 open oil tanks. The test specimens were made in sets of 3, and 1 specimen was placed in each of the oil boxes and immersed in the oil in which it was impregnated. The oil tanks were themselves deeply immersed in an outer bath of circulating oil permitting temperature adjustment between 25 deg and 80 deg. The whole assemblage of test tanks was enclosed in a large outer wooden box with thermal insulation, through which high voltage porcelain bushings permitted connection of the test specimens to the high voltage source. More detailed descriptions of the test samples as well as of the methods of drying, impregnation, measurement of power factor, temperature, loss, voltage, life, etc., have been given in a foregoing paper.[1]

Measurements, Tests, and Results

The d-c conductivity and the dielectric strength of each oil was measured as received and after the vacuum treatment referred to above. Measurements were also made of the viscosity and surface tension and the penetrative power,[2] or capillary constant, in each case, the results being given in Table I. The power factor and initial or short time conductivity measurements were made on several of the oils, the values for which, and their significance as bearing on dielectric loss in the impregnated sample and other discussion, have been given in a separate paper.[3]

The impregnated specimens were constructed in sets of 3; usually 2 such identical sets were tested for each oil; often there were 3 sets and sometimes more. Before the life test, measurements of power factor, as related to voltage in the range of 180 to 300 volts per mil and at 40 deg C were made on each of the 3 specimens of 1 set. The results of these tests are

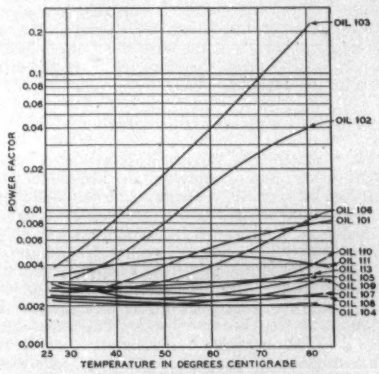


Fig. 2. Power factor-temperature curves

Kraft paper samples impregnated with various oils
Power factor measured at 180 volts per mil

assembled in Fig. 1. Also in each case power factor at 180 volts per mil was measured over the temperature range of 25 to 80 deg C. The results of these tests are given in Fig. 2. Power factor at 180 volts per mil was also read at intervals during the life tests as given in Fig. 3 for the entire series of tests, and in Figs. 4 and 5 for special cases.

In the accelerated life tests (150 in all) each sample was tested singly, being taken one by one from the impregnating chamber within which an atmosphere of nitrogen at atmospheric pressure was maintained. The life test was started at 400 volts per mil, maintained for one hour, then 500 volts per mil for one hour, then 600 volts per mil for 10 hours, 650 volts per mil for 10 hours, 700 volts per mil for 37 hours, 750 volts per mil for 40 hours, 800 volts per mil for 40 hours, 850 volts per mil to failure. These tests were made at 40 deg C, this value being maintained within a fraction of a degree by automatic means.

The results of the life tests on all the oils are summarized in Tables II and III. Table II reports those oils either known to be or believed to be of so-called

1. For references see numbered list at end of paper.

paraffin base, and as furnished by several different refiners; and Table III reports a special group of oils developed for these tests by one refiner and all stated to be of naphthenic base. Exact information as to the origins and differences in processes of refinement has been withheld in all cases. It will be noted from Tables II and III that the complete history of the test as regards the duration of life at each value of stress, together with the total life of each sample, and the average life of the entire group for each oil, are given. Moreover, in the last column the average life per group as reduced to 400 volts per mil by the eighth-power law is also given. As is well known in breakdown tests of this character, there is usually a fairly wide variation in the results as observed on successive similar samples. We have not escaped this difficulty and in the results as reported we have had to use our judgment as to the weight to be attached to life values of individual specimens falling well away from the average value pertaining to the group. As indicative of the results of individual tests we note as of average uniformity set *SS*, oil No. 111 giving 5,706, 6,322, and 5,119 hr respectively at 400 volts per mil. One of the poorer examples as regards spread of results was set *MM*, oil No. 102, giving 4,004, 1,427, and 2,494 hr, respectively, at 400 volts per mil. In the curves and figures as reported, the values are the average values (see Table III) of groups of 3, 6, or 9, as the case may be, with occasional elimination of one apparently abnormal specimen.

The collected results of the life tests, as based upon the average performance of all specimens tested, are shown in Fig. 3 in which the horizontal scale is the actual life in hours and the vertical scale gives the power factor at 180 volts per mil, as measured at intervals during the life run. At the top of the figure successive increments of stress and the duration of each are also given. Each curve refers to a single oil. The dotted sections show the life after the last measurement of power factor. If the values of life are reduced to 400 volts per mil, say by the eighth-power law, the differences among specimens as reported with the various oils are much more pronounced than as indicated in Fig. 3.

A more intimate picture of the change of power factor during the life test is given in Figs. 4 and 5 as taken for single samples. In these the horizontal scale is again linear in actual hours of test. Figure 4 is typical of those specimens having relatively long life with no material change in power factor until the very last stages, within which the rise in power factor is very rapid. In Fig. 5 is shown a slow and uniform rise of power factor throughout a relatively long life followed by a rapid rise in the last stages of the approach to breakdown. In Fig. 5 is also shown the

Table II—Paraffin Oils, Accelerated Life Test History of 2.0-mm Mercury Sets

Oil	Specimen	Number of Hours at: (Volts per Mil) 400	500	600	650	700	750	800	850	Total No. Hours	Avg No. Hours	Avg Life at 400 V/M Hours
	KK-1	1	1	10	3.4					15.4		
100	KK-2	1	1	10	10.0	19.3				41.3	24.4	1,118
	KK-3	1	1	10	4.5					16.5		
	S-1	1	1	10	10.0	5.5				27.5		
101	S-2	1	1	10	10.0	5.6				27.6	23.6	974
	S-3	1	1	10	3.7					15.7		
	H-2	1	1	10	10.0	37.0	40.0	1.5		100.5		
	H-3	1	1	10	10.0	37.0	40.0	30.8		129.8		
104	I-1	1	1	10	10.0	37.0	11.0			70.0	106.1	12,882
	I-2	1	1	10	10.0	37.0	30.7			89.7		
	I-3	1	1	10	10.0	37.0	40.0	40.0	1.5	140.5		
	N-1	1	1	10	10.0	6.6				28.6		
	N-2	1	1	10	9.0					21.0		
105	N-3	1	1	10	10.0	31.2				53.2	31.6	1,599
	P-1	1	1	10	10.0	8.5				30.5		
	P-2	1	1	10	10.0	7.9				29.9		
	P-3	1	1	10	10.0	4.5				26.5		
	CC-3	1	1	10	10.0	4.4				26.4		
107	HH-1	1	1	10	10.0	1.7				23.7	25.7	1,053
	HH-2	1	1	10	10.0	4.0				26.0		
	HH-3	1	1	10	10.0	4.7				26.7		
	EE-1	1	1	10	10.0	37.0	40.0	1.4		100.4		
108	EE-2	1	1	10	10.0	37.0	14.1			73.1	91.6	9,081
	EE-3	1	1	10	10.0	37.0	40.0	2.2		101.2		
	SS-1	1	1	10	10.0	37.0	11.2			70.2		
	SS-2	1	1	10	10.0	37.0	15.3			74.3		
111	SS-3	1	1	10	10.0	37.0	7.3			66.3	75.5	6,510
	TT-2	1	1	10	10.0	37.0	10.0			69.0		
	TT-3	1	1	10	10.0	37.0	38.7			97.7		
	VV-1	1	1	10	10.0	23.0				45.0		
112	VV-2	1	1	10	10.0	8.5				30.5	35.4	1,929
	VV-3	1	1	10	10.0	8.8				30.8		
	XX-1	1	1	10	10.0	21.3				43.3		
105	XX-2	1	1	10	10.0	25.8				47.8	54.8	3,904
(At 70° C)	XX-3	1	1	10	10.0	37.0	14.2			73.2		
	AA-1	1	1	10	10.0	3.9				25.9		
106	AA-2	1	1	10	10.0	10.6				32.6	26.8	1,176
	AA-3	1	1	10	9.9					21.9		

temperature variation in the oil just outside the specimen, upper curve, and that inside the tube forming the high voltage electrode. As a general thing these 2 temperatures were closely the same except in the last stages of life when the losses were increasing rapidly and when the difference would sometimes rise to 4 or 5 deg.

Of the total number of breakdowns observed 97 per cent occurred under the central electrode. A few occurred under the guard electrodes, and 1 or 2 failures under the reënforced ends have not been recorded. The failures for the most part were clean punctures, perhaps a milimeter or more in diameter at the inner and outer electrodes and 5 mm in diameter and often smaller within the insulation wall, usually with some adjacent scorching, dendrites, and gas formation. Conditions throughout the sample after failure generally were uniform longitudinally, although there was often a pronounced variation in the amount of gas formation radially through the thickness of the insulation wall. In general the appearance of the samples after failure was such as to indicate that the deterioration leading to failure was quite uniform over the whole length of the sample. One of the striking features evident on dissection, particularly in the paraffin oil samples, was the presence, practically in every case, of gas, uniformly distributed through 4 or 5 layers and the further fact that the occurrence of this gas was limited to the last stages of life. The amount of this gas was definitely less in the naphthene group. A number of samples of both types of oil were opened after long life and before approach to failure. No gas was ever found in these specimens. Furthermore, a number of specimens were carried to 800 volts per mil, maintained at this stress for a number of hours and then removed without failure. No gas was found in these specimens. No wax has ever been found in any of the specimens. These facts lead us to feel that gaseous ionization in the ordinary acceptance of the term was not present in any of these specimens and that impregnation, in the ordinary sense of the term, that is to say, complete absence of visible gas, was complete.

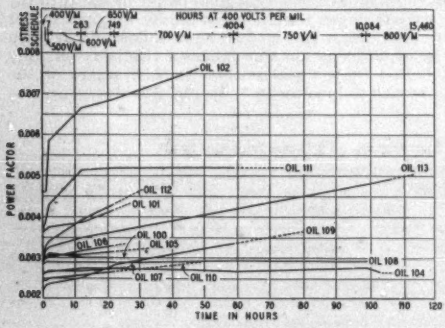


Fig. 3. Power factor-time curves

Representative samples, each oil power factor measured at 180 volts per mil
Life test at 40 deg C

Discussion

Power Factor. The power factor values given in Figs. 1 and 2 indicate a fairly wide variation both in value and type of behavior of the oils. The high values and rising character of the curves for oils No. 102 and No. 103 are in some measure accounted for by the fact that these naphthene base oils were not as thoroughly refined as some of the paraffin base oils submitted to the cable trade by the same manufacturer. Oils Nos. 109, 110, and 113 are more highly refined oils from the same base as No. 102. With this in mind, it may be seen that the variation in power factor values over the whole temperature range studied is relatively small for the entire series of oils. It will be noted also that the variation of power factor with stress is very small over the whole group, up to 300 volts per mil, thus indicating again the absence of gaseous ionization.

Table III—Naphthene Oils, Accelerated Life Test History of 2.0-mm Mercury Sets

Oil	Specimen	Number of Hours at: (Volts per Mil) 400	500	600	650	700	750	800	850	Total No. Hours	Avg No. Hours	Avg Life at 400 V/M Hours
	V-1	1	1	10	10	37.0	10.8			69.8		
	V-2	1	1	10	10	21.6				43.6		
	MM-1	1	1	10	10	37.0				59.0		
102	MM-2	1	1	10	10	7.7				29.7	45.9	2,947
	MM-3	1	1	10	10	19.8				41.8		
	NN-1	1	1	10	10	3.0				25.0		
	NN-2	1	1	10	10	16.5				38.5		
	NN-3	1	1	10	10	37.0	1.0			60.0		
	OO-2	1	1	10	10	37.0	6.3			65.3		
	OO-3	1	1	10	10	37.0	17.5			76.5		
109	PP-1	1	1	10	10	37.0	40.0	5.2		104.2	78.5	7,146
	PP-2	1	1	10	10	37.0	33.7			92.7		
	PP-3	1	1	10	10	32.0				54.0		
	RR-1	1	1	10	10	26.5				48.5		
110	RR-2	1	1	10	10	5.0				27.0	42.7	2,568
	RR-3	1	1	10	10	30.4				52.4		
	WW-1	1	1	10	10	37.0	40.0	12.3		111.3		
113	WW-2	1	1	10	10	37.0	28.0			87.0	113.3	14,304
	WW-3	1	1	10	10	37.0	40.0	42.6		141.6		

The influence of sustained stress on power factor is seen best in Fig. 3. Some of the oils maintain their power factor fairly well up to breakdown (*e. g.*, Nos. 104, 108, and 111) while others (Nos. 109, 113) showed a uniform increase of power factor throughout relatively long lives. There is no relationship apparently between the value of power factor or its rate of increase under increasing stress, and the life of the specimen. In those specimens showing a uniform rise of power factor with increasing stress through life, this relatively slow increase is to be distinguished from the final rapid rise of power factor as failure is approached. The slow increase with stress apparently is an inherent property of the oil involving no instability. The final rapid rise of power factor evidently is the onset of instability and

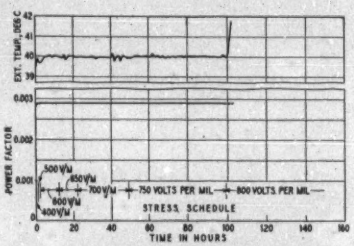


Fig. 4. Power factor-temperature-time curves

Specimen *EE*-3, compound No. 108
Power factor measured at 180 volts per mil
40 deg C

temperature rise in accordance with the thermal theory of breakdown.

Differences in Life. It is evident from Tables II and III and Fig. 3 that there are wide differences in the lives of the various groups of samples, all of which have been impregnated under identical conditions and tested in the same program, the various groups differing only as regards the oil. Looking for an explanation of these differences, it may be noted that for the most part the samples showing the shortest lives are those impregnated with compounds of relatively high viscosity, commonly used in solid cables, as for example, Nos. 100, 101, 105, and 107. In this class also is found oil No. 106 containing 25 per cent of rosin. On the other hand, 2 oils giving exceptionally long lives, Nos. 104 and 108, are both thin light oils of low viscosity. The naphthene base oils seem to fall in a group to themselves. They are characterized by a power factor increasing with increasing stress, but also by relatively long life. In a general way it may be concluded, therefore, that higher viscosities tend to shorten lives and carefully refined thin oils of low viscosity may give exceptionally long lives. Further, an influence of the basic chemical character of the oils is indicated by the divergence of the naphthene group as shown later.

Life-Capillary Properties. In these studies it has been hoped to go much further than a mere experi-

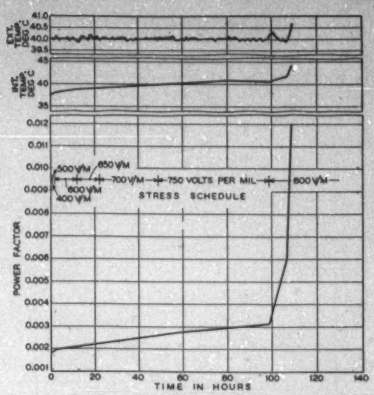


Fig. 5. Power factor-temperature-time curves

Specimen *QQ*-1, compound No. 109
Power factor measured at 180 volts per mil
40 deg C

mental comparison of the lives of paper samples as impregnated with various oils. The chief purpose before us has been to find if possible some relation between the physical or chemical properties of the oils and the lives of samples impregnated with them. We believe that we have found an important relationship of this character in the capillary properties of the oils as related to the paper. We have found, for example, that the rate of rise of each one of these oils in a vertical strip of the paper obeys the well-known law of the rise of a liquid in a small capillary tube. This means that it is possible to assign to each oil a definite value of "penetrative power" K, which is a measure of its power for penetrating the pores of the paper. The penetrative power depends upon the viscosity and the surface tension of the oil, and upon the effective capillary radius of the pores within the paper. The complete expression for K is:

$$K = \left(\frac{r}{2}\right)^{1/2} \cdot \left(\frac{\gamma}{\eta}\right)^{1/2}$$

in which

r = the effective capillary radius of the paper pores
γ = the surface tension in dynes per centimeter
η = viscosity in poises

Over such a group of oils as tested here the variation in surface tension (see Table I) is much less than that of the viscosity and so the latter is by far the more important factor determining the differences in their penetrative powers.

The rise of an oil in a vertical strip of paper is given by the equation $l = K \cdot t^{1/2}$, where K = the penetrative power, l = the height of rise in centimeters, and t = the time in seconds. A complete account of the experiments leading to the determination of the values of K for each oil, its variation with temperature, the effective capillary radii of different papers, and other interesting data on capillary action

have been given in a separate paper.[2] The values of K at 40 deg C for each of the oils studied, as related to the 0.004-in. paper are given in column 8 of Table I. It will be seen that K ranges from 2.28 for the

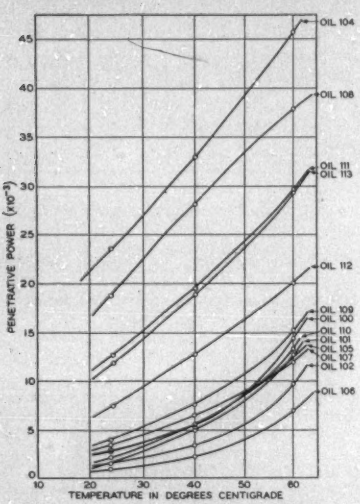


Fig. 6. Penetrative power versus temperature

Various insulating oils
4-mil kraft paper

rosin oil mixture, No. 106, up to 33 for the thin white oil, No. 104. The variation of the penetrative power with temperature for each of the oils is shown in Fig. 6.

In Figs. 7 and 8 the average life of the several samples impregnated with each oil has been plotted as related to the penetrative power. In Fig. 7 the abscissas are the values of the over-all lives in hours without reference to the values of stress. In Fig. 8 the total life in each case has been reduced to 400 volts per mil by the eight-power law. As seen clearly in these figures, 2 definite lines or curves are indicated connecting in definite relationship the penetrative power with the life of the oil. The oils constituting the lower curve are all of naphthene base. All of the oils on the upper curve except oil No. 108 are known to be of paraffin base. Oil No. 108 is said to be of naphthenic base but is known to have a different origin from the oils constituting the lower curve.

In order to test the interesting relationship indicated here, several auxiliary studies were made. For example, a set of samples was constructed using oil No. 105 in which, however, the temperature of impregnation and test was 70 deg C instead of 40 deg C, thereby lowering the viscosity and increasing the penetrative power markedly. The result was to more than double the life as indicated in Fig. 7. Impregnation at higher temperatures with subsequent life test at 40 deg gave no increase of life. In another case, the viscosity of a well-known paraffin oil (No. 105) was lowered substantially by mixing with ligher oils. The results showed corresponding increases of life as shown by points 111 and 112, Figs. 7 and 8. Similar variations of the viscosity carried out by the refiner on the oils of the naphthene group, for the purpose of both increasing and decreasing their penetrative powers, were reflected immediately in corresponding differences in life.

There appears to be no doubt, therefore, that in gas-free cable insulation there is a definite relationship between the capillary properties of the oil as related to the paper, and the life of the insulation under high stress. The relationship perhaps is not quite so definite as indicated in Figs. 7 and 8 because the spread of the results on each oil is not indicated. If, however, all of the life test results from Tables II

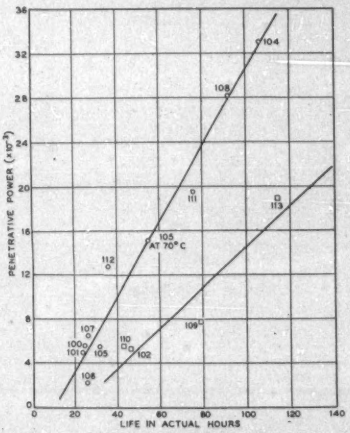


Fig. 7. Penetrative power-life curve

Kraft paper impregnated with various oils at 2.0-mm mercury
Life test at 40 deg C

and III be included, it still will be found that there is no overlap among the values giving the 2 curves of Figs. 7 and 8, which are based upon the average values for each oil. A linear relationship is suggested in Fig. 7, but this is scarcely possible in view of the continually increasing values of electric stress. On the other hand, the upper parts of the curves in Fig. 8, based on life at 400 volts per mil, also approach fairly closely to a linear relationship. Uncontrollable variations among the specimens and the spread of test results are quite sufficient to account for the differences in the shapes of the 2 curves of Fig. 8.

The 2 separate curves for the paraffin and naphthene groups clearly suggest that the basic chemical structure of the oil also has a bearing on life. This

indication is still further strengthened by the apparent identity of the law connecting penetrative power and life in 2 groups.

It is interesting to speculate on the particular significance of the indication of the importance of capillary penetration. It immediately suggests that failure is removed to longer periods, the more completely the paper fiber is penetrated or saturated with the oil. This picture then immediately suggests as a cause of failure some action such as ionization in the microscopic channels of the cellulose fiber. That this picture is a true one is borne out also by tests made at evacuation pressures of 0.25 mm[1] in which a noticeable increase of life was found. It seems certain, therefore, that the residual air or gas remaining in the paper even below evacuation and impregnation pressures of 1 mm also plays a part in the life history. It is to be noted, however, that these residual traces of air are those existing in microscopic channels only. There is no evidence in these experiments that gaseous ionization in the original acceptance of the term, plays any serious part in the deterioration of these specimens. Gaseous ionization, if involved in the failure, is of a different and much smaller order of magnitude than that occurring in solid cables. Moreover, it is of such a character as to be subject to influence or control by the capillary forces of the oil in its penetration into the paper.

In a recent paper M. Höchstadter and W. Vogel[4] reach the conclusion that breakdown in thoroughly impregnated paper insulation is of pure electric rather than thermo-electric character. The evidence of our experiments is against this view. As indicated above, we find no serious temperature change at high stress over long periods of time, thus far bearing out the conclusions of the authors mentioned. On the other hand, we have clear evidence of approach to breakdown over several hours, during which there is a relatively rapid rise of both temperature and power factor. We conclude, therefore, that while thoroughly impregnated paper insulation may withstand extremely high stress for long periods at constant values of loss and temperature, breakdown, when it comes, is not of pure electric or other sudden type, but has all the characteristics of the so-called thermo-electric failure.

It should be emphasized again, perhaps, that the results reported here pertain to a degree of impregnation and its protection which are quite unattainable under the present methods of manufacture, handling, and operation of high voltage cables. Nevertheless, it has been shown that under controlled conditions impregnated paper can withstand stresses and attain life under stress far in excess of the values pertaining to the present usage of this important type of insulation. It appears a pertinent question whether it is not advisable therefore by modified methods or increased costs to take up some of this difference, not only in the oil filled cables of the upper ranges of voltage, but also possibly in those of solid type for lower voltages.

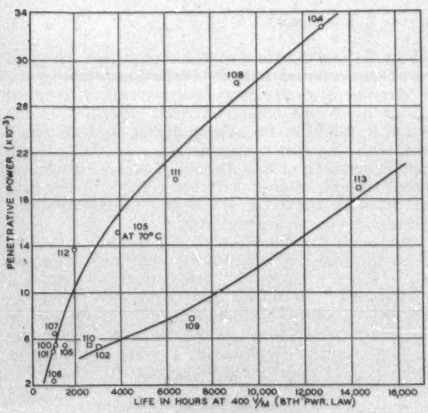


Fig. 8. Penetrative power-life curve

Kraft paper impregnated with various oils at 2.0-mm mercury
Life test at 40 deg C

Conclusions

1. A series of accelerated life tests has been made on one grade of paper as impregnated with 14 different high grade insulating oils. Wide differences in life have been found.

2. The influence of dielectric loss on the life of impregnated paper is within wide limits, negligible as compared with other factors.

3. The values of power factor and their characteristic changes during life tests have no apparent relation to the life of well-impregnated paper.

4. It is shown that the origin or basic chemical structure of the oil has an important bearing on the life of the impregnated paper.

5. Thoroughly impregnated paper will withstand electric stress far in excess of the values of practice over long periods of time without apparent change. Breakdown, when it comes, is of thermo-electric type, the approach to which may extend over several hours.

6. The differences in life in the oils of one base or origin are related directly to the capillary penetrative power of the oil into the paper. Measurements have been made of this capillary constant for each oil. For oils of one type and for a single grade of paper the life of the paper under electric stress is directly proportional approximately to the penetrative power of the oil into the paper.

This work has been carried on under the auspices and with the support of the committee on research of the underground systems committee of the National Electric Light Association, to whom grateful acknowledgment is made. Thanks are also extended to E. W. Greenfield, C. E. Young, and C. O. Newman, research assistants in The Johns Hopkins University, for their skillful and enthusiastic coöperation.

References

1. Residual Air and Moisture in Impregnated Paper Insulation, III, J. B. Whitehead and F. Hamburger, Jr. A.I.E.E. Trans., v. 50, 1931, p. 1,430–40.

2. The Dielectric Losses in Impregnated Paper, J. B. Whitehead. A.I.E.E. Trans., v. 52, 1933, p. 667–81.

3. Capillary Action in Impregnated Paper Insulation, J. B. Whitehead and E. W. Greenfield. *Physics*, v. 3, 1932, p. 324–30.

4. The Problem of Insulation of High Voltage Cables, M. Höchstadter and W. Vogel. *Elek. u. Mach.*, v. 51, 1933, p. 218–22.

External Impedance Vs. Short-Circuit Currents

Effects of external impedance on short-circuit currents in synchronous machines and in networks are discussed in this article. The material presented is not claimed to be new; its chief value lies in the confirmation of calculations by test results, which tends to increase confidence in formulas previously developed. The formulas and test data are given in a form convenient for ready reference.

By
B. L. ROBERTSON
MEMBER A.I.E.E.

T. A. ROGERS
ASSOCIATE A.I.E.E.

Both of University of California, Berkeley

IN THE CALCULATION of short-circuit currents on synchronous machines or in networks, it is usual practice to treat the circuit as though it consisted of reactance only. The results of such calculations are approximate for several reasons, the 2 factors causing the greatest errors being resistance of the armature circuit and saturation of the machines, both of which usually are neglected. In many cases the consideration of reactance only is justifiable because of its predominant effect over resistance, and also because of the accuracy of the results obtained with the attending greater ease of calculation.

At present, the problem presented by saturation in general is unsolved, but is treated in some cases by the use of arbitrary factors. Resistance, however, has been taken into account in 3-phase short circuits on synchronous machines,[1] but is in need of further treatment in single phase systems.

Questions often arise concerning the manner in which resistance is to be considered in 3-phase short circuit computations for steady state and transient currents, and its effect upon system decrements. Material of such nature is not yet available in text books, but is to be found only in technical literature in relatively recent years.

It is the intent in the present article to give in brief form, the effect of external resistance and reactance in the field and armature circuits. The fundamental equations from which calculations of open- and short-circuit time constants, and transient and steady state currents of a simple 3-phase system may be made are stated, together with a table of additional comparative test data. Further, it is indicated how these equations may be applied to system decrement curves.

Field

The short-circuit characteristics of a synchronous machine depend upon both the field and armature time constants, as shown by Park and Robertson.[2] This is evident also from physical reasoning. The open-circuit time constant of the field circuit normally is given by the relation

$$T'_{do} = \frac{L}{R} \text{ seconds} = \frac{\omega L}{R} = \frac{X}{R} \text{ radians} \qquad (1)$$

where L is the total inductance in henries of the field to direct current, and R the total resistance. The time constant, when given in radians, may be converted to seconds by dividing by ω, the angular velocity of the system. The time constant may be expressed also in cycles as the product of its value in seconds and the system frequency.

Usually L and R are taken with reference to the field coils alone, which is quite correct when the open-circuit time constant is obtained through test by short-circuiting the field winding. Under conditions of armature short circuit, however, the field circuit is untouched, and hence L and R are total quantities and are composed of all inductance and resistance in the field circuit.

Usually the exciter armature constants are small in comparison with the field quantities, and hence are neglected; but should the field current be supplied from a constant voltage source and controlled by means of a field rheostat, this external resistance must be taken into account. Additional inductance also may be present, and consequently, the open-circuit time constant of the field is then

$$T'_{do} = \frac{X + X_e}{R + R_e} \text{ radians} \qquad (2)$$

where X_e and R_e are the field circuit reactance and resistance external to the field coils themselves.

This open-circuit time constant may be determined either by a test similar to that described in the A.I.E.E. report of the subcommittee on definitions,[3] but with the closed circuit including the external field impedance, or from the rise of field current under sudden application of a direct voltage to the field circuit with the rotor stationary. Auxiliary rotor circuits, of course, are neglected.

Although the definition of T'_{do} is thus stated as in eq 1, perhaps it should be thought of as expressed by eq 2 which is general. For systems of individual excitation, the external field impedance is usually negligible; but for common systems of excitation, or for constant potential sources of field supply, the external impedance is usually present and must be considered in calculations of alternator short circuits.

Armature

Armature currents of a synchronous machine on short circuit, and system currents under conditions

Written especially for ELECTRICAL ENGINEERING. *Not published in pamphlet form*

1. For numbered references see bibliography at end of article.

of fault in a network, are affected by the short-circuit time constant of the field. For the case of negligible armature resistance, the direct-axis transient short-circuit time constant of the field is given by the relation[3]

$$T'_d = \frac{x'_d}{x_d} T'_{do} \text{ seconds} \tag{3}$$

where x'_d is the direct-axis transient reactance of the circuit and x_d is the direct-axis synchronous reactance. Any change in the field resistance hence alters the value of T'_d because of the effect on T'_{do}. Upon inclusion of resistance r in the armature circuit, the time constant used in 3-phase short-circuit calculations of a synchronous machine becomes

$$T'_d = \frac{r^2 + x'_d x_q}{r^2 + x_d x_q} T'_{do} \tag{4}$$

where x_q is the quadrature-axis synchronous reactance of the machine. This expression has been developed by Doherty and Nickle,[1] and is given also by Park.[4] It is an approximation, its accuracy being greater the greater is T'_{do}. For the generator tested, $T'_{do} = 0.70$ sec, the agreement between calculation and test was within $^1/_4$ of one per cent, an accuracy greater than the determination of the machine constants would allow. For a large machine of normal design in which the open-circuit time constant is about 5 sec, eq 4 may be considered exact.

This equation includes the 4 external constants of a synchronous machine which may be varied, i. e., external field resistance and reactance, and external armature resistance and reactance. The first 2 quantities affect T'_{do} as stated by eq 2. The total resistance of the armature and the external circuit is given by r, while any external reactance in the armature circuit is added directly to each of the various machine reactances. In detail

$$T'_d = \frac{(r_a + r_e)^2 + (x'_d + x_e)(x_q + x_e)}{(r_a + r_e)^2 + (x_d + x_e)(x_q + x_e)} \frac{X + X_e}{R + R_e} \text{ radians} \tag{5}$$

where the subscript e refers to the external circuits.

Relations for transient and steady state armature currents for 3-phase short circuits on synchronous machines were developed by Doherty and Nickle.[1] Their equations include both resistance and reactance of the external circuits. Knowing the armature flux linkages at the instant of the short circuit, the complete transient wave can be calculated. Considering only the symmetrical value of the alternating component of the short-circuit current, the expression for the effective value of the initial transient current is

$$i' = \frac{e'\sqrt{(r_a + r_e)^2 + (x_q + x_e)^2}}{(r_a + r_e)^2 + (x'_d + x_e)(x_q + x_e)} \tag{6}$$

and for the effective value of the steady state current

$$i = \frac{e'\sqrt{(r_a + r_e)^2 + (x_q + x_e)^2}}{(r_a + r_e)^2 + (x_d + x_e)(x_q + x_e)} \tag{7}$$

where e' is the terminal voltage preceding the short circuit. If x'_d is replaced by the direct-axis subtransient reactance x_d'', eq 6 gives the symmetrical value of the subtransient current at the instant of short circuit.

It is physically evident that the effect of external impedance in the armature circuit is to decrease both i' and i. External field resistance alters neither the initial nor the steady state values; but external field reactance, however, since x'_d is dependent upon it,[6] affects the initial current. Both field quantities influence the intervening current magnitudes. The

Table I—Comparison of Test Data and Calculations

Test No.	Circuit Constants R	Circuit Constants r	Circuit Constants x_e	T'_d, Seconds Test	T'_d, Seconds Calc.	i', Amperes Test	i', Amperes Calc.	i, Amperes Test	i, Amperes Calc.	Ratio i'/i Test	Ratio i'/i Calc.
1	1.00	0.07	0	0.156	0.157	94.2	93.6	22.3	21.6	4.22	4.33
2	1.24	0.07	0	0.127	0.126	84.0	83.9	20.0	19.4	4.20	4.33
3	1.87	0.07	0	0.088	0.086	85.6	84.2	19.9	19.5	4.29	4.32
4	1.23	0.49	0	0.258	0.256	39.3	40.6	18.0	18.2	2.18	2.23
5	1.00	0.85	0	0.420	0.448	23.5	23.9	16.0	15.8	1.47	1.52
6	1.87	0.85	0	0.244	0.245	23.3	23.7	15.9	15.7	1.47	1.51
7	1.00	0.45	1.47	0.487	0.483	11.5	11.5	7.9	8.0	1.46	1.44
8	1.23	0.49	0.14	0.278	0.278	35.0	34.5	16.3	16.2	2.15	2.13
9	1.87	0.45	1.47	0.254	0.258	11.5	11.5	7.9	8.0	1.46	1.44

Fig. 1. Oscillogram of short-circuit current corresponding to test No. 1 of Table I. Test ratio of $i'/i = 4.22$

Fig. 2. Oscillogram of short-circuit current corresponding to test No. 5 of Table I. Test ratio of $i'/i = 1.47$, showing effect of external armature resistance

change in magnitude of the symmetrical component of the short-circuit current is less with greater armature impedance, that is, with increasing values of armature circuit impedance the ratio i'/i decreases, as shown by the oscillograms of Figs. 1 and 2. The upper limit for the ratio is x_d/x'_d, in which case the external impedance is zero and the armature resistance is considered negligible; the lower limit of the ratio approaches unity as the external armature impedance approaches infinity.

Test Results

To illustrate the applicability of the foregoing expressions, Table I gives test and calculated values of short-circuit time constants, and transient and steady-state armature currents on a standard alternator. Also included in the table is the ratio of the symmetrical components of the initial transient and steady-state currents. A 3-phase machine was used for the tests having a rating of 35 kva, 1200 rpm, 60 cycles, 440 volts. The test results were obtained from short circuit at no load and approximately 200 volts. The machine constants are: $x_d = 1.04$, $x_q = 0.565$, $x'_d = 0.234$, and $r_a = 0.07$ in per-unit terms; $R_f = 13.7$ ohms.

Quantities varied were field circuit resistance, and armature circuit resistance and reactance. Respectively these constants are R, r, and x, and, on the basis of normal ohms for field and armature, are total per-unit values for those circuits. To illustrate the accuracy of the relations, the values of the external quantities were varied purposely over fairly wide ranges. The agreement between test and calculations is good, being about 2 per cent in the majority of cases.

Calculation of the short-circuit time constants involved the use of T'_{do}, the open circuit time constant. It was found to be 0.70 sec and was obtained by both of the methods discussed in this article, the results agreeing to within less than 1 per cent. Figures 3 and 4 show oscillograms of both methods.

The equations that have been given for the armature currents and short-circuit time constants of a synchronous machine on 3-phase short circuits apply directly where externally lumped impedances are closed across the armature terminals. Further than this, though, is the application to system decrement curves. Present practice[5] in determining system currents under conditions of fault makes use only of the reactances of the network and of the connected apparatus, and of the short-circuit time constants as affected by the reactance. Calculations and required test data are determined for 3-phase short circuits, but by the method of symmetrical components may be applied to single phase faults.

When the system can be condensed conveniently, it may be treated as a lumped impedance at the terminals of the machine and calculations made as indicated by the relations given in this article. The importance of including resistance lies in both the determination of current magnitudes and the rate of decay during transient conditions because of their bearing on relay settings for circuit breaker operation. For large external armature circuit impedances, resistance considerably affects the transient time constant.

Perhaps it should be pointed out that for a completely offset current wave, in which case the d-c component of armature current is equal in magnitude to the peak of the initial symmetrical component, the resultant effective value of the short-circuit current is given by

$$i_{initial} = \sqrt{i'^2 + (\sqrt{2}\,i')^2}$$
$$= \sqrt{3}\,i'$$

This is the upper limit for the magnitude of the initial current when it is calculated by using transient reactance; however, the maximum possible current would be found from calculations using subtransient reactance.

Bibliography

1. Three-Phase Short Circuit Synchronous Machines—V, Doherty and Nickle. A.I.E.E. Trans., v. 49, 1930, p. 700–14.
2. The Reactance of Synchronous Machines, Park and Robertson. A.I.E.E. Trans., v. 47, 1928, p. 514–35.
3. Proposed Definitions of Terms Used in Power System Studies, a report of the A.I.E.E. subject committee on definitions. Elec. Engg. v. 51, 1932, p. 106–07.
4. Two-Reaction Theory of Synchronous Machines—II, Park. A.I.E.E. Trans., v. 52, 1933, p. 352–4.
5. Standard Decrement Curves, Hahn and Wagner. A.I.E.E. Trans., v. 51, 1932, p. 353–61.
6. The Operational Impedances of a Synchronous Machine, Waring and Crary. *G. E. Rev.*, Nov. 1932.

Fig. 3. Decay of armature voltage on open circuit from which open-circuit time constant may be obtained

Fig. 4. Field build-up with no external impedance in the field circuit. The open-circuit time constant may be obtained also from this test

Measurement of Wetting of Dielectrics

Penetrability studies have been made to measure the wetting of dielectrics, in an effort to secure information on the electrical characteristics of impregnated fibrous structures. The results of these studies are discussed in this article, which includes studies of the penetration of water, benzene, and several insulating materials.

By
D. A. McLEAN
G. T. KOHMAN

Both of Bell Tel. Lab., Inc., New York, N. Y.

THE ELECTRICAL behavior of impregnated fibrous structures is a complex function of the nature and distribution of the constituents. Lowry[1] has pointed out that in many cases calculations of the dielectric constants of solutions and heterogeneous mixtures on the basis of relations which have been proposed do not agree with the experimental facts. It is not surprising to find statements by Riley and Scott[2] and by Wiseman[3] to the effect that it is impractical to discuss dielectric properties of systems of impregnated fibers as functions of the fiber or impregnant alone. It must be expected, rather, that the dielectric properties will in any case depend upon the particular combination of fiber and impregnant, and that in such a combination certain effects may be noted which might not be readily predicted from a study of the constituent materials separately.

Characteristic of such a combination of liquid and solid is the degree of wetting, which aside from its obvious influence during the process of impregnation serves also as a measure of the adhesive forces between the phases. For these reasons it appears fitting to consider methods for arriving at a measure of wetting and to discuss the significance of such measurements. The experimental data obtained so far are preliminary in nature, but they do indicate that the line of attack described here is capable of providing significant data to those interested in impregnated dielectrics.

General

Several investigators, including Whitehead and Hamburger,[4] Roper,[5] and Riley and Scott[2] have stressed the importance of complete impregnation and removal of residual air and moisture. The latter authors correctly state that complete impregnation requires the natural force causing the liquid to penetrate the fine capillary spaces to be high.

This capillary force is a function, not alone of the capillary dimensions of the structure and the properties of the liquid, but also of the specific mutual attraction operative between the solid fiber and liquid impregnant. Thus it will be related to the retention of impregnant in the pores between the fibers, and the displacement of impurities from the fiber surface; probably also to surface conductance and through this indirectly to the dielectric strength, losses, and life of the insulation.

Conduction on cellulose fibers in contact with water has been demonstrated by Stamm[6] and especially Briggs.[7] Murphy and Lowry[8] have discussed the possibility of an electrical conduction in textiles consisting of a movement of ions over fiber surfaces. Riley and Scott,[2] in discussing breakdown of impregnated paper, attach much importance to this type of breakdown.

High adhesion may reduce the conduction by ions on the fiber surface by (1) the impregnant being held firmly to the outer surfaces of the fiber and thus decreasing the solid gas leakage paths, (2) the increase in viscosity of the interfacial phase by high adhesive forces, and (3) the displacement of ionic impurities from the surface owing to high attraction between cellulose and impregnant.

The wetting of cellulose may determine to some extent the effectiveness of a wax impregnant in sealing the fibers from moisture, since good wetting minimizes the possibility that cracks formed on cooling will follow the interface.

In the process of impregnation, the force promoting wetting is measured as the product of the surface tension of the liquid and the cosine of the contact angle liquid-solid. With contact angles other than zero, this corresponds to the Freundlich "adhesion tension" which Bartell and Osterhof[9] have accepted as a measure of the degree of wetting. This product, $\lambda \cos \theta$ (where λ is the surface tension of the liquid and θ the contact angle solid-liquid), will be referred to here, as the "penetration tension" γ thus recognizing (1) that where the contact angle is zero this product may be smaller than the adhesion tension, and (2) that the contact angle may vary depending upon the direction of movement of the liquid-solid-air boundary line over the solid surface. In restricting ourselves to consideration of penetration tension we will be interested in the movement in the direction of the unwetted solid, as occurs in impregnation.

Experimental Attack—Qualitative

If the penetration of 2 liquids of equal viscosity and density into identical paper strips held vertically is observed, it is obvious that the liquid having the higher value of penetration tension will penetrate the farther in a given time. If, on the other hand, a single liquid is employed with strips of dissimilar

Prepared especially for Electrical Engineering. *Not published in pamphlet form.*

1 For all numbered references, see list at end of article.

paper, the liquid will rise in a given time to different heights, dependent upon the capillary structure of the paper, and upon the value of penetration tension peculiar to the combination of liquid and fiber. This latter procedure forms the basis for many

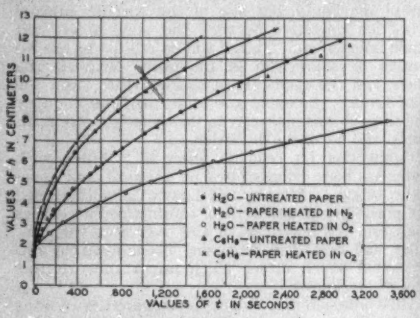


Fig. 1. The effect of treatment of paper upon penetration of water and benzene

current tests of "capillarity." What is often overlooked, however, is that a group of paper samples may fall in entirely different order as regards capillarity depending upon the liquid used.

That this is true has been demonstrated by treating paper to change the surface of the fiber so as to inhibit the penetration of water while leaving the penetration of benzene unaffected. Filter paper was chosen for all tests as representing a pure form of cellulose suitable for a fundamental study of this sort. Experiments are in progress now, however, in which papers employed commercially in dielectrics are being used.

Strips of filter paper 0.5 in. wide were marked lightly with a pencil at each half-centimeter of length. The rise of liquid when one end was suspended below the liquid surface was observed as a function of time. These tests were carried out in a narrow glass tube closed except for a small capillary opening in order to minimize any effect of evaporation. Alternate strips from a particular sheet were exposed to an atmosphere of dry oxygen for 3 days at 130 deg C after which they were tested for penetration with water and benzene and the results compared with those obtained using the original strips.

In Fig. 1 is illustrated the large decrease in the rate of penetration of water caused by the oxygen treatment, an inhibition not shared by benzene, which it may be noted is more akin to the impregnating compounds normally used than is water.

That the change brought about in the paper is not due to heat alone is shown by the fact that heating in nitrogen produces no change in the penetration of either liquid. That it is not due to absorption of grease to which the paper might accidentally have been exposed and which might retard the water is shown by the fact that extraction with benzene does not increase the water penetration. The paper can in some degree be revivified with respect to water penetration by extraction with water.

The explanation must be found in some change in the surface of the cellulose fibers which increases the contact angle water-cellulose without changing the contact angle benzene-cellulose. Recent experiments have shown that similar effects are noted

Fig. 2. The effect of oxygen treatment upon the attraction of cellulose for water and for benzene

A. Strip heated in oxygen
B. Untreated strip

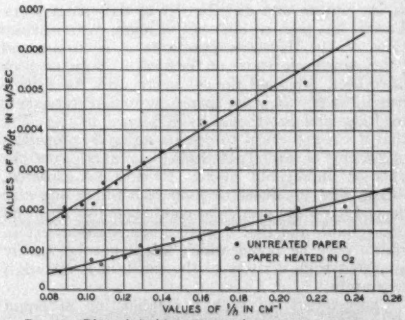


Fig. 3. Plot of dh/dt against $1/h$ using penetration data of Fig. 1

when paper is subjected to much less severe treatments than that described here.

That we are dealing here with actual attractive forces between the solid and the liquid is demonstrated convincingly by Fig. 2. An untreated strip and an oxygen-treated strip are shown suspended through a benzene-water interface. For the former the attraction of the fiber for the water is greater than for benzene and hence the interface around the strip is drawn up above the general level of the interface, while for the treated strip, exactly the reverse is true; i. e., the attraction for water is less than for benzene and the interface is drawn downward.

Experimental Attack—Quantitative

An analysis of penetrability data such as given in the preceding paragraphs may occasionally give all desired information. However, in general it is desired to relate the rate of rise to the capillary forces exerted and hence to the penetration tension of different liquids, for which something of the effect of viscosity in resisting the movement must be known.

For a uniform capillary tube the rise of liquid is represented by the equation:

$$\frac{dh}{dt} = \frac{R\gamma}{4\eta h} - \frac{R^2 dg}{8\eta}$$

where h is the height of rise in time t; R is the radius of the tube; γ the penetration tension; g the acceleration due to gravity; and η and d the viscosity and density, respectively, of the liquid.

Where a structure such as paper is dealt with, this equation cannot be expected to hold owing to the complexity of the capillary arrangement. In another paper, however, Peek and McLean[10] have developed a very similar equation for penetration into a disperse system, as follows.

$$\frac{dh}{dt} = \frac{A\gamma}{4\eta h} - \frac{Bdg}{8\eta} \quad \text{(see footnote*)}$$

A and B are constants determined by the pore size distribution function. B will be equal to A^2 only for the case of uniform pores. Using a given fibrous structure and different liquids, straight lines should be obtained for plots of $\frac{dh}{dt}$ against $\frac{1}{h}$. The slopes m of such lines would be proportional to $\frac{\gamma}{\eta}$ and the intercepts to $\frac{d}{\eta}$. The paper[10] just cited gives results on the penetration of several pure liquids into filter paper confirming the equation developed. Certain limitations of the methods and precautions which must be observed in the experimental set-up are given which will not be treated here.

In Fig. 3 is shown the analysis applied to the data of Fig. 1 on the penetration of water into untreated and oxygen-treated paper strips. Straight lines are obtained, the slopes having values of 0.0288 and 0.0120, respectively, so that it can be stated that the penetration tension has been decreased 58 per cent by oxidation of the cellulose.

If the data on penetration of benzene are attacked in the same way, the slope of the line being designated as m, the following are obtained:

Untreated, $m = 0.0728$
Oxidized, $m = 0.0768$

Since the former run was made at 27 deg C and the latter at 31 deg C it is necessary to multiply the slopes by the viscosity of benzene at these temperatures, which shows that there is no significant change in the penetration tension.

Untreated, $m\eta = 0.0427$
Oxidized, $m\eta = 0.0426$

Results on Impregnating Materials

Results obtained with several insulating materials at elevated temperatures are shown in Figs. 4 and 5. All results are referred to the value of $m\eta$ for benzene. In Table I the values of penetration tension, relative to that of the benzene, are designated as γ' and were calculated as follows for a given liquid, X:

$$\gamma'(X) = \frac{m\eta\,(X)}{m\eta\,(\text{benzene})}$$

The varying values of $m\eta$ for benzene are due to the fact that paper of the same porosity was not used in all of the tests. These data show that for

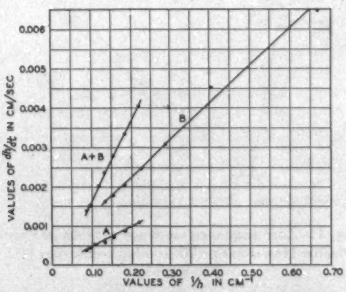


Fig. 4. Penetration of wax A, wax B, and 90 per cent wax B + 10 per cent wax A into paper strips

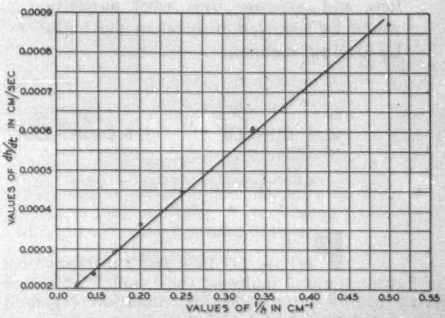


Fig. 5. Penetration of liquid C into paper strips

* Obviously if the average pore size is small and the heights of rise studied small, the second term representing the hydrostatic head becomes negligible and the equation integrates to give $h^2 = \frac{A\gamma t}{2\eta h}$ (for $t = 0$ when $h = 0$). In this event a plot of h^2 against t should give a straight line with a slope proportional to $\frac{\gamma}{\eta}$. Our results on filter paper strips have in general shown a small but significant negative intercept on the $\frac{dh}{dt}$ axis when $\frac{dh}{dt}$ is plotted against $\frac{1}{h}$ showing that while the effect of hydrostatic head is small, it is not entirely insignificant.

these particular materials the ratios of the penetration tensions to that for benzene are in the neighborhood of unity. The value for liquid C, a chlorinated hydrocarbon, is significantly higher than for the waxes. The value for the wax A-wax B mixture falls, as might be expected, between those for the constituents.

Table I—Calculation of Penetration Tension

Fig.	Material*	Temp. °C	η Poises	m	$m\eta$ (Benzene)	γ'
4	Wax A	106	0.0800	0.00506	0.000427	0.95
4	Wax B	120	0.0265	0.00964	0.000247	.02
4	Wax B + 10% Wax A	125	0.0260	0.0200	0.000536	0.97
5	Liquid C	105	0.0255	0.00197	0.000427	1.17

* All of these materials are commercial products. Wax A is a hydrocarbon wax, was B a chlorinated naphthalene and liquid C a chlorinated diphenyl.

References

1. The Significance of the Dielectric Constant of a Mixture, H. R. Lowry. *Jl. Franklin Inst.*, v. 203, 1927, p. 413–39.
2. Electrical Insulating Papers for the Manufacture of Power Cables, T. N. Riley and T. R. Scott. *The Jl. of the Inst. of Elec. Engrs.*, v. 67, 1929, p. 946–67.
3. Insulation Variability (Discussion), R. J. Wiseman. A.I.E.E. Trans., v. 50, 1931, p. 1457–8.
4. Residual Air and Moisture in Impregnated Paper Insulation—II, J. B. Whitehead and F. Hamburger, Jr. A.I.E.E. Trans., v. 50, 1931, p. 1430–40.
5. Report of Committee on Elec. Insulation, D. W. Roper. Div. Engg. and Ind. Research, Nat. Research Council. December 1931.
6. Electroendosmose Through Wood Membranes, A. J. Stamm. *Colloid Symposium Monograph*, v. 4, 1926, p. 246–57.
7. The Determination of the ζ-Potential on Cellulose—A Method, D. R. Briggs. *Jl. Phys. Chem.*, v. 32, 1928, p. 641–75.
8. The Complex Nature of Dielectric Absorption and Dielectric Loss, E. J. Murphy and H. H. Lowry. *Jl. Phys. Chem.*, v. 34, 1930, p. 598–620.
9. Determination of the Wettability of a Solid by a Liquid, F. E. Bartell and H. J. Osterhof. *Ind. and Engg. Chem.*, v. 19, 1927, p. 1277–80.
10. Paper to be published in *Ind. and Engg. Chem.*, R. L. Peek and D. A. McLean.

Locating Grounds by Distribution Ratio Method

A method of locating ground faults on electric power transmission lines has been developed wherein the location of a fault can be determined accurately and conveniently from the percentage distribution of ground current fed into the fault from the 2 ends of the line. This method has been applied to the Pennsylvania-New Jersey 220-kv interconnection since 1930; results obtained indicate a large saving in time and expense over what normally would be involved in locating the faults by previous methods.

By
W. F. DUNKLE
ASSOCIATE A.I.E.E.

J. S. DeSHAZO
ASSOCIATE A.I.E.E.

Both of the Pennsylvania Power & Light Co., Hazleton

PRIOR TO 1930 the 2 methods used for locating ground faults on the Pennsylvania-New Jersey 220-kv interconnection employed (1) fault current-distance curves and (2) distance measurements in ohms by several types of impedance or reactance relays. Because of varying changes in generating capacity and fault impedance during fault conditions, certain errors are inherent in both of these methods. During subsequent study of the problem, it became evident that the zero sequence system constants seldom were affected by switching operations. It was obvious also that the ground currents fed from the ends of any line were functions of the fault distance from the line terminals, and that the ratio of these currents is unaffected by the

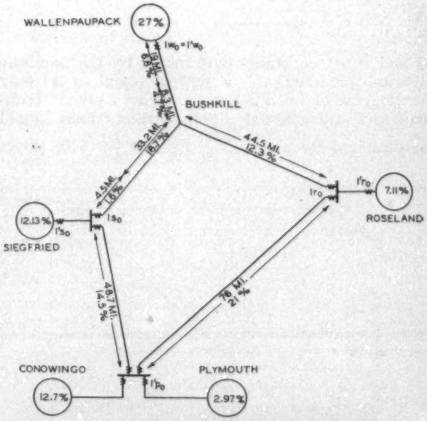


Fig. 1. Zero sequence reactance diagram of Pennsylvania-New Jersey 220-kv interconnection; 100,000-kva base

Written especially for Electrical Engineering. *Not published in pamphlet form.*

impedance of the fault. From these facts it was deduced that if ground current distribution ratios could be used for locating faults, the discrepancies inherent in methods previously used would be eliminated. This led to the development of the distribution ratio method which subsequently has been used successfully for more than 2 years.

This method employs curves of ground current distribution showing the ground current fed from one end of the line in per cent of total, plotted against line miles to the fault. Since only zero sequence reactance affects the distribution of ground current, an extensive knowledge of symmetrical components is unnecessary. Curves using per cent of total current fed from the ends of the line employ line residual

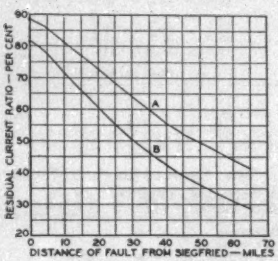


Fig. 2. Curves for locating faults on Siegfried - Wallenpaupack 220-kv line by the distribution ratio method during 1931

Curve A. Ratio of $\frac{\text{Siegfried}}{\text{Siegfried + Wallenpaupack}}$ line residual currents

Curve B. Ratio of $\frac{\text{Siegfried}}{\text{Siegfried + Wallenpaupack}}$ transformer residual currents

currents. Curves using per cent of part total employ residual currents fed from grounded transformers. Either may be used depending upon which can be recorded with the greater accuracy and economy. A single current element when connected to record transformer residual current will suffice in locating faults on any number of lines radiating from that transformer. Similarly, a single current element is required on the grounding bank at the far ends of these lines.

Calculations

There are 3 methods of obtaining fault location curves for the distribution ratio method; they are:

1. Calculation when zero sequence reactance values are available.
2. Staged tests at 2 or more locations on a line.
3. Chance recording of ground current at each end of the line for faults at several locations.

For method 1 only the grounding transformer zero sequence reactance values and the physical characteristics of the line need be known. The division of ground current is the inverse ratio of zero sequence reactances. Methods 2 and 3 eliminate errors due to current transformers, instrument calibration, and the zero sequence reactances used in calculations.

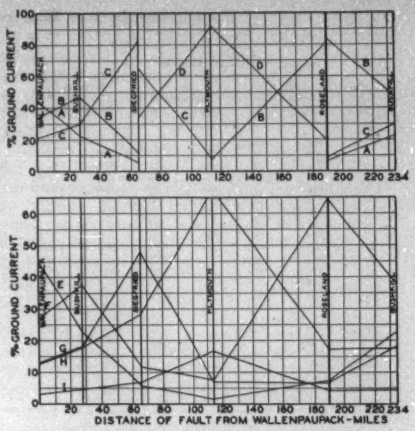


Fig. 3. Curves for locating ground faults by the distribution ratio method on the Pennsylvania-New Jersey 220-kv interconnection

Upper curves show the division of total ground current between the ends of the faulted line; lower curves show this distribution between the 5 stations with grounding transformers

Curves	Per Cent Current From
A and E	Wallenpaupack
B and F	Roseland
C and G	Siegfried
D and H	Plymouth
I	Conowingo

Where the line is of uniform construction and is not affected by adjacent parallel lines, the per cent residual fed from either end is a straight line function. Consequently a straight line may be drawn through any 2 points determined by faults at different and known locations.

A sample application of line residual currents to the location of a fault follows:

Siegfried-Wallenpaupack residual at Siegfried = 1,580 amp
Siegfried-Wallenpaupack residual at Wallenpaupack = 400 amp

$$\frac{\text{Siegfried residual}}{\text{Siegfried + Wallenpaupack residual}} = \frac{1{,}580}{1{,}980} = 79.7 \text{ per cent}$$

This value when applied to curve *A*, Fig. 2, indicates the fault location as 12 miles from Siegfried. The actual location was 12.3 miles.

In a similar manner transformer residual currents are applied to curve *B*, Fig. 2.

Automatic Recording Instruments

Three types of recording instruments have been applied to fault location on the Pennsylvania Power and Light Company system; they are:

1. Graphic high speed ammeters.
2. Oscillographs.
3. High speed photographic recorders.

The only limitation preventing the exact locating of faults is the accuracy of current measurements.

Table I—Fault Location Data for Wallenpaupack-Siegfried Line, 1931

Tripout No.	Transformer Residual, Amperes: By Ammeters I''_{w_0}	By Ammeters I''_{s_0}	By Oscillographs I''_{w_0}	By Oscillographs I''_{s_0}	Line Residual Amperes by Oscillographs I_{w_0}	I_{s_0}	Current Ratios: Transformer Residuals I''_{s_0}/I''_{t_0}	I''_{s_0}/I''_{t_0}	Line Residual I_{s_0}/I_{t_0}	Fault Distance Miles From Siegfried: Calculated By I''_{s_0}/I''_{t_0}	By I''_{s_0}/I''_{t_0}	By I_{s_0}/I_{t_0}	Actual by Flashover Indicators
1*	150	1,200				2,880	0.890			0			0
2	375		390	1,655	390	2,080		0.811	0.842		1.0	6.7	6.6
3	594	700	630	730	630		0.540	0.537		26.5	26.9		30.2
4	495	1,056		1,055		1,230	0.682			13.3			16.5
5	414		400	1,200	400	1,855		0.750	0.823		7.4	9.0	7.5
6	354	500	520	885	520	1,310	0.586	0.630	0.716	22.3	17.8	21.3	20.8
7	685	550	720	592	720	907	0.445	0.444	0.561	37.0	37.1	39.5	39.7
8	542	624		657			0.535			27.0			37.8
9	369	870	500	657	500	1,875	0.703	0.568	0.790	11.0	23.7	12.0	9.3
10	306	672	399	600	399	1,580	0.687	0.600	0.797	12.5	20.7	12.0	12.3
11	512	768		770		968	0.600			20.7			27.3
12	548	600	584	795	584	1,050	0.526	0.576	0.642	29.0	23.6	31.0	26.5
13	548			738		937							29.3
14		1,320	315	1,396	315	1,937		0.816	0.860		0.3	4.8	5.3
15	433	1,320	400		400	1,597	0.735		0.800	8.5		11.4	9.2
16**	783		890	552	890	350		0.383	0.282		46.0	65.0	65.0** & 38.0
17	613	552		982		783	0.473			32.5			29.5
18	450	490	670	844	670	814	0.520	0.557	0.548	28.5	24.9	41.3	36.0
19	426	864	624	1,039	624	855	0.670	0.625	0.574	14.2	18.3	37.7	26.5
20	468	1,032	480	1,218	480	1,442	0.687	0.717	0.750	13.0	10.0	17.5	15.7
21†													
22			400		400	400			0.500			49.0	45.0

*Tripout No. 1 developed after several cycles from a two phase into a solid three phase fault.
**Tripout No. 16 was double fault to ground.
†Tripout No. 21 was due to control trouble at Siegfried.
Iw_0, Is_0, etc., refer to the diagram shown in Fig. 1; It_0 represents the total residual amperes or the summation of all ground currents.

For this reason too much emphasis cannot be placed upon the type of instruments used and the care taken in their maintenance. Graphic high speed ammeters should be properly and identically damped at all locations.

Some knowledge of oil circuit breaker performance is essential in order that high speed records of current may be applied properly to fault location. Any single fault location curve is applicable only so long as the system set-up exists for which the curve was determined. Therefore, it is imperative that current values used in fault location be taken at the same time from the start of the fault and prior to switching operations which change the distribution of ground current. The use of high speed oil circuit breakers requires quick initiation and recording by the current instruments.

Application to 220-Kv Pennsylvania-New Jersey Interconnection

Figure 1 shows the line and equipment zero sequence reactances for this interconnection. These values are for the maximum connected capacity. Residual current measurements are made at points indicated by current transformers.

That section of the interconnection between Bushkill and Roseland was not in service until December 1931. Curves shown in Fig. 2 were calculated for this condition, and hence applied to the Siegfried-Wallenpaupack line only. Curves shown in Fig. 3 were calculated for the completed interconnection, and are applicable to fault location at any point around the loop. Ratios obtained from any 2 current records permit fault location; the large number of possible combinations of records thus enables faults to be located even though some of the records may be lost. Current values from stations adjacent to the fault are larger and lead to greater accuracy.

Table II—Fault Location Data, Siegfried-Roseland-Wallenpaupack Tap Line, 1932

Tripout No.	Calculated Miles From Siegfried by the Ratios: $\frac{Is_0}{Is_0 + Iw_0}$	$\frac{Is_0}{It_0}$	Actual Miles From Siegfried	Number Phases Faulted to Ground
1			0	1
2	7.0		6.7	1
3	33.7		37.4	1
4			14.5	1
5	32.4	30.7	30.0	1
6	38.0	34.5	38.8	1
7*			65.0* & 34.5	1
8	26.0	33.7	22.7	1
9*	61.6	57.5	65.0*	1
10	37.0	47.5	37.8	1
11			12.0	3
12	65.0	63.0	65.0	1
13	65.0	63.0	65.0	2
14	65.0	64.0	65.0	2
15		81.2	81.2	1
16		81.2	81.2	2
17	37.0	35.0	37.7	1
18	41.0	35.0	37.7	2
19	0	0	0	1

Faults 1 to 11 were caused by lightning, and 12 to 19 were staged tests.
*Tripouts 7 and 9 were caused by double faults to ground.
Is_0 and Iw_0 refer to Fig. 1; It_0 is total residual current.

During 1931 and 1932, 43 faults occurred on the interconnection, 33 of which were on Siegfried-Roseland-Wallenpaupack tap line. Part of this line, 41.5 miles, is not protected by overhead ground wires; 32 of the 33 faults occurred on this unprotected section. Actual fault locations on the Siegfried-Wallenpaupack section were indicated to line patrolmen by line flashover indicators and confirmed by lightning stroke recorder records. During 1933, of the 17 faults that have occurred to date, 13 have been located by this method within a distance of about 2 miles.

Table I shows current values with calculated and actual location of faults which occurred during 1931.

Table II shows only calculated and actual distances from Siegfried for faults which occurred during 1932.

Conclusions

Experience so far with the distribution ratio method has led to the following conclusions:

1. The immediate availability of graphic high speed ammeter records and their close agreement with the oscillograph renders the method of great value for quickly locating and clearing a permanent failure of line insulation. The simplicity of using ammeter records facilitates the station chief operators in approximating fault locations and intelligently directing line patrols.

2. This method provides for a possible economy estimated to be 80 per cent of the cost of line patrolling.

3. It is applicable to any type of fault resulting in ground current whether it be single phase, 2-phase or unbalanced 3-phase.

4. It is not applicable to simultaneous faults at different locations.

Protective Relays on Pa. Locomotives

No current rupturing device is provided between pantograph and main transformer on electric locomotives recently placed in operation on the Pennsylvania Railroad; instead a "pantograph relay" is used which is connected so as to utilize the substation circuit breakers to open high voltage short circuits, grounds, or overloads on the locomotive. A voltage relay is used to change the field strength of the traction motors at a predetermined speed, and slip relays provide protection against wheel slippage.

By
BENJAMIN LUTHER
General Elec. Co., Erie, Pa.

PROTECTION of a-c locomotives against electrical faults never has been standardized nor has any system been applied in which one or more groups of engineers have not believed that objectionable or questionable features were involved. Engineers of the Pennsylvania Railroad, in common with many others, do not favor oil switches on locomotives; accordingly, they have developed a system in which locomotive faults ground the trolley wire, thus short circuiting the faulty locomotive and throwing the duty of clearing the resulting current on the substation circuit breakers. This system brought forth the development of an interesting relay known as the pantograph relay, though its functions are not confined to, nor primarily concerned with, the pantographs.

Modern a-c series motors such as those used on the new Pennsylvania locomotives are operated at low magnetic flux to minimize commutation troubles; during the starting period the exciting fields are weakened further by the use of inductive shunts. A newly developed voltage relay makes possible the proper selection between weak and full fields. The high peripheral speeds of these motors make it advisable to protect against wheel slippage, particularly at the higher operating speeds; special slip relays, therefore, have been developed for this purpose. Operation and characteristics of these 3 relays as applied to the type *P5A* heavy duty passenger locomotive are described in this article.

Voltage Relay

The voltage relay is used to change the field strength of the traction motors from weak to full at a proper speed, in this case approximately 15 mph. It has been found that armature voltage gives a sufficiently accurate indication of speed, and that a shaded-pole induction motor operated on voltage may be the actuating element. The requirements are:

1. An operating element to function at the desired speed.

2. Means to prevent the increase in tractive effort, when changing to full field, causing wheel slippage or the tripping of the overload relays.

3. Means to prevent burning out the a-c element at high speeds, when the voltage is approximately 6 times that at pick-up.

4. Provision for the relay to drop out again if the locomotive is slowed down below a desirable full-field operating speed.

5. Provision against a weak field when power is turned on after coasting at high speeds.

6. A high inherent drop-out point, since the voltage on full field at the speed of operation is some 40 per cent greater than at the same speed on weak field.

Essential connections of the voltage relay are shown in Fig. 1. Contact *A* lights a warning lamp just before changeover takes place, so that the engineman will not move the controller and superpose a normal notch on the increment caused by the changeover. Contact *C* makes the changeover and the warning light is put out by an interlock on one of the switches. Contact *B* energizes a locking coil which holds the relay and also opens contact *D*, removing the a-c voltage.

Weak field cannot be obtained on any forward or backward movement of the controller above notch 6. If the controller is shifted to a lower notch, the locking coil is deënergized, reclosing contact *D* before changeover to weak field can take place. This returns control of the field strength to the operating relay element. The actual drop-out of the relay is properly commutated by the auxiliary coil and contact *E* which controls a drop-out resistor.

The locomotive thus is controlled fairly accurately

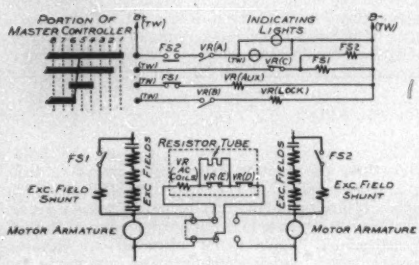
Written especially for Electrical Engineering. *Not published in pamphlet form.*

to operate at all times with weak field below, and full field above, a predetermined speed.

Slip Relays

The slip relays, one in each motor circuit, are operated by the same type of motor elements as the voltage relays. They obtain their indication for operation from the differential in voltage between 2 motors connected in series, when one slips or the 2 slip at different speeds.

Figure 2 shows part of one motor circuit, an auto-transformer being connected across 2 traction motors on different axles. The coils of the slip relays are connected between the midpoint of the pairs of motors and the midpoint of the auto-transformer. Except for a certain variation because of regulation, the midpoint of the auto-transformer is always at a potential half way between the points to which its end leads are connected. So long as neither motor is slipping, the voltage at their midpoint is the same and there is no voltage across the slip relay.



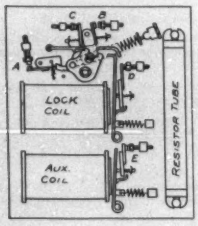


Fig. 1. Voltage relay for changing from weak to full field, and connections

B+ positive lead
B− negative return
FS1, FS2 interpole shunt switch
(TW) train wire
VR voltage relay

Sometimes the 2 motors are not identical, or tire diameters cause them to divide the total voltage unequally. To compensate for such differences, adjusting taps are provided on the auto-transformer; by means of these the slip relay may be so connected that, with neither motor slipping, practically no current will flow through the operating coils of the slip relay.

The voltage balance between the 2 motors is disturbed as soon as one motor slips; as the voltage at the midpoint of the auto-transformer changes only slightly, voltage appears across, and current flows through, the slip relay, starting at a low value and increasing as the differential in speed between the 2 motors increases.

At a nominal differential speed of 5 mph, sufficient current passes through the slip relay to cause it to start to rotate, and to close a contact which actuates a buzzer and an indicating lamp in front of the engineer who then shifts the controller to a lower speed notch. If he can stop the slipping by this means, the relay will return to its original position and the acceleration will continue; should he be unable to stop the slipping or should he take no action, the relay will remain energized and when a nominal differential in speed of 20 mph is reached a second set of contacts open and latch, removing power from the traction motors. It is then necessary for the engineer to turn the controller fully off before he is able to reset the relay by means of the reset switch at his operating position.

Pantograph Relay

The pantograph relay (Fig. 3) is designed to take care of faults that might develop on the locomotive and cause heavy overloads in the transformer primary, and grounds in the primary or in any of the circuits connected to the secondary. Short circuits in the secondary, except where protected by fuses or the motor-overload relays, must go to ground before they are removed, unless they cause a primary overload sufficient to trip the pantograph relay. Any heavy short circuit, however, will go to ground in a brief time.

The primary function of the pantograph relay, called the *PR* relay, is to operate the grounding switch that grounds the trolley thereby shunting the resulting current around the locomotive and causing the feeder breakers in the substation to open. This method effectively protects the locomotive, but is a decided disadvantage to the rest of the system. One of the functions of the *PR* relay, therefore, is to prevent closing this grounding switch if the fault can possibly be cleared by the apparatus on the locomotive. The relay also must be highly sensitive, and yet not trip on surges caused by energizing the main transformer, by sleet, section breaks, etc. A further function, from which it gets its name, is to lower the pantographs after the fault is cleared and thus permit the feeder breakers to reclose. This latter is necessary only when the locomotive apparatus is unable to clear the fault. As the trolley wire is very low in some places, particularly in the tunnel under the Hudson River, it is further necessary to

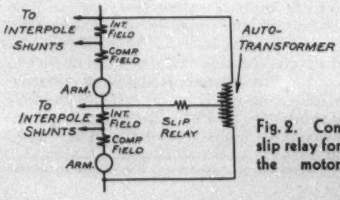


Fig. 2. Connections of slip relay for protecting the motors against wheel slip

prevent lowering the pantographs unless and until the feeder breakers actually do open.

Faults in the main transformer or the bus bar immediately connected thereto cannot be cleared by the locomotive apparatus; hence, when faults of this nature occur the *PR* relay must operate the ground switch. Faults anywhere in the main motor circuits may be cleared by opening the line switches.

The relay consists of a motor element similar to the voltage and slip relays, but with a 2-circuit coil arrangement. One section acts as an overload coil in series with 2 current transformers, one in each primary lead of the main transformer. The other section acts as a differential coil, measuring the difference between current entering and current leaving the transformer primary. This coil also may be separately excited to obtain tripping from other sources as noted later.

The relay has a considerable travel and works against a spring which pulls the moving parts counterclockwise. The normal reset position is approximately in the center of the travel range, the spring holding the moving parts against a latch held in place by an a-c holding coil. Torque caused by energizing either set of motor coils moves the relay clockwise. Early in the travel the *A* and *A1* contactors are actuated. If torque remains, contact *B* is energized at the extreme clockwise travel. If the holding coil and its latch be released and torque removed, the spring rotates the moving parts counterclockwise to extreme position, actuating the *B* and *C* contacts.

If a surge be caused by the starting current when energizing the transformer, the slight resultant movement of the relay takes place without tripping the *A* group of contacts, and the relay resets automatically.

If a ground (including one from motor arcover) occurs in the traction motor circuits, current will circulate through the ground resistor and current transformer connected to the midpoint of a reactor between *D* and *E* taps of the transformer. This sends a corresponding current through the differential coil of the relay and causes it to travel far enough to actuate the *A* group of contacts. These open the motor line switches and incidentally all auxiliary contactors, thereby clearing the trouble, and also operate a buzzer and light an indicating lamp at each operating position. As soon as the trouble is cleared, relay torque is removed and the moving parts reset automatically, but the *A* group of contacts remain tripped. These can be reset remotely by the control switch at the operator's position.

If a ground occurs in the secondary of the main transformer or in the connected bus bars or switches, torque is similarly developed by the relay through the grounding current transformer connection. This time the *A* contacts open nothing that will clear the trouble and the relay continues until the *B* contact closes and throws the main ground switch. This removes voltage from the locomotive and causes the holding coil and latch to drop. The ground current, however, flows through one primary current transformer only and keeps torque on the relay. Only when both voltage and current have disappeared can the relay retract under the spring action to the fully tripped position which lowers the pantographs. The relay then must be reset manually.

If a ground occurs in the main transformer primary, the relay differential coil is excited directly from the 2 primary current transformers, and the operation is the same as in the preceding paragraph.

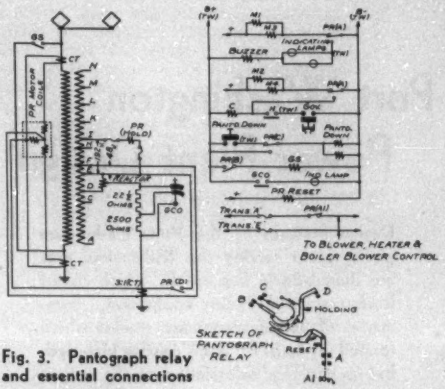


Fig. 3. Pantograph relay and essential connections

B+ positive wire
+ positive from apparatus not shown
B− negative wire
C− compressor contactor coil
CT current transformer
GCO ground cut out switch
Gov compressor governor
GS ground switch
H back circuit interlock
M1, 2, 3, 4, motor line switch coils
PR pantograph relay
(TW) train wire

A heavy primary overload will cause the relay to operate directly through the action of the overload coils. The same sequence of contact operation again takes place.

If on any of these faults the primary current should be so great that the feeder breakers open before the relay has time to close the ground switch, this removes the fault and the relay torque, and retraction takes place lowering the pantographs the same as under the other conditions.

If in any case the engineman finds or believes that the fault is merely a single ground, 2 extra positions of the ground cutout switch (*GCO*) are available. These insert extra resistance in the grounding current transformer circuit to limit the flow of current resulting from the ground fault. It may be possible to run the locomotive to the terminal on one of these connections, but a warning lamp will burn to indicate that operation is taking place partly or wholly without fault protection.

If a succession of surges and interruptions occur, the relay may trip and retract beyond the reset position during an interruption. Return of power at any time before the pantographs start to lower will apply, through the *D* contact, 48 volts to the differential coil and cause the relay to motor back and reset automatically, with no indication to the crew.

Protection thus is afforded under most fault condi-

tions. Only when the locomotive apparatus cannot clear a fault is the ground switch allowed to close, and never are the pantographs lowered so long as current is being taken from the trolley wires.

Port Washington Power Plant Design

Design features of the Port Washington power plant serving the Milwaukee area are described in this article, which covers both steam and electric equipment. Summaries of certain economic studies which formed the basis for decisions are included, but no statistical information on the various pieces of equipment is given. The initial installation includes an 80,000-kw unit, utilizing 1,230-lb steam pressure, and 825 deg F steam temperature.

By
G. G. POST
FELLOW A.I.E.E.

The Milwaukee Elec. Ry. and Lt. Co., Milwaukee, Wis.

THE PORT WASHINGTON generating station of The Milwaukee Electric Railway and Light Company, now under construction is located on the west shore of Lake Michigan at East Port Washington, Wisconsin, 28 miles north of Milwaukee. The station's initial capacity will be 80,000 kw (one unit) with a possible ultimate capacity of 400,000 kw (5 units). The outstanding feature will be its unit design, that is, there will be a single boiler for each single turbine-generator and also one set of transformers, one 132-kv transmission line, and one set of auxiliaries for each unit. The next most important advancement is the adoption of 825 deg F temperature for both throttle and reheat.

Selection of Site

Load growth made it apparent in 1928 that generating capacity would have to be added to the Wisconsin-Michigan system of the North American Company in order to maintain the proper relation between system capacity, peak demand, and reserve capacity. The selection of a site resolved itself into a search for one which would most nearly fulfill the following requirements:

1. Be north of the Milwaukee metropolitan area better to insure continuity of service. (The existing major generating station, Lakeside, is south of Milwaukee.)
2. Be located as close to the load center as practicable.
3. Be adjacent to Lake Michigan where the condensing water supply is ample and cold.
4. Be at a location where harbor facilities for lake boats have been established or could be provided at reasonable cost. In the Milwaukee area, water-borne coal has a distinct advantage over all-rail coal, due to the decided and abrupt railroad rate increase on coal in passing through the Chicago district.
5. Be at a location to which large industries might be attracted so that these could be served with energy directly from the station bus bars.
6. Be located so that connections to railroad lines (preferably the company's own) could readily be made, if in the future, combination of coal prices and freight rates should become such as to give rail-borne coal an advantage over water-borne coal.

Port Washington was the only place that met satisfactorily all of these requirements. It will have a coal dock which will eliminate the intervening rail haul with its attendant costs. The effect of this will be to lower its fuel cost about $2.59 per hundred million Btu below that of the Lakeside plant.

Determination of Size

In determining the size of the plant and of the units desire to make it possible to coöperate with industrial concerns that might wish to locate in the vicinity of the plant was an important factor. Because of its harbor, dock, and railroad facilities, Port Washington offers to new industries advantages far superior to those that can be found anywhere else in the vicinity of Milwaukee. Because of this it was felt that it would not be beyond reason to contemplate the possibility of industrial development in the vicinity of the plant to the extent of about 150,000 kw. The fact that Lakeside's last 2 additions were of 75,000 kw capacity each, that normal load in 1928, when Port Washington was originally planned, had been increasing at the rate of nearly 40,000 kw per year, and that there was a possibility of a large industrial load in addition to the normal growth, prompted the decision to install 80,000 kw initially at the new station.

Mercury-Steam Cycle Consideration

The possibility of large industrial plants locating in close proximity to the power station, some of which might require large amounts of process steam in addition to their electrical demands, suggested that serious consideration be given the mercury-steam cycle. For a given process steam demand the mercury cycle can generate over twice as much by-product electrical energy as can a straight steam cycle, or conversely, the net heat consumption in Btu per switchboard kilowatt-hour would be considerably less with the mercury cycle than with a

Essentially full text of "Design Features of the Port Washington Power Plant" (No. 33-68) presented at the A.I.E.E. summer convention, Chicago, Ill., June 26-30, 1933.

straight steam cycle if the kilowatt-hour outputs were the same. On the basis of straight condensing plants of equal capacity (100,000 kw) it was found that the mercury-steam cycle in order to equal the 1,200-lb steam cycle in total annual costs would have to be operated at an annual load factor on the plant of at least 65 per cent. At lower load factors the 1,200-lb steam cycle showed a saving. For the particular project under consideration, the 1,200-lb steam cycle showed a saving in investment costs of $18.74 per kilowatt while the mercury cycle showed a gain of 2,550 Btu per kilowatt-hour in station heat consumption. With coal at $3.80 per ton and fixed charges taken at 13 per cent the total annual costs (including fixed charges) would be the same at 63$^1/_2$ per cent load factor, while with coal at $3.60 per ton they would be the same at 67 per cent load factor. In these calculations allowances have been made for the smaller amount of auxiliary power and the lower capacity of condensing water and coal handling and preparation facilities required by the mercury cycle. It is obvious that with lower coal costs the money saving due to saving a certain quantity of coal becomes less and the installation of the more expensive mercury equipment becomes more difficult to justify.

Table I—Comparison of Actual 1,200-Lb Generation With 300-Lb Generation at Lakeside, 1929

Economy		
Station generation	Million kwhr	993.9
Station output	Million kwhr	948.7
Generation by 1,200-lb cycle	Million kwhr	236.0
Per cent of generation by 1,200-lb cycle		23.8
Overall station heat consumption	Btu/kwhr net	14,882
Heat consumption of an all 300-lb plant	Btu/kwhr net	15,400
Heat consumption of an all 1,200-lb plant	Btu/kwhr net	13,225
Heat saving on 1,200-lb generation	Btu/kwhr net	2,175
Per cent saving of 1,200-lb over a new 300-lb plant = item 8 divided by item 6		14.12
Total 100 million Btu saved = item 3 times item 8 divided by 100,000,000		5,133
Cost of fuel per 100 million Btu		$17.41
Total saving for 1929, 1,200 lb over 300 lb		$ 89,365
Investments		
Greater investment cost of 1,200-lb equipment over 300 lb. (per unit)		$900,000*
Greater annual fixed charges at 13 per cent		$ 30,400
Net Saving		
Net saving for 1929, 1,200-lb cycle over new 300-lb cycle		$ 58,965

Actual operating statistics showed that Lakeside's 1,200-lb cycle had saved 14.12 per cent in coal over that which would have been burned had 300-lb equipment been installed. Maintenance costs were no higher and, except for slightly higher fixed charges, the fuel savings indicate the net savings.

*Second unit started in commercial operation November 1, 1929.

It was concluded that the mercury cycle should not be adopted for the initial section of the plant for the following reasons:

1. The net savings, if any, which the mercury cycle could show over the 1,200-cycle were small.

2. The untried portions of the fundamental parts in the mercury equipment might cause an outage when the capacity could not be spared for any appreciable time, especially not for correcting developmental defects.

3. The mercury cycle could be installed in succeeding units very readily, should these experimental matters prove successful.

At the time of making the mercury-steam study, indications of future price trends both of fuel and construction materials were taken into consideration. Recent trends have been along the lines assumed and have not altered the conclusions reached.

Selection of 1,200-Lb Steam Cycle

The design for the Port Washington plant has as its underlying basis the design and operating experiences of the Lakeside plant. Lakeside's first 1,300-lb boiler was placed in operation in October 1926. In October 1929, its second high pressure boiler went into service. By the time that a decision on the pressure for the Port Washington plant had to be made, 3$^1/_2$ years of operating experience had been had with the Lakeside equipment. The availability factors for the last 2 of these 3$^1/_2$ years on high pressure boilers were 84.3 per cent and 88.5 per cent, respectively. (It may be interesting to record that during 1932 the availability for the 4 high pressure boilers at Lakeside averaged 93.7 per cent.) A careful analysis of the operating statistics for 1929, the last full year before making decisions for Port Washington, showed that Lakeside's high pressure system had in that year effected an actual net saving of $58,965 over straight 300-lb equipment of the latest and the most modern design. The actual fuel saving resulting from 14.12 per cent less coal burned amounted to $89,365 against which was made an offset of $30,400 for annual fixed charges on the larger investment; maintenance costs being the same for 1,200 lb as for 300 lb. (See Table I.)

These economy and reliability figures definitely established 1,200-lb pressure as being far superior to 300 lb, 300-lb pressure being used in this comparison because the existing equipment in the plant, before the installation of the 1,200-lb equipment, was built for it. But in order to exhaust all possible claims for intermediate pressures, a comparison was made between 600 lb and 1,200 lb. The results, shown in Table II, indicated that the 1,200-lb cycle would save $36,754 annually over the 600-lb cycle in the initial installation at Port Washington, after deductions had been made for fixed charges on the greater investment required. This table is based upon reheating to same temperature for both pressures.

Table II—Comparison of 1,200-Lb Generation With 600-Lb Generation, Estimated for Port Washington

Economy		
Estimated annual generation for initial installation 80,000 kw at 60 per cent annual load factor	Million kwhr	421
Saving in heat consumption by 1,200-lb cycle over 600-lb (average all loads)	Btu/kwhr	856
Annual saving in favor of 1,200 lb	100 million Btu/yr	3,610
Cost of fuel per 100 million Btu		$14.83
Total annual fuel saving, 1,200 lb over 600 lb		$ 53,500
Investments		
Greater investment for 1,200-lb boiler room equipment		$147,168
Greater investment for 1,200-lb turbine room		$ 19,300
Lesser investment for 1,300-lb turbine room equipment		$ 20,000
Lesser investment for 1,200-lb station tunnels, circulating water system, and coal handling system		$ 17,650
Net greater investment for 1,200-lb installation		$128,818
Annual fixed charges on greater 1,200-lb investment at 13 per cent		$ 16,746
Net Saving		
Net annual saving of 1,200-lb installation over 600-lb installation of 80,000-kw capacity		$ 36,754

In comparing the economies of 1,200-lb generation with 600 lb, a considerable saving in fuel was found. This, together with the unexcelled reliability record of Lakeside's 1,200-lb equipment decided the issue in favor of 1,200 lb

Consideration of the possibilities of the Benson cycle showed that it held no inducements at this time. Efficiency gains from going beyond 1,200 lb were found to be slight because of rapidly increasing feed pumping costs and steadily decreasing energy gains. The savings shown in Tables I and II, together with satisfactory overall operating experiences at Lakeside, were sufficient to warrant the adoption of 1,200 lb for Port Washington.

Table III—Comparison of 825 Deg F and 750 Deg F Temperature at Both Throttle and Reheat Estimated for Port Washington

Economy		
Estimated annual generation for initial installation, 80,000 kw at 60 per cent annual load factor	Million kwhr	421
Saving in heat consumption, 825 deg over 750 deg	Btu/swbd. kwhr	300
Annual Btu saving, 825 deg over 750 deg	100 million Btu	1,263
Cost of fuel per 100 million Btu		$14.82
Total annual fuel saving, 825 deg over 750 deg		$ 18,720
Investments		
Investment saving of 825 deg due to lower heat consumption	%	2.5
Unit investment to which heat saving applies	$ per kw	47.30
Total investment saving of 825 deg = $47.30 times 80,000 times 2.5 per cent		$ 94,600
Total investment saving assuming 75 per cent of total saved		$ 71,000
Additional investment saving in 2 steam drums, due to lesser storage required		$ 5,670
Additional investment saving due to deferring replacing last rows of blades because of lesser moisture in exhaust		$ 10,920
Total investment saving, 825 deg over 750 deg		$ 87,590
Greater investment cost of 825-deg turbine		$ 89,000
Greater investment cost of 825-deg valves and fittings		$ 8,000
Greater investment cost of 825-deg superheater and reheater		$ 18,760
Total greater investment cost, 825 deg over 750 deg		$115,760
Net greater investment cost, 825 deg over 750 deg (item 16 minus item 12)		$ 28,170
Net Saving		
Annual fuel saving, 825 deg over 750 deg		$ 18,720
Annual fixed charges on greater investment at 13 per cent		$ 3,650
Net annual saving, 825 deg over 750 deg		$ 15,070

An increase in operating temperature to 825 deg F from 750 deg F for both throttle and reheat showed a 2.5 per cent improvement in station performance. When the saving was capitalized on the basis of reducing equipment costs in the boiler room, it offset the increased cost of the turbine, valves and fittings and showed a substantial net saving for the higher temperature.

Selection of 850 Deg F Maximum Steam Temperature

Among the improvements over Lakeside which were considered was the use of a higher steam temperature. Superheater manufacturers, valve, pipe, and also turbine makers were consulted. All expressed their willingness to coöperate and subsequently quoted prices on equipment necessary not only to produce 825 deg F at the turbine throttle and reheat point, but to maintain it continuously; 850 deg F was specified as the maximum. The increase of 75 deg F in actual operating temperature (Lakeside's is 750 deg F) brings the total steam temperature up to the point where ordinary steels cannot be used in the turbine. Alloys require greater investment particularly in large turbines where they had not been previously applied to the extent that they had been in steam superheating equipment and in valves. The net greater cost of 850 deg F equipment totaled $28,170 in investment. With fixed charges taken at 13 per cent, the annual rate amounted to $3,650. The fuel saving on the other hand amounted to $18,720 per year, resulting from an improvement of 2.5 per cent in station heat consumption rate. The net saving therefore was calculated to be $15,070 per year. The greater investment resulted from a more expensive turbine, greater cost of valves and fittings, and greater cost of superheaters and reheaters. These greater costs were offset by investment savings in boiler plant equipment due to the smaller amount of steam required, less water storage required in steam drums, and by deferred expenditure for replacing the last row of turbine blades due to less moisture in the exhaust steam. (See Table III.)

A higher steam temperature than 825 deg F at the turbine throttle with no reheat was considered purely experimental because it involved untried alloys. Creep in metals is hardly a consideration at 825 deg F, but at 1,000 deg F or thereabouts, it is extremely important. A throttle temperature of 825 deg F with reheat at the same temperature is a reliable, non-base-load combination, one that is made particularly attractive through the application of radiant superheating and reheating surfaces in the same furnace.

Lakeside's operating experiences with reheat are positive proof that variable loads are easily and safely carried. Reheat introduces minimum complications into the cycle.

One Turbine, One Generator, and One Boiler

A previous study had shown that one large turbine generator would save $7.15 per kilowatt over 2 half-size units in investment costs (turbine generators, foundations, turbine room building, electrical equipment, and switch house) and about $25,000 per year in operating costs due to a better rate of heat consumption. These savings were considered sufficient to warrant the installation of an 80,000-kw unit rather than 2 40,000-kw units. Incidentally an 80,000-kw machine would match almost exactly the 90,000-kva transmission lines which had been adopted for the Milwaukee district. (See "The 60-Cycle Primary Transmission System of The Milwaukee Electric Railway and Light Company and Associated Companies in Wisconsin and Upper Michigan," by C. D. Brown and E. W. Hatz; A.I.E.E. paper No. 32M3.)

Most of the original 1,200-lb installations in this country consist of 1,200-lb non-condensing turbines superimposed on existing 300-lb stations. In such installations, of course, new full capacity 1,200-lb boilers were required but the turbines were of comparatively small generating capacity. The economy of such installations due to having to maintain a practically constant pressure at the exhaust of the high pressure turbine for all loads, drops off rapidly in going from full load to partial load. Multiple-valve admission to the high pressure turbine has been used as a partial means of overcoming this difficulty, but the process effects a saving in the high pressure turbine only, whereas the largest part of the loss occurs at the exhaust of this turbine.

If the exhaust pressure is permitted to vary accord-

ing to load through the use of so-called compound operation, savings of considerable magnitude can be made. Such operation naturally would have to be followed in a station which had boilers generating steam at but one pressure. The high pressure turbine, however, could still remain segregated from the low through the adoption of a cross-compound machine. There then would be 2 separate turbines each with its own generator, a combination which has the advantage of keeping the low pressure turbine in service when trouble is encountered in the high pressure turbine. Should the low pressure section be forced from service at any time, the entire unit would be down and because of this fact a reserve equal to the capacity of the whole unit must be kept available at all times. The ability to operate the low pressure section at times of high pressure turbine outage, therefore, loses much of its significance. Besides, the reserve capacity in most cases can be operated at an economy very close to that of the low pressure section alone. The advantages of tandem compounding on the other hand are such as to win approval; they are, net investment savings of $1.12 per kilowatt resulting from (1) a lower cost of the turbine-generator itself, (2) fewer electrical connections because of having only one generator, (3) less building volume, and (4) a credit for a smaller turbine room crane because of a narrower turbine room.

Many of the arguments presented against the cross compound unit apply to the steeple compound unit also, although the economic advantage of the tandem over the steeple is not as great as it is over the cross compound. Inconvenience in operation and maintenance also were factors in deciding against the steeple compound unit.

After having established the size and type of the turbine to be installed, the next consideration was the number, size, and type of boilers. Detailed comparisons were made on the installation of 2 boilers of small size (345,000 lb per hour capacity) and of 1 boiler of large size (690,000 lb per hour capacity).

One boiler was selected rather than 2, because:

1. An investment saving of approximately $250,000 could be made.

2. The operation would be simpler due to not having to apportion the exhaust steam from the high pressure section of the turbine to each of the 2 reheaters.

3. The presence of an 80,000-kw turbine generator on the system would require 80,000-kw reserve in any event. Therefore, no additional losses in capacity would occur due to boiler outage.

At Lakeside, 3-drum bent-tube type boilers with comparatively large low-heat release furnaces had unprecedented reliability records. Certainly records of this nature could not be ignored in making selections for the Port Washington boilers. This fact notwithstanding, all arguments for the single-drum straight-tube boiler and high-heat release furnace were obtained and carefully weighed. Prices were secured and tentative layouts prepared so that an unbiased opinion as to their merits might be formed.

Exponents of the straight-tube boiler design with its complementary equipment maintained that with it a better proportioning of all of the heat reclaiming surfaces could be secured together with a lower over-all investment cost. The use of less of the comparatively high cost boiler surface and more of the less expensive economizer surface formed the basis for their arguments. They also maintained that less building volume would be needed. Contrary to expectations, the latter was not found to be true for

Table IV—Comparison of Boiler Designs for Port Washington, Initial Installation

	Bent-Tube Boiler Low-Heat Release Furnace	Straight-Tube Boiler High-Heat Release Furnace
Total investments in boiler, furnace, superheater, reheater, economizer, air-heater, feeders, burners, and milling equipment*	$937,137	$838,805
Greater investment of bent-tube boiler	98,332	
Greater annual fixed charges at 13 per cent	12,783	
Increased operating costs		
a. Greater pressure drop in superheater		$ 156
b. Greater pressure drop in reheater		1,920
c. Loss of heat in molten ash		1,780
d. Lower over-all boiler efficiency		6,370
e. Poorer availability		3,900
f. Lower reheat temperature		2,720
g. Greater furnace maintenance cost		5,700
h. Total greater operating costs		$ 22,546
Net annual saving of bent-tube boiler with low-heat release furnace		$ 9,763

The bent-tube boiler with a low-heat release furnace not only will produce an annual saving of $9,763 but will also permit the use of radiant superheat and reheat surfaces within the furnace, and afford other operating advantages.

*Building not included because costs would be identical.

Port Washington conditions, principally because of a 10-ft higher building which would be required. It was true, however, that a small saving in investment was shown with the straight-tube boiler layout over that of the bent-tube type but this saving was more than offset by operating losses. Table IV summarizes these gains and losses. Then too, high-pressure economizers (1,600 lb) which are an essential part of the straight-tube boiler layout were considered a potential source of trouble. As explained later, economizers were eliminated entirely from the Port Washington design.

It was concluded finally to adopt the bent-tube type boiler fired from one side only with a low-heat release hopper-bottom furnace beneath it. Besides the economic gains and the possibility of eliminating economizers, the following additional reasons influenced its selection:

1. About 50 per cent more water storage space is available; this is very important when only a few minutes total storage is available.

2. Tubes being nearly vertical permit rapid water circulation which eliminates wide variations in drum-water levels throughout the load range.

3. Dry steam is obtained since the rear drum acts as a dry drum, it having little steam released from the water it contains.

4. Water wall connections can be made easily because of accessibility of the drums.

5. Suspended solids in the boiler water are removed effectively in the lower drum.

Furnace

The slag-tag furnace, which was given some consideration, is a high-heat release furnace of relatively small size because the temperature in the furnace

must be kept sufficiently high to maintain the ash in a molten state. The small size and high temperature preclude the use of radiant superheaters and reheaters. The latter are desirable because their inherent characteristics are such as to give automatically the most economical operating conditions at all loads. Superheaters and reheaters of the all-convection type give decidedly variable steam outlet temperatures with variations in load on the boiler necessitating desuperheating at the higher loads. This was considered objectionable because of the general unreliability of the desuperheating process. No desuperheater is required with the radiant surfaces in the Port Washington station design. On the other hand, large furnaces with a low rate of heat release (15,000 Btu per cubic foot per hour, maximum) are conducive to low maintenance costs and high availability. With steel walls, consisting of steam and water cooled surfaces on all 6 sides, there can be no wall erosion. Radiant superheater and reheater surfaces for side and rear walls and water tubes for the front wall and the ash screen were the final answer to the furnace problem after all advantages and disadvantages of other combinations had been carefully balanced.

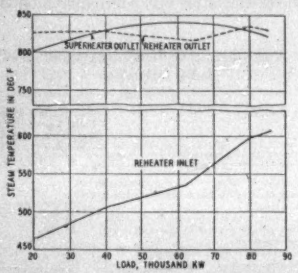


Fig. 1. Uniform steam outlet temperatures such as these, from both the combination radiant and convection superheater, and the radiant reheater, over a load range from full to quarter load will tend to produce high over-all plant efficiency

Radiant Superheater and Reheater

Selection of radiant heat absorbing surfaces for superheater and reheater rather than all-convection surfaces was prompted by economic considerations as well as the adaptability of these surfaces to the low-heat release furnace mentioned in the previous paragraph. More uniform steam temperatures over wide load ranges can be obtained automatically and thus the overall station economy can be improved. This is particularly true at low loads when all other factors in the system are working toward poorer economy. By virtue of the higher superheat the turbine efficiency is maintained higher than it would otherwise be at the lower loads.

The superheater selected has a radiant section and a convection section. The steam will pass first through the former and then the latter. With this combination the steam temperature to the turbine throttle will vary only from 830 deg F at full load to 802 at quarter load. The reheater on the other hand is radiant entirely and its outlet temperature will vary from 834 at full load to 827 at quarter load. (See Fig. 1.)

Air Heater and Economizer Considerations

Economizer and air heater surfaces (all waste heat reclaiming surfaces for that matter) are closely related to the type of cycle adopted for the station. In the case of Port Washington, a tentative cycle was decided upon at the time of placing the turbine contract. This called for the use of extraction heaters at 5 points. A comparison between 4 extraction heaters plus an economizer-air heater combination, and 5 extraction heaters plus an air heater only, indicated that a net annual saving of $7,429 could be made through the use of the latter. The comparison of these 2 methods is summarized in Table V, based upon 4 extraction heaters plus an air-heater only, the figures being estimated for the Port Washington plant. The major portion of the saving shown is effected by the 1.3 per cent better heat rate of the turbine due to the fifth heater. Although the addition of an economizer would reduce the flue gas temperature 25 deg F and thus make a substantial saving in boiler efficiency, the fixed charges on the greater investment for the economizer and piping (after taking credit for the smaller air heater) and the maintenance costs on the economizer would more than offset this gain. Five-stage heat-

Table V—Comparison Between 4 Extraction Heaters Plus Economizer-Air Heater Combination and 5 Extraction Heaters Plus Air Heater Only

	Gain	Loss
Four-Stage Heating and Economizer		
Saving due to lowering of flue gas by 25 deg F	$4,520	
Maintenance cost on economizer		$2,000
Pumping cost for pressure drop through economizer		120
Fixed charges on greater investment cost for economizer and piping after deducting credit for smaller air heater, $35,800 at 13 per cent		4,654
Total costs	$4,520	$6,774
Net annual loss for economizer		2,254
Five-Stage Heating		
Better heat consumption rate due to fifth-stage heaters—112 Btu per kwhr	$6,995	
Maintenance cost on fifth-stage heaters		400
Pumping cost for pressure drop through heaters		120
Fixed charges on investment in fifth-stage heaters, also necessary piping, $10,015 at 13 per cent		1,300
Total costs	$6,995	$1,820
Net annual gain for fifth-stage extraction heaters	5,175	
Net Comparison		
Net gain due to fifth-stage heaters	$5,175	
Net loss due to economizer	2,254	
Net annual difference in favor of fifth-stage heaters	$7,429	

Economizers ordinarily are thought of as equipment used to enhance power plant operating efficiency. This tabulation shows that extraction heaters do this more effectively, and with far less need for worry about operating difficulties under the higher pressures encountered.

ing with an air-heater but with no economizer was therefore decided upon.

Bin and Feeder Versus Unit System

In determining the method of firing to be adopted, a thorough investigation was made into the adaptability of the unit system and of the bin and feeder system to the contemplated plant layout. The results showed that the boiler efficiency obtainable with the unit system was about equal to that of the bin and feeder system with no gain for either on such items as carbon loss, uniform grinding, etc. There were, however, inherent advantages of the bin and feeder system which influence total station economy rather than only boiler efficiency and it was these which decided the matter in its favor. The most outstanding of these advantages are:

1. Greater reliability. With the unit system any outage of a mill for any reason will cause a reduction in capacity of the boiler or complete outage of the boiler. Whenever a reduction in load occurs, it must be picked up by some standby or less efficient station, and a loss of 0.1 per cent in economy might result.

2. Flexibility. The low rating limitation of the unit mill is absent entirely from the bin system. This is particularly important at times of starting when low furnace temperatures are desired to prevent damaging superheater tubes.

3. Mill drying with flue gas can be used in the storage system to advantage, while on the other hand it cannot be used efficiently in the unit system. Venting flue gases back into the furnace is not conducive to efficient combustion and to the maintaining of proper flame control. With flue gas drying in a storage mill, 6 per cent of the total flue gas discharges to the stacks at a temperature 200 deg F lower than the usual exit temperature. In addition, air heater performance is improved due to the greater mean temperature difference and the lesser heat absorption in the air heater. After the flue gas mill drying system has been charged with the small coal vent loss, it shows a net gain of 0.5 per cent over using hot air and venting to the furnace.

4. Coal feed can be regulated more closely with the storage system resulting in the maintenance of high average CO_2 and fine control of excess air. With radiant superheaters and reheaters this is important. Coal feed variations of 10 per cent as are common with the unit system without hand adjustment can cause a 50 deg variation in reheat temperature and 0.6 per cent decrease in station economy.

5. Coal feed control at Lakeside where the storage system is used has been found to be so regular that boiler pressure can be regulated to within 5 lb of a standard. With the unit system, the pressure variations might be on the order of 50 lb. The difference of 45 lb in pressure at the turbine could cause 0.6 per cent difference in economy.

6. When using air drying with unit mills the heated air to the mill must be tempered with room air. This reduces the amount of air to be taken through the air heater and reduces the boiler efficiency about 0.3 per cent below that of a storage system boiler where flue gas drying is used.

7. Automatic combustion control is much more positive on a storage fired boiler than on a unit fired one. With the latter, difficulties are encountered in coördinating the mill speed, primary air volume, and sizing of the pulverized coal particles with the requirements of the boiler. Lower overall efficiencies will result.

These advantages, totaling 2.1 per cent in station economy, can be credited to the storage system. Investment costs were found to be 74 cents per kilowatt lower for the unit system. Labor, maintenance, and power were slightly in favor of the unit system. An important point in favor of the storage system is that most of its motors can be shut down at the time of the station peak. The unit system on the other hand requires peak electrical demand for auxiliaries coincident with the peak station demand and to provide the same margin in capacity, an equivalent in generating capacity must be installed at the same station or elsewhere.

Another important advantage of the storage system is the safety to personnel and equipment occasioned through the use of flue gas for mill drying. A 12 per cent volume of CO_2 (an inert gas) is maintained in the mill system and collectors, so that danger of fire or of an explosion from smoldering coal is lessened materially.

The analysis, of which Table VI is a summary, showed the bin and feeder system to effect a net annual saving of $11,062 and this, together with certain operating advantages, formed the basis for its adoption.

Table VI—Comparison of Storage System and Unit System of Pulverized Fuel Firing, Estimated for Port Washington

Economy		
Estimated annual generation for initial installation, 80,000 kw at 60 per cent annual load factor	Million kwhr	421
Saving in heat consumption, storage over unit	%	2.1
Btu saving, storage over unit	Btu/kwhr	252
Annual Btu saving, storage over unit	100 million/yr	1,061
Cost of fuel per 100 million Btu		$14.82
Total annual fuel saving, storage over unit		$15,750
Labor, Maintenance and Power		
Greater cost of labor (1 extra man) storage over unit		$ 2,400
Greater cost of maintenance, storage over unit		$ 950
Lesser cost of power, storage over unit		$ 575
Net greater operating costs, storage over unit		$ 2,775
Investments		
Greater investment cost in mills, feeders, burners, motors, starters, duct work, foundations, air compressors, fuel bins, etc., storage over unit		$59,112
Greater annual fixed charges at 13% storage over unit		$ 7,685
Station Peak Capacity		
Greater kilowatt demand of unit system motors at time of station peak		592
Value of 592-kw station capacity at $75 per kw		$44,400
Lesser annual fixed charges on station capacity, storage over unit		$ 5,772
Net Saving		
Net annual saving, storage system over unit system (item 6 minus item 10 minus item 12 plus item 15) =		$11,062

The battle of storage versus unit system of pulverized fuel firing was waged for many weeks in the company's engineering department before the storage system was awarded the decision. Its merits include not only an annual saving of $11,062, but greater reliability and flexibility, as well as safety, due to the possibility of using flue gas mill drying with it.

Extraction Heaters and Feed Pumps

After having determined the number of extraction heaters to be used in the heat cycle, a very important decision had to be made in regard to the location of the boiler feed pumps in the cycle. The high pressure boiler feed pumps at Lakeside, although they had been operating continuously for over 4 years and had never been the cause of 1,200-lb equipment outage, had demanded considerable attention and were creating maintenance costs which were considered too high. Their operation as a whole was rather delicate. An investigation showed the cause of the difficulties to be fluctuations in feed water temperatures which set up uneven expansion and contraction in the various component parts of the pumps causing clearance variations, packing leaks, etc. The maximum feed water temperature delivered to the Lakeside 1,600-lb pressure pumps is 360 deg F while it might go down to 300 deg F or slightly below at light loads. The pumps at Port Washington, if they are placed on the discharge side of the extraction heaters, would be required to handle water to as high as 432

deg F temperature at full load and as low as 290 deg F at quarter load, a condition much more severe than that at Lakeside. Should they be located after the second heater, however, and made to discharge through the heaters at the remaining 3 extraction

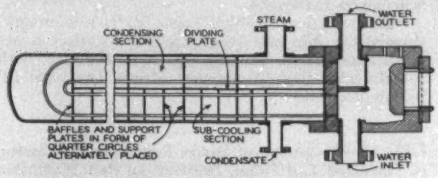


Fig. 2. Bolted heads with gaskets and stay-bolts are eliminated in this extraction heater built for a water pressure of 1,600-lb

points, the temperature of the water entering the pumps could be held constant at 200 deg F. The manufacturers of the feed pumps were in hearty approval of the suggestion that the lower temperature be used in spite of the relatively low delivery pressure to the suction of the pumps, and promptly quoted on pumps with efficiency quarantees somewhat improved over those at Lakeside. This improvement in efficiency is incidental to the improved reliability of the pumps and to the 12 per cent saving in pumping energy occasioned by the lower specific volume of 200 deg F feed water compared with that of 400 deg F feed water. The somewhat higher cost for the high pressure extraction heaters over the lower pressure type was not nearly enough to offset the advantages mentioned.

Two sets of high pressure extraction heaters will be used, one on each of the feed lines to the boiler. Each feed line will have a separate high pressure pump with a spare pump so connected that it can be substituted in either line. Two feed lines to the boiler will be used because better parallel operation of centrifugal feed pumps can be obtained when discharging through heaters and piping before pressures are equalized. Then, too, it was found economical to use 2 sets of heaters because by-passes around the heaters with their expensive fittings could be eliminated.

Interesting design details involved in the construction of the high pressure extraction heaters are worthy of mention because they have heretofore never been attempted. It is common knowledge that bolted heads with gaskets and stay-bolts are a serious problem in the use of high pressure heaters. These have been entirely eliminated through the adoption of a head made from a solid forging bored out and supplied with an internal head cover, similar to a boiler manhole plate design. (See Fig. 2.)

Steel tubes with U-bends have been decided upon because experience at Lakeside has proved them to be more reliable than brass tubes, and they cost less. Corrosion of the tubes can be prevented entirely by complete de-aeration which is essential in any event in a 1,200-lb pressure plant.

Flash losses between the high pressure heaters will be eliminated by cooling the drains in the lower sections of the heaters before cascading them into the next lower heaters. Separate drain pumps on individual high pressure heaters would be impractical because of having to pump against 1,300-lb boiler pressure. Calculations show an improvement of

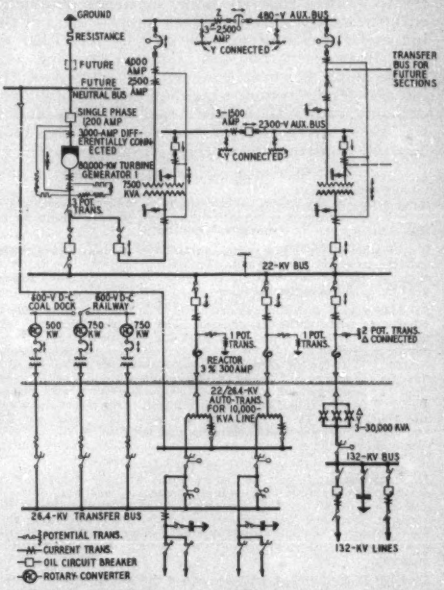


Fig. 3. Single line wiring diagram of the initial installation at the Port Washington power plant

about 0.75 per cent in plant economy through the elimination of flash losses.

Generation at 22,000 Volts

In selecting the generator voltage, the following were considered:

1. No pioneering in generator voltages was desired.
2. A voltage was desired that would enable industries which might locate in the vicinity of the plant to connect their lines to the bus bars as economically as possible.
3. If any economies could be effected in the plant investment and operating costs by using a voltage higher than 13,800 (the Lakeside voltage) such economies should be realized.
4. It would be desirable to adopt a voltage which would permit the connection of the existing 26,400-volt secondary transmission lines of the company with a minimum of expense. This is not a matter of much importance because very little of the energy will be delivered at this voltage. Most of it will be stepped up directly to 132 kv.
5. A voltage was desired that all manufacturers would be willing to use in their machines without resorting to special construction, such as concentric conductors.

The voltage which most nearly met all of these conditions was found to be 22,000 volts. In using this voltage it was found that a saving of 0.3 per cent could be realized in investment and operating costs of generators and electrical equipment over similar costs for 13,800 volts. No saving could be effected by adopting 26,400 volts because equipment in the 34,500-volt class, which is more expensive, then would have been necessary. Because of the adoption of 22,000 volts, it is necessary to use auto-transformers to connect to the lines operating at 26,400 volts.

Indoor Switching Equipment of 22,000 Volts

The main electrical connections of the initial and ultimate installations are shown in Figs. 3 and 4. Whether to build a switch house and install indoor 22,000-volt switching equipment or to install metal clad equipment outdoors was given a great deal of consideration. Regardless of the decision on this point, it was recognized that it would be necessary to build a transformer repair house and control house, which limited the decision simply to the switching equipment itself, main bus bars, reactors, etc. All of the comparative estimates made included the control house and transformer repair building. Estimates were obtained from the manufacturers on various kinds of switching equipment and it was assumed in the case of the outdoor metal clad equipment that there would be a likelihood of a reduction in cost of about 10 per cent during the time that the station was growing from its initial to its ultimate size. It was found that for the initial section the outdoor metal clad equipment would require an expenditure of $6.03 per kilowatt while the vertical indoor isolated phase construction, including building and foundations, would require an expenditure of $5.62 per kilowatt, or $0.41 per kilowatt in favor of the indoor vertical isolated phase arrangement. In the ultimate station, with relatively more switching equipment because of the duplication of switches on certain lines and the use of a ring 22,000-volt bus with reactors, the corresponding figures would be $7.62 per kilowatt for the outdoor metal clad and $5.78 per kilowatt for the indoor vertical isolated phase arrangement, including building a saving in favor of the indoor arrangement of $1.84 per kilowatt. In view of the economies that could be effected and other advantages, such as the greater ease of making changes from the original layout and the use of oil-less circuit breakers in the indoor arrangement, it was decided to put all of the 22,000-volt switching equipment indoors. After deciding upon the use of indoor equipment, it was thought desirable to consider the merits of various kinds of indoor equipment and so cost figures were prepared on indoor 3-pole assembly metal-inclosed equipment. It was found that in the initial installation the metal inclosed equipment would cost $0.17 per kilowatt more than the vertical-isolated phase arrangement and $0.31 per kilowatt more in the ultimate installation. Vertical-isolated phase construction therefore was selected.

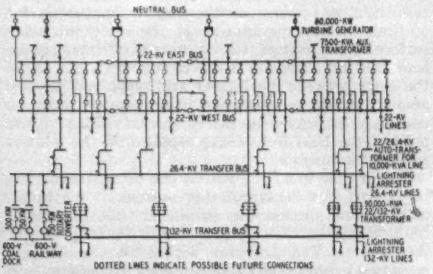


Fig. 4. Single line wiring diagram of the contemplated electrical connections at the Port Washington power plant when 4 80,000-kw turbine generators had been installed

Auxiliary Power Supply System

A-c auxiliary service will be provided by 7,500-kva 3-winding transformers stepping down from 22,000 volts to 2,300 and 480 volts. There will be one transformer connected directly to the leads of each generator and one spare transformer connected to the 22,000-volt bus. Each transformer will supply auxiliaries for its own unit with automatic provisions for transferring the load instantaneously to the spare transformer in case of trouble on the normal supply. (See Fig. 5.) Motors of 100-hp capacity and larger will be supplied at 2,300 volts and motors of less than 100 hp at 480 volts.

D-c service supplied from motor-generator sets with a battery floated across the busses will be used to supply pulverized coal feeders, electrically operated valves, turbine room cranes, elevators, emergency lights, and magnetic pulleys. The only steam-driven auxiliaries in the plant will be one emergency feed water pump and one emergency house service water pump.

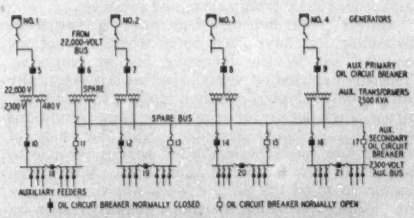


Fig. 5. Single line wiring diagram of connections to principal auxiliaries. Automatic relaying is used to maintain service on the maximum number of auxiliaries possible for a fault at any given location

Corona Loss Vs. Atmospheric Conditions

In previous investigations of corona loss on electric conductors, variations in loss were observed that were believed to be caused by daily variations in atmospheric conditions. Consequently, a series of tests was made to investigate the effects of humidity, pressure, temperature, and smoke; the results are given in this article.

By
L. HEGY
ENROLLED STUDENT

G. W. DUNLAP
ENROLLED STUDENT

Both of Stanford University, Calif.

SINCE the first corona loss measurements were made, much has been learned about the nature of corona loss on electric conductors. It is known now that corona loss varies with numerous factors; these may be grouped roughly under 3 heads. The first of these has to do with the conductor itself; the loss is known to vary with the diameter of the conductor, the shape of the cross section, the spacing between conductors, and the distance from ground. The second group includes changes in the conductor due to outside causes; under this heading may be classed the effect of dirt and grease on the surface of the conductor. The third group includes all extraneous affecting conditions such as weather, and atmospheric temperature and pressure.

During recent investigations, however, variations in corona loss have been noted which are not accounted for by the foregoing line of reasoning. The only explanation seems to be that it is practically impossible to duplicate daily atmospheric conditions; hence some means of controlling these conditions obviously is highly desirable. Also the study of corona loss would be facilitated were it possible to reduce all results to the same base. With these factors in mind the present work was started early in 1932 at which time the study was undertaken by Victor Siegfried (A'32), a graduate student of Stanford University.

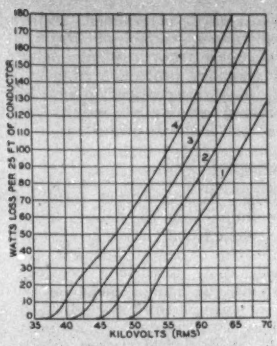
The original equipment consisted, first of all, of an air-tight steel tank 30 ft high and 5 ft in diameter mounted vertically in a corner of the laboratory. An attempt was made to approximate atmospheric conditions inside of this tank. Atmospheric pressures corresponding to various altitudes were obtained by partially evacuating the tank, for which purpose a reversible air pump was used; and the pressure could be varied above or below that of the atmosphere. The test specimen, consisting of a conductor 25 ft in length, was suspended from the end of a brass rod passing through a porcelain high voltage bushing in the top of the tank. A 5-in. lead ball was attached to the free end of the conductor to hold it straight and prevent swinging. The conductor was connected through the brass rod and a shielded lead through a high voltage wattmeter to a 350,000-volt transformer. Losses to the bushing were supplied through the shielding system directly from the transformer and were not read on the wattmeter. In this way only the loss on the test specimen could give a wattmeter deflection. The tank was maintained at ground potential. The high voltage wattmeter and electrical connections are essentially the same as described by J. S. Carroll and B. Cozzens ("Corona Loss at 220–330 Kv," ELECTRICAL ENGINEERING, v. 52, March 1933, p. 178–83).

Besides variations in pressure, an attempt was made to change the temperature and humidity within the tank. Some progress was made in this regard. However, because of the limitations of the original set-up, some additions were made to the equipment in the fall of 1932. The first of these was a circulating system consisting of a 6-in. pipe joining the top and bottom of the tank through a large blower. The blower was belt-driven by a d-c motor making possible a variable speed. The next improvement was to insulate the tank against radiation of heat, leaving the blower as the only radiating surface of the system. As a means of introducing heat into the tank a 7.5-kw heater was placed in the entry between the blower and tank. With this amount of heat concentrated in one spot it became necessary to provide a safety device which would prevent the heat from being applied if the blower were not in operation.

To vary the humidity within the tank, steam was introduced into the circulating system. The boiler used for this purpose was so placed that the steam could be injected directly into the air stream back of the blower. Temperatures within the tank were measured by means of thermocouples projecting into the atmosphere of the tank through air-tight bushings. Temperature measurements were taken at the top and bottom opposite the ends of the conductor. Previous experiments showed that there was no difference between the temperature at the surface of the conductor and the temperature of the air next to the wall of the tank at the same height. The temperature of the outside air also was read by means of a third thermocouple. Humidity within the tank was determined by means of a wet and dry bulb thermometer. Preliminary tests showed that the average temperature within the tank could be maintained at about 140 deg F. There was a difference of several degrees between top and bottom, but the even gradient justified the use of an average temperature in computations.

Humidity was found to have no appreciable effect on corona loss over the range investigated, this included humidity as high as 90 per cent. With the

Essentially full text of a paper presented at a joint meeting of the A.I.E.E. San Francisco Section, and the University of Santa Clara, University of California, and Stanford University Branches, Berkeley, Calif., April 13, 1933. *Not published in pamphlet form.*



1.Fig. Corona loss at various pressures; solid copper No. 2 B&S gauge conductor

Curve	Absolute Pressure, Inches of Mercury
1	29.95
2	26.69
3	23.84
4	20.86

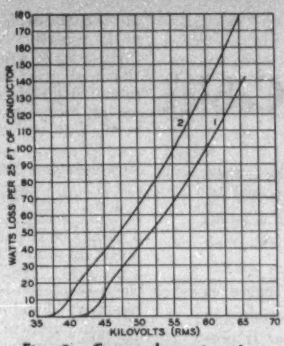


Fig. 2. Corona loss at various temperatures; solid copper No. 2 B&S gauge conductor

Curve 1. 18.85 deg C (65.5 deg F)
Curve 2. 53.25 deg C (127.5 deg F)
Absolute pressure 20.88 in. mercury

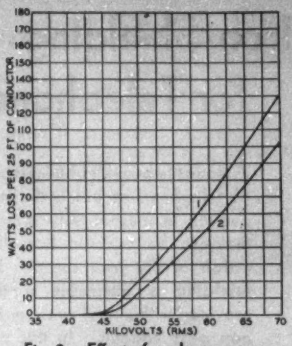


Fig. 3. Effect of smoke on corona loss; 7-strand steel cable, maximum diameter 0.240 in.

Curve 1. Conductor in clear air
Curve 2. Conductor in smoke formed by burning rag soaked in lubricating oil
Temperature, pressure, and humidity constant at the values of the outside air

exclusion of humidity as an affecting factor, it was possible to determine the effect of temperature and pressure in various combinations. Data for several corona loss curves were taken, using a smooth solid copper conductor No. 2 B&S gauge; a few representative curves are reproduced in Figs. 1 and 2. It is noticeable that the shape of the curve is not appreciably changed by variations in pressure and temperature. Instead the curve is shifted in the direction of lower voltage as temperature is increased, or as pressure is decreased, or both. The amount of this shift has been found to bear a relation to the change in air density. It has been thought previously that the critical corona voltage is proportional to the air density. Results of these experiments, however, show that the amount of shift due to a given change of air density depends on whether the density was changed by variations in pressure or by variations in temperature. By means of fairly simple computations it may be shown that where the air density has been changed by a variation in pressure the shift of critical corona voltage is proportional to about 70 or 80 per cent of the change in density; and where the change is caused by variation in temperature the shift is approximately proportional to the density change.

In this connection it must be remembered that while the critical voltage is theoretically the voltage required to break the conductor into corona, in practice it is a somewhat fictitious quantity. For this reason it may not be determined with any great degree of accuracy and its usefulness lies only in the locating of the loss curve.

It was thought desirable to study also the effect of smoke on corona loss. First the loss in clean air was measured; then it was measured after introducing into the tank a dense smoke formed by burning a rag soaked in lubricating oil. For these tests a 7-strand steel cable having a maximum diameter of 0.240 in. was used. Results of these tests may be seen in Fig. 3. The effect of smoke was not to shift the curve but rather to change the shape, decreasing the loss 25 to 30 per cent throughout the range of test voltage.

As regards the difference between the effects of temperature and pressure it is supposed that the greater effects of temperature may be accounted for by the change in velocity of the gas molecules. When the density is decreased by decreasing the pressure, a certain percentage of the gas molecules is withdrawn without increasing the velocity of those remaining; whereas, when the density is decreased by increasing the temperature, this same percentage of gas molecules is driven out because of an increase in the molecular velocity. Now, in the latter case, the remaining molecules, having a higher velocity than in the former, may ionize to a greater extent and the loss becomes greater.

In regard to the effect of smoke, the explanation again seems to lie in the consideration of the ion. The charges moving out from the conductor become attached to the smoke particles which being heavy retard their progress; a shielding effect is built up by the immobility of this space charge.

No definite conclusions have been reached regarding the effect of different types of conductor, although both the results of Siegfried and those of the more recent experiments show differences in the curve shapes for the 2 conductors used. Further, the smooth conductor seems to be more sensitive to changes in surrounding conditions.

The pursuit of this investigation carries great promise of interesting and valuable discoveries, and it is hoped that in the near future some definite laws of corona behavior will be established and that some of the problems suggested by the present results may be followed through.

Iron Shielding for Telephone Cables

Among the benefits obtained by the cabling of telephone circuits is the substantial reduction in magnetically induced voltages that can be realized from the shielding action of the lead sheath. Even greater shielding is attainable if the cable is provided with a steel armor or is installed in iron pipe conduit. In this paper is presented a method for the quantitative prediction of the electromagnetic shielding effected by such iron-surrounded telephone cable sheaths, experimental verification of its applicability, and the necessary impedance data for its utilization.

By
H. R. MOORE
ASSOCIATE A.I.E.E.

Am. Tel. & Tel. Co.,
New York, N. Y.

VOLTAGES of fundamental and harmonic frequencies, induced along communication cables by neighboring power or electric railway systems, can be reduced by the electromagnetic shielding action of the sheath, if this is grounded continuously or at the ends of the exposure.[1] The shielding, particularly at the fundamental frequency, is improved greatly by the provision of a steel tape armor, while a surrounding iron pipe conduit effects a very great improvement at both the fundamental frequency and the higher harmonics.

This paper presents methods for the quantitative prediction of the shielding, expressed by a "shield factor" or the fraction to which a disturbing voltage is reduced. Necessary impedance data are given for numerous iron-surrounded cable constructions and working charts are supplied for the convenient determination of the shielding obtainable with commercially available steel tape armored cables.

On the basis of data presented in this paper, prediction of the shielding to be obtained from steel tape armored cable sheaths or those inclosed in iron pipes is concluded to be both feasible and practical. With internal impedances measurable on short length samples of a chosen construction, the accuracy of prediction is limited principally by the precision to which the disturbing field and the grounding resistances of the cable sheath may be determined. Either of the constructions discussed is capable of effecting a high order of shielding against low frequency induction and practically complete protection from harmonic disturbances. Field observations on installed cables, both tape armored and in pipe conduit, have verified the computational methods presented.

Full text of a paper recommended for publication by the A.I.E.E. committee on communication. Manuscript submitted June 5, 1933; released for publication October 2, 1933. *Not published in pamphlet form.*

1. For references see bibliography at end of paper.

Theoretical Discussion

The term "shielding" designates the action of altering, and usually diminishing, the induction into a circuit or circuit element from charges or currents borne by some other circuit or circuit element. The adjectives "disturbed" and "disturbing" describe these respective systems, the name "shield" or the modifier "shielding" denoting a third system which, by the action of charges or currents set up in it, effects the reduction. A disturbed system so protected is termed the "shielded" system, while the degree of the reduction is denoted by a "shield factor," η—the ratio of the resultant or shielded effect to the initial or nonshielded effect.

The shielding of cabled communication conductors by a grounded sheath is so complete in the case of electric induction that only the shielding action toward magnetic induction need be considered. Further, because of the close proximity and continuous transposition of the wires, the voltages directly induced in the metallic circuit formed by a cable pair are unimportant. Consequently, only longitudinal voltages, observable as voltages between conductors and sheath or ground, remain to be considered. Even with completely metallic communication circuits and under normal conditions in an adjacent power system these longitudinal voltages may be of interest, for, although small, their harmonic constituents may act through unbalances to cause circuit noise. Under abnormal conditions in the power system, the longitudinal voltages of fundamental frequency in the absence of shielding may attain values of a thousand volts or more.

For simplicity the disturbing system will be treated as a ground return circuit, thus simulating a fault condition of a power line or the operating condition of an electric railway. Conclusions resulting from this treatment are equally applicable for corresponding magnitudes of induction from balanced power circuits.

Nomenclature and units used in this paper are as follows:

I_1 = current in disturbing circuit, amperes
I_2 = current in cable sheath circuit, amperes
E_3 = induced or nonshielded voltage in disturbed circuit per thousand feet
V_3 = resultant or shielded voltage in disturbed circuit per thousand feet
η = shield factor, V_3/E_3, numeric
Z_{13} = total mutual impedance between disturbing and disturbed circuits, ohms per thousand feet
Z_{22} = total self-impedance of cable sheath with earth return, ohms per thousand feet
Z_{23} = total mutual impedance between cable sheath and disturbed circuits, ohms per thousand feet
Z°_{23}, Z°_{33} = external components of impedances
z_{23}, z_{33} = internal components of impedances
R = resistance of end ground connections of cable sheath, ohms

r_{22} = d-c resistance of cable sheath, ohms per thousand feet
Δr = effective resistance increment for steel armored sheath, ohms per thousand feet
x = internal reactance of armored sheath, ohms per thousand feet
l = exposure length, thousands of feet
G = "leakance" of underground cable sheath, mhos per thousand feet

The longitudinal electric fields set up along both the sheath (2) and the core (3) of a cable exposed to an adjacent grounded disturbing conductor (1) are the same and may be noted by $E_2 = E_3$. The field is formulated as the product of the disturbing current and the mutual impedance between the disturbed and disturbing circuits: $I_1Z_{12} = I_1Z_{13}$. Grounding the sheath at both ends of the exposure results in a current, I_2, which by its counter field, I_2Z_{23}, effects a reduction in the voltage along the core to a value V_3. If the cable is removed sufficiently far from the disturbing conductor so that there is no interaction from this current, there may be written:

$$0 = E_2 + I_2Z_{22}$$
$$V_3 = E_3 + I_2Z_{23} \qquad (1)$$

as the total voltages around unit length sheath and core circuits. Solving:

$$\frac{V_3}{E_3} = 1 - \frac{Z_{23}}{Z_{22}} = \eta \qquad (2)$$

Thus, the field along the cable conductors is reduced by the shielding action of the sheath to a fraction η, the shield factor, of that otherwise present.

In order that the shield factor may be low, it is desirable that the self and mutual impedances, Z_{22} and Z_{23}, be of like magnitude and phase. The added reactance and the resistive loss increments due to a surrounding iron armor or pipe, being more or less common to the 2 impedances, are obviously of advantage. A reduction in the d-c resistance of the sheath or the grounding resistances is of benefit since these are components of the self impedance only.

Computation of the shield factors for iron-surrounded sheaths is complicated by the dependence of the self- and mutual impedances upon the sheath current. To consider this effect, it is convenient to resolve the impedances into their "external" and "internal" components. Of these, the latter are properties solely of the conductor, comprising the d-c resistance (for the self-impedance only), resistive increments due to iron losses, and reactances due to linkages of such fluxes as exist within the outer radius of the cable. The external components, which are dependent upon the radius of the cable, the placement with respect to the earth, and the resistivity of that earth, are those formulated by Carson[3] and others; they are identical for both the self- and mutual impedances.

The suggestion for resolving out an internal impedance component which could be determined by laboratory scale measurements on short length samples of cable was made by R. G. McCurdy in 1926. Part of the measurements reported herewith were made in the following year.

Internal Impedance Data

Measurements of the internal impedance components have been made for 7 sizes of steel tape armored cables of the construction shown in Fig. 1, and, in addition, for cables enclosed in several sizes of wrought iron pipe. The method of measurement in either case was the same. (A similar method of measurement has been described recently by Zastrow and Wild.[3]) A voltage drop along a 20- to 100- t sample was measured by means of a fine insulated wire laid along the outer surface, the vector quotient of this voltage and the current in the sample representing the internal self-impedance. The voltage in a loop composed of the outside wire and a conductor inside the cable provided a measure of the internal mutual impedance, while the voltage drop along the inside of the sheath as measured by a core wire served to indicate the vector difference between the 2 impedances. Both voltages and currents were measured with an a-c potentiometer. All impedance values were corrected to a chosen base temperature of 70 deg F.

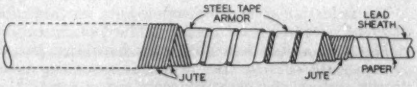


Fig. 1. Construction of steel tape armored telephone cable

Table I—Physical Dimensions, D-C Resistances, and Correlating Factors for Test Samples of Steel Tape Armored Cables

Sample No.	Dimensions: Lead Sheath o.d., In.	Lead Sheath t, Mils	Steel Armor* $\bar{a}$, In.	Steel Armor t, Mils	Steel Armor b, In.	Steel Armor s, In.	Steel Armor α	D-C Resistance at 70°F, Ohms Per 1,000 Ft: Sheath	Sheath Plus Armor	Correlating Factors 25 Cycles k_x	25 Cycles k_r	60 Cycles k_x	60 Cycles k_r
1	2.63	125	1.54	61	2.0	0.45	14.7	0.108	0.102	1.51	1.15	3.62	2.76
2–4 (Avg)	2.63	125	1.49	43	2.0	0.42	15.0	0.108	0.103	1.12	0.87	2.69	2.07
5–7 (Avg)	2.38	125	1.33	44	2.0	0.45	17.0	0.118	0.110	1.22	0.91	2.93	2.19
8–9 (Avg)	2.38	125	1.37	42	1.25	0.33	10.6	0.118	0.112	1.17	0.90	2.80	2.15
10	1.75	125	1.07	43	1.75	0.44	19.1	0.165	0.145	1.43	1.01	3.43	2.44
11	1.56	155	1.02	43	1.75	0.44	20.1	0.155	0.135	1.48	1.04	3.56	2.50
12	1.38	125	0.90	40	1.25	0.38	16.7	0.205	0.175	1.56	1.09	3.74	2.63
13	1.22	125	0.73	40	1.25	0.31	20.0	0.245	0.215	1.94	1.37	4.66	3.29
14	0.85	75	0.55	42	1.25	0.28	26.5	0.525	0.395	2.48	1.61	5.95	3.86
15	0.47	70	0.31	19	0.75	0.095	25.6	1.110	0.905	2.32	1.68	5.58	4.03

Notes: Column headings are interpreted as follows: o.d., outside diameter; t, thickness; $\bar{a}$, mean radius of armor; b, tape width; s, air gap width; α, angle of lay measured to plane perpendicular to cable axis, in degrees.
Samples 2–4 are of the standard "full sized" dimensions.
For a discussion of the correlating factors and their use, see text (Internal Impedance Data).
* Two overlapped tapes of the indicated dimensions.

Complete physical dimensions of the steel tape armored cable samples are given in Table I together with the d-c resistances for both the lead sheath and the paralleled sheath and armor. The measured reactances and resistance loss increments for ranges of 25- and 60-cycle sheath currents are shown in Figs. 2 and 3. In these curves are presented the averages of the measured values for all sizes of cables

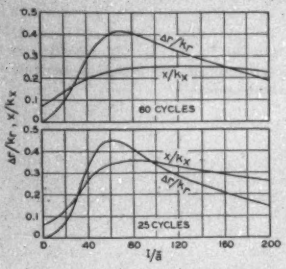


Fig. 2. Internal impedance components for steel tape armored telephone cables—composite chart for cables with tapes 40 mils thick

Ordinates × k_r or k_x from Table I give components in ohms per thousand feet. Abscissas × $\bar{a}$ (mean radius of armor) in inches give sheath currents in amperes

armored with tapes of given thicknesses. The armor steel may be identified as having an initial d-c permeability of 250, a peak permeability of 1,500 at a field strength of 5 oersteds, and a resistivity of 12.9 μohm-cm. Although the steel employed in all of the samples was nominally the same, variations in its effective anneal were prominent. Hence, a more typical value for the impedance of a given cable may be expected from the composite representation than would be available from data on an individual sample.

The reduction of the impedance data on cables of different sizes to permit their combined presentation is based upon the following considerations: For a given sheath current (the armor is assumed, as is nearly enough the case, to carry no current) the magnetic field strength within the armor of a given size of cable is inversely proportional to the mean radius ($\bar{a}$) of the armor. Hence the parameter $I/\bar{a}$ may be employed to correlate conditions of equal magnetizing forces for the several cable sizes, and also the conditions for equal permeability if the μ-H characteristics for the respective steel armorings are the same. Since the internal reactance and loss resistance are determined by the permeability and the physical dimensions of the armor, it remains only to weight the differing dimensions properly in order to provide a common relationship in terms of $I/\bar{a}$. Such weighting is accomplished by the division of the impedance components observed for each size of cable by the corresponding "correlating factors" of Table I. Thus, in Figs. 2 and 3 are plotted the quotients x/k_x, $\Delta r/kr$ versus $I/\bar{a}$. To determine the components x, Δr for a particular size of cable at a given current requires only the multiplication by the proper constants from Table I.

The correlating factors, derived from considerations similar to those treated in items 4 and 5 of the bibliography, are as follows:

$$k_x = \frac{nifb\cos^2\alpha}{(b+s)\bar{a}} \qquad k_r = \frac{nif}{\bar{a}}\left(\frac{b\cos^2\alpha}{b+s}\right)^2 \tag{3}$$

Notations and units employed in the evaluations of Table I are:

n = number of armor tapes, numeric
t = thickness of armor tapes, mils
f = frequency, cycles per second
b = width of armor tapes, inches
s = width of air gap between tape turns, inches
α = angle of lay of tapes, degrees.

Although frequency and tape thickness appear in this formulation, the failure to consider the influence of eddy current screening limits the application to fixed values of these variables. Changes in dimensions other than tape thickness are accounted for completely, however, so that by computation of the proper correlating factors the curves of Figs. 2 and 3 may be used to predict the impedance values for cables other than those listed in Table I.

For cables armored with spirally wrapped tapes, the cross section, resistivity, and effective length of the tapes compared with those of the lead sheath make the armor currents unimportant. The validity of the foregoing considerations is dependent upon this condition. Under the same condition, the internal impedance components are the same for the self-impedance of the sheath and the mutual impedance between the sheath and the cable conductors, as was verified by the measurements. The internal impedances are, therefore:

$$z_{22} = r_{22} + \Delta r + jx \qquad z_{21} = \Delta r + jx \tag{4}$$

where r_{22} is the d-c resistance of the sheath or paralleled sheath and armor.

With cables installed in iron pipe conduit, a major

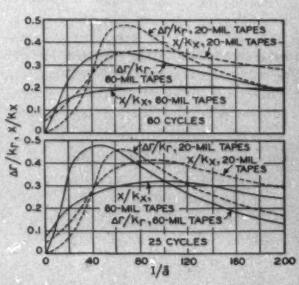


Fig. 3. Internal impedance components for steel tape armored telephone cables—composite chart or cables with tapes 20 and 60 mils thick

Ordinates × k_r or k_x from Table I give components in ohms per thousand feet. Abscissas × $\bar{a}$ (mean radius of armor) in inches give sheath currents in amperes

fraction of the current is carried by the pipe, skin effect is prominent, and a more complicated picture results. Presentation of the data for each individual construction is required, and the different flux linkages constituting the self- and mutual impedances

demand separate consideration. Figure 4 indicates the internal self-impedance for the combination, in parallel, of a full-sized lead sheath ($2^1/_8$-in. outer diameter, $^1/_8$-in. walls) and an enclosing wrought iron pipe (nominal size $3^1/_2$-in. inner diameter, $^1/_4$-in. walls); also, the difference or "leakage" impedance, $z_{22}-z_{23}$.

Harmonic Frequencies. Since in the range of harmonics of 25- and 60-cycle fundamentals the shielding against magnetic induction afforded by an ordinary lead sheath usually is sufficient to meet practical needs, the improvement afforded by iron seldom will be required. Furthermore, the gain from the armor is by no means as large at the higher frequencies. Hence, although extensive impedance data have been obtained for the voice frequency range, they will not be presented.

Another aspect of the higher frequency problem is the matter of harmonic generation by iron armor or pipe conduit. A thorough experimental study of this effect has demonstrated that there is little possibility of serious voice frequency interference from such cause.

Practical Computations

The initial step in any shielding computation is the determination of the unshielded value of the longitudinal disturbing voltage at the position of the disturbed conductor. The magnitude of this electric field is formulated as the product of the disturbing or fault current and the mutual impedance between the disturbing and disturbed circuits;[6] upon its value and the self-impedance of the grounded cable sheath depend the magnitude and phase of the induced shielding current. However, since the impedance of an iron-surrounded sheath varies with the current carried, it is necessary to solve the analytical expression for that current by successive approximations from the experimental impedance-current relations. Thence, the determination of the shield factor and, finally, the resultant or shielded voltage is straightforward. Computations for aërial and underground cables differ only in the analytical expressions required to represent the sheath current: in one case, for an essentially insulated conductor with definite grounding connections; in the other, for a continuously leaky conductor.

Aërial Armored Cables. For an aërial cable with ground connections only at the ends of an exposure or at points beyond, separated by a length l, the relations of the introductory discussion are directly applicable. The sheath current is given by:

$$I_2 = -\frac{E_3}{Z_{22}} = -\frac{E_3}{z_{22} + Z^o_{22} + R/l} \qquad (5)$$

where z_{22} and Z^o_{22} represent, respectively, the internal and external components of the self-impedance of the armored sheath per unit of length, and R the sum of the ground connection resistances. Computation of the external impedance component is discussed in reference 6 of the bibliography. Rough figures, assuming average values of earth resistivity, cable size, and elevation above ground, are $0.01 + j0.11$ at 25 cycles and $0.02 + j0.25$ at 60 cycles, both expressed in ohms per thousand feet.

In irregular exposures where the mutual impedance per unit of length is not constant, the total disturbing field is to be computed and divided by the exposure length to yield an average field value per unit of length, E_3.

The laborious solution of eq. 5 by successive approximations may be avoided by computing, for a series of arbitrary values of I_2, and for several values of R/l, the disturbing fields that would produce such currents ($E_3 = -I_2Z_{22}$). In these computations the appropriate values of z_{22} are chosen from Fig. 2 or 3 and Table I. For the same ranges of I_2 and R/l

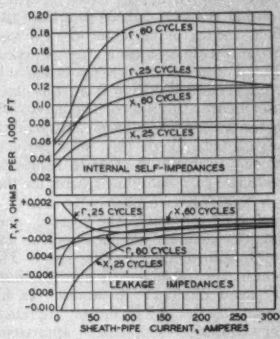


Fig. 4. Internal self- and leakage impedances for a full sized lead cable sheath enclosed in a $3^1/_2$-in. wrought iron pipe conduit

preliminary computations also should be made for the shield factor, which is simply:

$$\eta = 1 - \frac{Z_{22}}{Z^o_{22}} = \frac{Z^o_{22} - Z_{22}}{Z^o_{22}} = \frac{r_{22} + R/l}{z_{22} + Z^o_{22} + R/l} \qquad (6)$$

since $Z^o_{22} = Z^o_{23}$ and $z_{22} - z_{23} = r_{22}$. Thereafter from the plotted results of these 2 sets of computations (I_2 vs. E_3, η vs. I_2, both as families in R/l) may be found the shield factor obtaining under the conditions of a given problem.

Figures 5 and 6, representing the shield factors for full-sized tape-armored cable sheaths as functions of the disturbing field strength and the d-c resistance of the sheath and its grounds, were prepared by an elaboration of the foregoing process. Presented as contour diagrams, these charts permit the direct reading of a shield factor from the indexed contour line passing through or nearest to the intersection of the appropriate values of the coördinates E_3 and $R/l + r_{22}$. The inclusion of the d-c resistance of the sheath in the latter variable renders the charts applicable to sheaths with added conductivity, great improvements in the shielding being possible from the paralleling of unused core conductors or specially provided copper within the sheath.

A heavy ordinate drawn at the value $R/l + r_{22} = 0.103$ represents the case of a standard full-sized cable with perfect ground connections. In Fig. 5, which shows the shield factors for 60-cycle induction, it may be observed, upon following this ordinate through the range of field values, that the factor

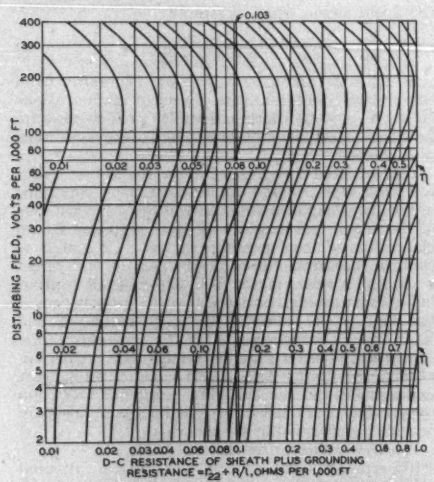
decreases from 0.18 to 0.08 and then increases. The corresponding range for 25 cycles, as read from Fig. 6, is 0.36 to 0.14. These may be compared with the factors for an unarmored cable sheath, otherwise identical, of 0.44 and 0.72 for the 2 frequencies. Since the latter are independent of field strength, the advantage of the armored sheath in the more severe exposures is particularly striking. Although it is not possible to set a figure for an "average" disturbing field, it may be stated that an exposure in which the field would exceed that for optimum shielding would be considered most severe.

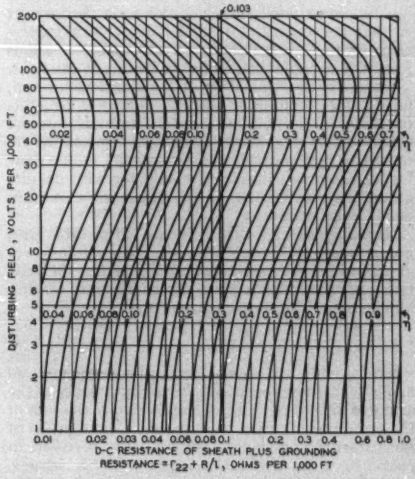
The shield factors for any of the smaller 40-mil tape armored cables listed in Table I are approximately the same, throughout the range of disturbing field values, as those for the full sized cable, perfect ground connections being assumed in either case. This is due to an increase in the internal impedance components resulting from the placement of the armor nearer the axis of the cable, which nearly compensates for the adverse effect of the higher sheath resistance. With less than perfect grounding, the shield factors for the smaller cables may be even lower than the corresponding figures for the full sized cable.

Underground Cables. By reason of their continuous contact with the earth, underground cable sheaths ordinarily do not require additional grounding to afford effective shielding. This is particularly true if the cable length exceeds that of the exposure by even moderate distances. In fact, in the latter instance, the shield factor applying to the voltage for the entire cable length approaches that obtained when the sheath is perfectly grounded at the exposure terminals.

Computation of the shield factors for an underground cable sheath is complicated by the fact that the shielding current is not constant along the extent of the cable, a difficulty that can be avoided only by consideration of average current values. To determine the latter, recourse must be had to the classical transmission equations for a continuously leaky line. Figures 7 and 8, representing the shield factors for buried full-sized tape-armored cables, exposed to 60- and 25-cycle induction, were prepared on that basis. Instead of the parameter R/l applied in the case of aërial cables, there appears the quantity $l\sqrt{G}$, in which l is the exposure length and G the shunt conductance or "leakance" of sheath to earth, per unit of length. The shield factors given include the additional reductions within moderate-length extensions by which the cable is assumed to overlap the actual exposure.

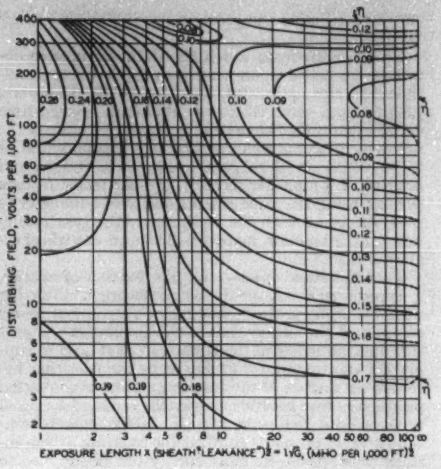
Although the "leakance" depends upon the nature and moisture content of the soil in which the cable is installed, the variation is not so wide as might be expected. Measurements of the "leakance" for full sized armored cables installed under widely different conditions have indicated a range of from 0 5 to 3 mhos per thousand feet, a value of 1 to 2 mhos being common. Hence, even with relatively short exposures, the product $l\sqrt{G}$ may attain values of 10 or more, for which the shield factors do not differ greatly from those for an infinite value. Since for the latter condition, the factors are the same as those for a cable provided with perfect grounds at the ends of an exposure, it is apparent that the simpler computational methods of the preceding section often will apply (R/l being set equal to 0).

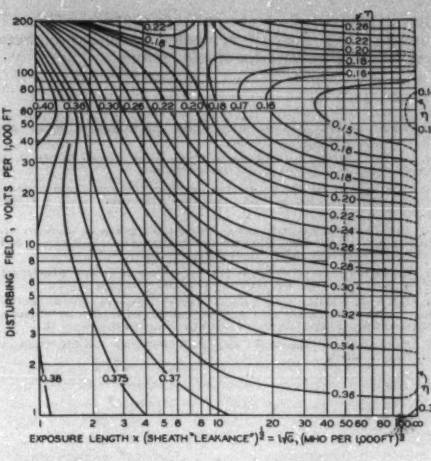




Figs. 5 and 6. Contour diagrams of 60-cycle (left) and 25-cycle (right) shield factors η for full sized steel tape armored telephone cable sheath, aerial

Grounding connections located at ends of exposure or beyond





Figs. 7 and 8. Contour diagrams of 60-cycle (left) and 25-cycle (right) shield factors η for full sized steel tape armored telephone cable sheath, underground

The cable is assumed to extend for moderate distances beyond the ends of the exposure; the added shielding within these extensions is included

Shield factors for cables installed in iron pipe conduit may be computed by this simplified method, the "leakance" being of even higher value than that for armored cable, and the derived shield factors of such low order as to minimize the need for more accurate evaluation (60-cycle factors of less than 0.01 are attainable). For this application:

$$\eta = \frac{z_{23} - z_{23}}{z_{23} + Z^0_{23}} \tag{7}$$

in which the numerator is the leakage impedance given in Fig. 4. The external impedance, Z^0_{23}, differs but little from that for a cable at the surface of the earth.[6]

Realization of the full shielding benefits of iron pipe conduit is dependent largely upon the maintenance of the electrical continuity of the pipe, both throughout the exposure and for at least short distances beyond. This necessitates welding the pipe joints and bonding around manholes.

Corrosion of an iron pipe conduit in service, if serious, would diminish the shielding benefits to a far greater extent than would similar damage to iron tape armoring which serves principally as a magnetic loading and not as a current carrying sheath.

Voltages From Sheath to Ground. Adequate grounding and complete continuity of a cable sheath passing through a severe inductive exposure are important not only for the more effective shielding of the communication circuits, but also as insurance against excessive voltages between the sheath itself and ground. Voltages from an iron-surrounded cable sheath to ground are less, under comparable conditions, than those for a plain lead-sheathed cable.

Field Observations

Two extensive field studies have been made of the shielding afforded by iron-surrounded cable sheaths. In the first of these, a 6,000-ft length of the Richmond-Petersburg (Va.) telephone toll cable was installed in an iron pipe conduit (full sized cable, 3-in. wrought iron pipe) and measurements were made

Table II—Comparison of Observed and Predicted Shield Factors

Cable		Frequency, Cycles Per Sec	Disturbing Field Volts Per 1,000 Ft	Shield Factors Observed	Shield Factors Predicted
Richmond, Va.	Full sized cable installed in 3-in. wrought iron pipe conduit	25	1.4	0.06	0.05
		60	2.7	0.009	0.008
Cisco, Texas	Full sized steel tape armored cable	60	1.4	0.18	0.18
			4.9	0.16	0.17

of the voltages induced by a paralleling ground return circuit carrying currents of various magnitudes at frequencies between 15 and 2,000 cycles. In the second, like measurements were made, at 60 cycles only, for a 12,000-ft experimental exposure on the Fort Worth-Cisco (Texas) toll cable, all of which (110 miles) was of iron tape armored construction.[7] These field studies were made possible through the extensive coöperation of engineers of the Chesapeake and Potomac and the Southwestern Bell Telephone companies.

Although it is impossible to present more than a

few items from the test results, the entries in Table II indicate the order of agreement obtained between observed and computed shield factors.

BIBLIOGRAPHY

1. SYMPOSIUM ON COÖRDINATION OF POWER AND TELEPHONE PLANT. A.I.E.E. TRANS., v. 50, 1931, p. 437–74.

2. WAVE PROPAGATION IN OVERHEAD WIRES WITH GROUND RETURN, J. R. Carson. *Bell System Tech. Jl.*, Oct. 1926, p. 539–54.

3. THE SHEATH PROTECTION FACTOR OF LONG DISTANCE COMMUNICATION CABLES, A. Zastrow and W. Wild. *Elektrische Nachrichten-Technik*, v. 9 1932, p. 10–26.

4. IMPROVEMENTS IN OR RELATING TO MEANS AND METHODS OF MAGNETIC AND ELECTRIC MEASUREMENTS IN ELECTRICAL CONDUCTORS, O. E. Buckley. *British Patent No. 206,104*, dated Oct. 24, 1922.

5. SCREW LIKE STRUCTURE OF THE MAGNETIC FIELD IN KRARUP CONDUCTORS, K. W. Wagner. *Elektrische Nachrichten-Technik*, v. 1, 1924, p. 157.

6. COUPLING FACTORS FOR GROUND RETURN CIRCUITS. *Report No. 14*, Engineering Reports of the Joint Subcommittee on Development and Research, National Electric Light Association and Bell Telephone System, v. 11.

7. TAPE-ARMORED TELEPHONE CABLE, C. W. Nystrom. A.I.E.E. TRANS., v. 51, 1933, p. 135–9.

Energy Consumption of Multiple Unit Cars

In this article are analyzed the effects of increasing the rate of acceleration, free running speed, and rate of braking upon the energy consumption of multiple unit electric passenger cars. Analyses of 4 typical one-mile runs are given.

By
F. A. COMPTON, JR.
ASSOCIATE A.I.E.E.

General Electric Company, Erie, Pa.

RELATION between energy consumption and schedule speed of electrically propelled trains for various operating conditions has been widely discussed, and the results are known to most electric railroad operators interested in either urban or interurban transportation. The object of this article is to show where energy can be saved by increasing the rate of acceleration, free running speed, and rate of braking, or by any one of these changes in operating conditions, keeping the schedule speed and length of run the same. By analyzing the distribution of the total energy input to a car it is not difficult to determine the greatest possibilities of energy saving.

Calculations from which the data given were obtained are based upon a modern 3000-volt d-c multiple-unit car equipment, operated by the Delaware, Lackawanna and Western Railroad. Speed-time curve calculations have been made on the basis of the following assumptions: an average line potential of 2,700 volts; level tangent track; acceleration and braking, 1.5 mph per second; a 4-car train, 70 tons per car, using the same gearing and wheel diameter as were furnished with the equipment (the gear reduction on the traction motors is 2.68 and the wheel diameter is 36.5 in.).

To understand clearly the distribution of energy, a typical run will be followed through. Starting with the input to the train (during the time of power on) part of the energy goes to the auxiliaries and part supplies the losses in the resistors; part goes to supply the traction motor losses, while the part that becomes the output of the traction motors is converted principally into kinetic energy; the remainder is used to overcome the train friction. This process continues until power is shut off for coasting. The instant power is off, no more energy can be supplied to the traction motors; hence, the kinetic energy stored in the train by virtue of its velocity is used to overcome the train friction for the remainder of the run. However, only a small part of this kinetic energy is used for work; the larger part becomes a braking loss.

From the following formulas the kinetic energy of the train and the work done can be calculated:

$$\text{Kinetic energy} = \frac{(wv^2)}{(2g)} \times 3.766 \times 10^{-7} \text{ kwhr}$$

$$\text{Work done} = Fs \times 3.766 \times 10^{-7} \text{ kwhr}$$

where

w = weight of train in pounds (increased by 9 per cent for rotational element)

v = velocity of train in feet per second

s = distance in feet

F = pounds friction of train

For an example of energy distribution, a one-mile run will be analyzed including 10-sec coasting and a 25-sec stop, giving a schedule speed of 26 mph. A speed-time curve and an energy consumption diagram for such a run are shown in Fig. 1. Power is applied until the train attains a speed of 47.1 mph

Values given in the chart are for one 70-ton car operating at 2,700 volts. Length of run, one mile; acceleration and braking, 1.5 mph per sec; schedule speed (including 2-5 sec stop) 26 mph

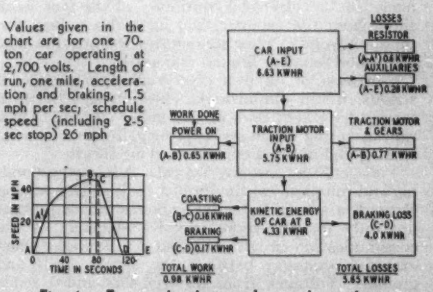


Fig. 1. Energy distribution chart and speed-time curve for run No. 1

Written especially for ELECTRICAL ENGINEERING. *Not published in pamphlet form.*

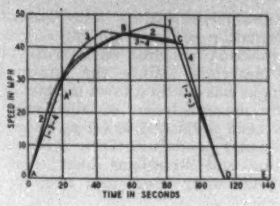


Fig. 2. Comparison of speed-time curves for the 4 runs analyzed

Schedule speed of all runs (including 25-sec stop) 26 mph

Table I—Analyses of Energy Consumption of One 70-Ton Car for 4 Typical One-Mile Runs

Run Number	1	2	3	4
Acceleration (mph per sec)	1.5	1.75	1.5	1.5
Braking (mph per sec)	1.5	1.5	1.5	1.75
Schedule speed (mph)	26	26	26	26
Gearing	59/22	59/22	56/25	59/22
Car input (kwhr)	6.63	5.85	6.14	5.74
Work done during "power on"	0.65	0.46	0.31	0.42
Work done during coasting	0.16	0.386	0.56	0.44
Work done during braking	0.17	0.134	0.13	0.11
Total work done (kwhr)	0.98	0.98	1.00	0.97
Resistor losses	0.60	0.55	0.79	0.60
Auxiliaries	0.28	0.28	0.28	0.28
Traction motor and gear losses	0.77	0.71	0.81	0.69
Braking loss	4.00	3.33	3.26	3.20
Total losses (kwhr)	5.65	4.87	5.14	4.77

at B and has traveled 3,553 ft; the train then coasts from B to C for 10 sec, covering a distance of 685 ft and slowing down to 46.2 mph. At C the brakes are applied and the train stops at D, the distance of braking being 1,042 ft.

During the run A to E 6.63 kwhr of energy per car is taken from the trolley; 0.6 kwhr is consumed by the resistors during acceleration (A to A^1) and 0.28 kwhr is used by the auxiliaries (A to E, dynamotor and compressor). This leaves 5.75 kwhr input to traction motors (A to B). For the time power is on (A to B) 0.77 kwhr is consumed by the traction motor and gear losses, leaving 4.98 kwhr output available for work. During this time the train has traveled 3,553 ft, which requires only 0.65 kwhr of work per car. Therefore, at B 4.33 kwhr is stored up in each car as kinetic energy, and if the train were allowed to coast from C to a standstill then all this kinetic energy would be used to do work. The train coasts only from B to C, however, using 0.16 kwhr per car for work, so at C the kinetic energy of each car is 4.17 kwhr. From C to D the brakes are applied. The energy required to cover the distance from C to D is only 0.17 kwhr per car, but 4.17 kwhr is available at C; hence, 4 kwhr must be consumed by the brakes and, of course, is a loss.

Thus, from the energy distribution chart in Fig. 1 it may be seen that the total work done is 0.98 kwhr and the total losses are 5.65 kwhr per car. For a given schedule speed the work will remain practically constant, so that in order to decrease the energy consumption the total losses must be reduced. For a given time the energy consumed by the auxiliaries will remain constant. Hence, there are 3 items to consider, namely: (1) resistor losses, (2) traction motor and gear losses, and (3) braking losses. The braking loss is the largest and offers the greatest possibility for improvement. The only way the braking loss can be reduced is to brake at a lower speed, which means more coasting; and in order to maintain the same schedule speed a higher rate of acceleration, either initial or average, or a higher rate of braking must be used. In other words, any time lost in coasting to a lower speed must be made up during the time power is on or during the braking time.

To determine the effect of increasing the rate of acceleration and braking, analyses of the energy consumption for 3 different types of one-mile runs were made; the results are given in Table I, with corresponding speed-time curves shown in Fig. 2. For comparative purposes, the data of Fig. 1 and the speed-time curve of Fig. 1 (run No. 1 also are included in Table I and Fig. 2, respectively.

Run No. 2 is the same as No. 1, except for the initial rate of acceleration, which is 1.75 mph per second for run No. 2. A comparison of the data for run No. 2 with that for No. 1 reveals the following: Total car input 5.85 kwhr, a saving of 0.78 kwhr over run No. 1. The total work done is the same, hence 0.78 kwhr is saved in losses. The resistor loss is 0.05 kwhr less, and the traction motor and gear losses are 0.06 kwhr less. The speed of braking was reduced from 46.2 to 42 mph, hence the braking losses were reduced from 4.0 to 3.33 kwhr, which means a saving of 0.67 kwhr in braking loss.

Run No. 3 has the same initial rate of acceleration and braking, length of stop, and schedule speed as No. 1, but with the gear reduction being decreased to 2.24. The change in gear ratio is to give a higher free running speed, hence a higher average acceleration while the power is on. Comparing the data for run No. 3 with that for No. 1, the total car input is found to be 0.49 kwhr less for No. 3. The resistor losses for run No. 3 are 0.19 kwhr greater because a higher initial accelerating current had to be used for a longer time than in No. 1 in order to obtain an acceleration of 1.5 mph per second with the reduced gear reduction. Because of the higher current the traction motor losses are 0.94 kwhr greater in run No. 3, but the greatest loss of all, that of braking, is 0.74 kwhr less than in No. 1. Although the resistor and traction motor and gear losses increase with a higher speed gearing, there is a net saving in energy consumption on account of the lower speed of braking, which for run No. 3 was 41.6 mph.

Run No. 4 has the same schedule speed, length of stop, rate of acceleration, and gear reduction as in No. 1, but employs a rate of braking of 1.75 instead of 1.5 mph per second. Comparing the data for run No. 4 with that for No. 1, the resistor losses are the same, the traction motor and gear losses are 0.08 kwhr less for No. 4, and the braking loss is 0.8 kwhr less.

By analyzing in a similar manner the distribution of total energy input for other combinations of operating conditions, it is possible to determine the possibilities of energy saving for any given length of run and for any given schedule speed.

Better Instrument Springs

The characteristics and stability of performance of the control springs used in electrical measuring instruments are important factors in the accuracy of such instruments. Supplementing the slight amount of published information on this subject, the following article presents some of the manufacturing knowledge necessary for the production of instrument springs of high quality.

By
ROBERT W. CARSON
ASSOCIATE A.I.E.E.

McGraw-Hill Pub. Co., New York, N. Y. Formerly of the Westinghouse Elec. & Mfg. Co., Newark, N. J.

ELECTRICAL measuring instruments play an important part in the development and testing of electrical machinery, in the operation and control of electrical equipment, and in the distribution and metering of electrical energy. In these applications of spring controlled instruments, the accuracy depends as much upon the performance and stability of the control springs as on the design of the torque producing elements. Such factors as jewels, pivots, permanent magnets, electrical design and the structure of the mechanism are well covered in the technical literature. However, the standard references on instruments, both in this country and abroad, cover only the usual data on the mechanics of spring design, and do not include the knowledge necessary to produce instrument springs of the high quality and performance required in modern sensitive instruments.

There are 2 unstable effects found in the application of spiral springs to electrical instruments: aging and hereditary hysteresis. Aging results in a slow permanent change in the zero position and calibration of the instrument over long periods of time. Hereditary hysteresis results in a time lag of the deflection in relation to the applied torque. Hysteresis is a temporary effect evidenced by the failure of the spring to return exactly to the zero position after having been deflected for a long period of time.

Information is needed regarding the effect on the performance of spiral springs of such factors as composition, mechanical condition of the spring material, rolling practice, forming methods, stabilizing heat treatments, design details, residual stresses, service conditions, and temperature. The present article includes information drawn from the results of several years of practical research on instrument springs and spring materials. While the information in this article might have been known in equivalent form by certain manufacturers of instrument springs, it has never been published so far as known to the author. Torsional pendulum tests, hardness tests, various forming and stabilizing heat treatments, spiral spring uncoiling tests, and measurements of hereditary hysteresis with the grid glow micrometer were used to obtain this information.

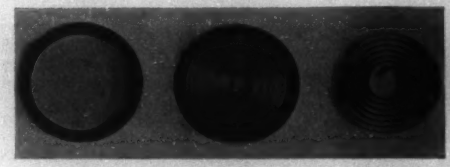
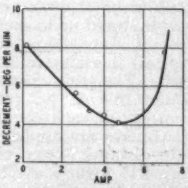


Fig. 1. Forming instrument springs. On the left is shown the forming barrel, in the middle is the barrel filled with spring ribbon ready for forming, and on the right is shown the formed spiral spring



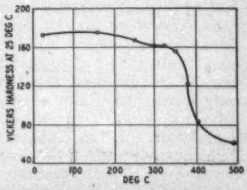


Fig. 2 (left). Effect of moderate heat treatment on the decrement of spring material in the torsional pendulum test. A current of 6 amp caused softening

Fig. 3 (right). Effect of forming temperature on the hardness of spring ribbon. The forming time was 15 min

Manufacture of Spiral Springs

In the usual shop method of making spiral instrument springs, hard drawn wire of a suitable material such as phosphor bronze is used. The degree of hardness or temper is measured usually by the amount that the cross section is reduced in cold drawing. This may be expressed by the number of wire sizes or the percentage cold reduction in area. For example, an annealed wire 0.064 in. diam drawn without further annealing to 0.010 in. diam is 16 numbers hard, or 97.5 per cent cold reduction in area.

The hard spring wire is rolled with several passes through the rolls to a hard, thin ribbon. Several

Essentially full text of a paper (No. 33-89) presented at the A.I.E.E. summer convention, Chicago, Ill., June 26–30, 1933.

lengths of the ribbon are wound together around an arbor, and held tightly wound with a close-fitting barrel as illustrated in Fig. 1. The ribbons in the barrel then are formed into a spiral shape by heating the assembly for several minutes at a moderate temperature, in some instances at 300 deg C. When the ribbons are removed from the barrel they retain an approximation of the spiral shape they assumed when wound in the barrel.

The stresses set up in the ribbons when they are wound into the forming barrel are very high. As the ribbons in the barrel are heated the elastic strength of the material decreases. At the forming temperature the elastic strength is but a small fraction of its value at room temperature, and the springs set to the form in which they are constrained in the barrel. However, the high stresses set up in winding the ribbons into the barrel are not completely relieved by the heat treatment, since the material retains some elastic strength at any temperature below the annealing or softening point. Proof of the presence of residual stresses in the ribbon is found in the fact that the springs expand when they are removed from the forming barrel.

Effect of Heat Treatment on Hysteresis

In the torsional pendulum tests a rotating pendulum was suspended by a 20-in. length of spring wire.

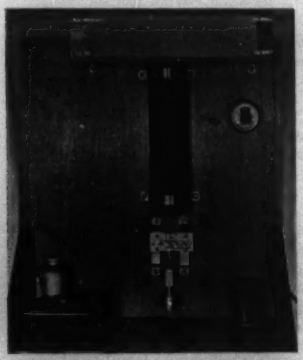


Fig. 4. Oven used in softening tests on spring wire

The maximum combined fiber stress at an amplitude of 100 deg was approximately 9,000 lb per sq in. with a wire diameter of 0.010 in. The wire was heat treated under the tension load of the pendulum weight by passing a current through the wire. The decrement of the torsional oscillations was measured after heat treatments at successively higher temperatures. In a typical test, shown in Fig. 2, a 2 per cent tin phosphor bronze wire with 45 per cent cold reduction in area was used. In this test the decrement or the hereditary hysteresis decreased rapidly as the heat treating temperature approached the softening point, as shown by the curve. In a series of tests using wires of various compositions and varying amounts of cold reduction in area similar results were obtained, with the exception that the effects were greater in wires with more cold working.

Hardness Tests

Phosphor bronze ribbons with varying amounts of cold reduction in area were subjected to successively higher temperatures, and the effect of this thermal treatment on the hardness of the strips was measured with a Vickers pyramid hardness tester. Large variations in the range of cold reduction in area did not produce corresponding variations in hardness. However, the softening range was found to be very critical as shown in Fig. 3 for a 2 per cent tin phosphor bronze ribbon, 0.015 in. thick and 0.165 in. wide, with 85 per cent cold reduction in area. Heat treating temperatures up to 350 deg C had little effect, but slightly higher temperatures caused a large decrease in hardness. A similar effect was found in all cold worked ribbons, but the initial hardness was not quite as high for lower amounts of cold working.

Softening Tests

One-foot lengths of phosphor bronze wire were heated in the small electric oven illustrated in Fig. 4, while under a constant tension load produced by a weight. The wire was clamped at the upper end of the oven and was passed between a pair of small rollers at the lower end. The rollers were held in contact with the wire by light spring pressure. Extension of the part of the specimen inside the oven was indicated by a pointer rotated by one of the rollers. When the wire was heated the pointer indicated the extension caused by thermal expansion. However, at elevated temperatures the tension load

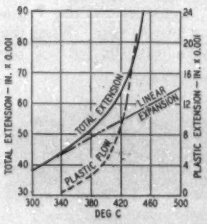


Fig. 5 (left). Softening test of spring wire

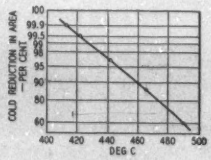


Fig. 6 (right). Effect of cold working on the softening temperature of spring wire

introduced permanent creep or plastic extension in addition to the thermal expansion effect. The test was performed by heating the oven at a uniform rate and measuring the temperature and total extension of the specimen. The plastic extension was obtained graphically by subtracting the calculated

temperature expansion from the total extension as shown in Fig. 5 for a typical test. The specimen illustrated was a 2 per cent tin phosphor bronze wire 0.010 in. in diameter, 12 in. long, with 97 per cent cold reduction in area. The tension load was 8,000 lb per sq in. and the heating rate was 35 deg C per minute. In this test there was no plastic extension until a temperature of approximately 330 deg C was reached. As the temperature was further increased the plastic extension increased very rapidly. The occurrence of plastic extension indicated that the material lost strength as the temperature was raised through 330 deg C.

Increased cold working in the spring material was found to lower the temperature at which the loss of strength or plastic extension occurred. The temperature at which the plastic extension reached 0.020 in. was determined for a series of specimens with varying amounts of cold reduction in area. In Fig. 6 it is shown that this temperature fell rapidly as the cold reduction in area was increased. Although this test method is not subject to rigorous interpretation, it demonstrates that the softening temperature of phosphor bronze spring wire is controlled by the amount of cold working in the material.

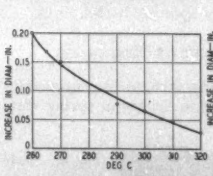
Effect of Temperature and Time on Forming

The effect of forming temperature and the time at temperature was investigated using a group of springs made from a spring ribbon prepared for a typical instrument spring. The spring material used was a commercial cold drawn 5 per cent tin phosphor bronze wire 0.008 in. in diameter. The ribbon was rolled in 8 passes to a cross section of 0.0022 in. by 0.023 in. The forming barrel, similar in shape to that shown in Fig. 1, had an inside diameter of 0.436 in. and accommodated 6 lengths of ribbon 9.5 in. long. The spring torque was 0.27 cm-g per revolution. Barrels filled with spring ribbon were formed at various temperatures from 250 to 320 deg C for 15 min. Other barrels were formed at 300 deg C for various lengths of time from 1 to 30 min. When the spiral springs were removed from the barrels, the springs expanded so that the outside diameter of the spring was larger than the inside diameter of the forming barrel. There was less increase in diameter of the spring when the temperature of forming approached the softening point, as shown in Fig. 8. The time at temperature also affected the amount of expansion. In Fig. 9 it is shown that a minimum time of 20 min at the forming temperature was required to complete the forming process.

The expansion of the spring as it was removed from the barrel provided a very useful method for determining the proper temperature and time for forming any given spring. In addition, the amount of expansion indicated the relative intensity of the residual stresses in the spiral spring.

Uncoiling Tests

When formed spiral springs are heated they show a tendency to uncoil. This uncoiling tendency was measured by heating the springs formed for 15 min



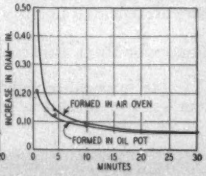
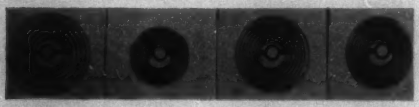


Fig. 8 (left). Effect of forming temperature on the outside diameter of spiral springs formed in the same barrel. Same springs as described in Fig. 7

Fig. 9 (right). Effect of forming time on the outside diameter of spiral springs formed in the same barrel. Same springs as described in Fig. 7. Formed at 300 deg C for 15 min

at 300 deg C to various temperatures. The rate of uncoiling is shown in Fig. 10 to increase very rapidly with only moderate increases in temperature. At 100 deg C the uncoiling rate was nearly 10,000 times as rapid as the rate at 35 deg C. The uncoiling at any constant temperature was found to proceed at a decreasing rate asymptotic to some final value, and the final amount of uncoiling was found to be larger with springs formed at lower temperatures. Measurements of the elastic modulus of the springs (torque per revolution) showed that the uncoiling was accompanied by an increase in the elastic modulus. The effect of forming temperature on the amount of uncoiling and change in elastic modulus is illustrated in Fig. 11. Springs formed at 260 deg C were subject to 3 times as much change as springs formed at 310 deg C. Tests on the springs formed at 300 to 320 deg C disclosed that the small initial uncoiling tendency was removed completely by heating the finished springs for 24 hr at 100 deg C. A small amount of uncoiling took place during this heat treatment, but there was no subsequent un-



A *B* *C* *D*

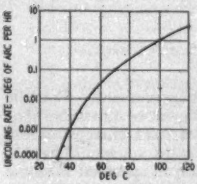
Fig. 7. Effect of forming temperature and forming time on the outside diameter of spiral springs formed in the same barrel

Springs *A* and *B* were fromed from identical ribbons in an air oven held at temperature for 15 min. Spring *A*, formed at 250 deg *C*, had an outside diameter of 0.633 in. Spring *B*, formed at 320 deg *C*, had an outside diameter of 0.461 in. Springs *C* and *D* were made from identical ribbons in an air oven held at 300 deg *C*. Spring *C*, formed for 4 min, had an outside diameter of 0.578 in. Spring *D*, formed for 30 min, had an outside diameter of 0.550 in.

coiling tendency at any lower temperature. Comparison of Fig. 8 and Fig. 11 shows that the uncoiling tendency, the aging tendency, and the expansion of the spring when removed from the barrel are all influenced in a similar manner by the forming temperature. This fact suggests that residual stresses are responsible for aging and uncoiling effects as well as the expansion effect in spiral springs.

Grid Glow Micrometer Tests

Hereditary hysteresis effects in spiral springs are very difficult to measure with precision. These



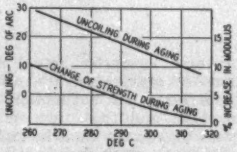


Fig. 10 (left). Effect of aging temperature on the rate of uncoiling of the spiral springs described in Fig. 7

Fig. 11 (right). Effect of forming temperature on uncoiling and increase in elastic modulus of spiral springs during aging. Same springs as described in Fig. 7. Aged at 100 deg C for 15 hrs

effects were investigated using flat strips of spring ribbon loaded in bending as illustrated in Fig. 12. A short length of ribbon was placed on 2 parallel horizontal pins and loaded with a weight hung midway between the pins. The deflection of the beam was measured with a micrometer head fitted with a sharp contact point. Contact between the micrometer point and the ribbon operated a grid glow tube to indicate the instant of contact. A large diameter drum and a magnifying lens was attached to the micrometer head to facilitate accurate readings; and a constant tension thread drive was used to make accurate settings of the micrometer. An autographic attachment was developed which produced a continuous record of displacements of the test specimen, so that a test could proceed without being disturbed. The grid glow micrometer was found to be sensitive to displacements of 0.00001 in. (ten millionths) with a contact circuit resistance of more than one megohm. With this apparatus precision measurements of hereditary hysteresis in instrument spring ribbon were made at low working stresses and over periods of time extending for several weeks.

Hereditary hysteresis in instrument spring ribbon was investigated under conditions of load and time similar to the service conditions of the instrument spring. The effect of heat treatment on hereditary hysteresis as obtained from the torsional pendulum test (Fig. 2) was confirmed. The continuous nature of the hysteresis effect is shown in Fig. 13 for a ribbon

Fig. 12. Grid glow micrometer used in hysteresis tests

of 5 per cent nickel bronze, 0.016 in. by 0.109 in., with 84 per cent cold reduction in area. The specimen was formed flat at 300 deg C for 15 min to relieve cold working stresses. At a maximum stress of 12,000 lb per sq in. the creep reached 0.28 per cent of the load deflection in 30 hr. After the load was removed recovery was approximately two-thirds completed in 30 hr. The recovery action was allowed to continue undisturbed for 7 days. When the recovery time was plotted to a logarithmic scale the recovery curve formed a straight line as shown by the right-hand curve of Fig. 13. Projection of the recovery curve to the point of complete re-

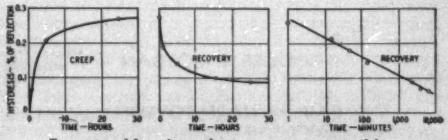


Fig. 13. Hereditary hysteresis in spring ribbon

covery gave a period of 42 days required to recover from the effects of a load sustained for 30 hr.

Conclusions

From these tests the following conclusions are drawn regarding the phosphor bronze spring materials used in the manufacture of spiral instrument springs:

1. Hereditary hysteresis is a minimum in instrument springs when the forming temperature is just below the softening point.

2. The softening temperature range for cold worked phosphor bronze spring material is very critical. Further, the softening temperature is lowered by an increase in the cold working of the material.

3. The increase in diameter of the spiral spring as it is removed from the forming barrel indicates the relative intensity of the residual stresses in the spring.

4. The tendency of the spiral spring to uncoil and increase in elastic modulus is a minimum under conditions that produce minimum

residual stresses. As in the case of hereditary hysteresis, forming at a temperature just below the softening point produces the minimum aging tendency.

5. The aging tendency of properly formed springs can be eliminated by low temperature heat treatment.

6. Hereditary hysteresis is of a progressively continuous nature, and the creep rate is more rapid than the subsequent recovery rate.

Springs made in accordance with the information presented in this article have been used in high grade indicating instruments with a marked improvement in performance. It is recognized that the details of the forming and aging process vary with the dimensions of the spring, and with the composition and mechanical condition of the spring material. However, the information given in this paper has been found to be sufficient for the development of manufacturing information for any of the usual instrument springs.

It is recognized that the work described in this article covers only one phase of the instrument spring problem. Additional information is needed on such subjects as the effect of composition, mechanical condition of the spring material, rolling practice, and temperature of loading on hereditary hysteresis and residual stresses. If some of the results presented here have been obtained by others but not reported a contributed discussion on the subject will be welcome.

Stray Load Loss Test on Induction Machines

A loading-back test has been used for the determination of the stray load losses in polyphase induction machines. This test, which was found to have a high degree of accuracy, enables the various losses to be separated. The application of the test is simple and convenient.

By
THEODORE H. MORGAN
MEMBER A.I.E.E.
Worcester Polytechnic Inst., Worcester, Mass.

PAUL M. NARBUTOVSKIH
ASSOCIATE A.I.E.E.
Stanford University, Calif.

THE experimental determination of the stray load losses in polyphase induction motors is a problem which still requires a satisfactory solution. In this paper is described a test, performed in the electrical engineering laboratory of Stanford University, which had for its object the establishment of a convenient and accurate method of determining these losses.

No discussion of the nature of stray load losses in induction machines will be given here as it is felt that this subject has already been covered by many excellent papers. Nor is it necessary to point out the desirability and need for a convenient method of arriving at an accurate determination of the amount of these losses by actual measurement. For the purposes of this paper it is sufficient to remember that these losses are a function of load current of the machine and that their magnitude is sufficiently great to warrant their inclusion in specified machine efficiency. Such being the case the designer requires the aid of dependable measurement of such losses.

The method employed for the determination of the stray load losses was essentially a loading-back test identical to that used with synchronous and continuous current machines. For the purpose of the tests 2 similar machines were connected by means of an ordinary belt drive in such a manner that one acting as a motor drove the other as a generator when connected to a common power line. Various degrees of loading were obtained by changing the pulley ratio, a few pulleys with slightly different diameters being used for this purpose.

The total losses of the combination were measured as power input to the system. The losses usually considered in calculating "conventional efficiency" and belt losses were subtracted from the total losses giving a value which is the sum of the stray load losses in both machines. This total stray load loss was plotted as a function of the arithmetical sum of the currents in the 2 machines and a simple method was developed for accurately proportioning the proper amount of the loss to its respective machine.

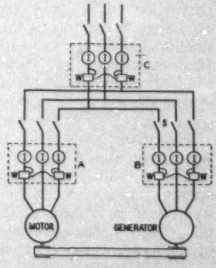


Fig. 1. Diagram of connections

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery. Manuscript submitted Nov. 24, 1932; released for publication Aug. 28, 1933. *Not published in pamphlet form.*

Certain minor incorrect assumptions which were made in the original calculations were investigated with the result that the errors caused by them were shown to be negligible.

The results of the test were compared with values obtained by a brake test and also by the "conventional method." While no refinements were employed in making the brake test the overall results from it and the loading-back test were in close agreement. The "conventional method" of course showed lower total losses and higher efficiency because of the omission of the stray load losses.

Three features of the test to be emphasized are:

1. Possibility of stray load loss determination in induction machines.
2. Separation of the various losses.
3. A high degree of accuracy.

Details of Method

The connection diagram of the machines showing the position of measuring instruments is given in Fig. 1. The input to the machine operated as a motor is measured by the instruments of group A; group B gives the output of the machine acting as a generator; and group C measures the losses in both machines and in the belt drive, all of which are supplied by the external circuit.

One of the important advantages of a loading-back test, in general, is the fact that losses are determined not as the difference between the input and output of a machine, but as a direct measurement. By the method used in this test the measurements of motor input and generator output are necessarily employed, and all the disadvantages of the input-output method would exist were not a correction applied to these measurements. To avoid completely any error which might arise from incorrect measurements of motor input and generator output a correction is applied to them so that their difference is exactly equal to the total power consumed by the losses as measured by the instruments of group C in Fig. 1. In other words, if the difference between the power readings in group A and group B meters is not equal to that of the group C meters the error thus determined is split equally between the motor and generator power readings. This completely eliminates the possibility of inaccuracy from the input and output readings as far as determination of losses is concerned.

The output of the motor is computed from its power input on the basis of "conventional efficiency" according to the rules of the A.I.E.E. Standards. This computed output is greater than the actual value by the stray load losses in the motor, i. e.:

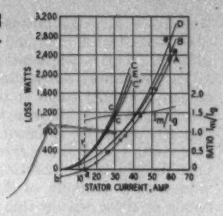
$$W_m' - L_m = W_m' \tag{1}$$

where W_m' is the computed output of the motor, W_m' is the actual output of the motor, and L_m is the stray load losses in the motor.

Likewise the input into the generator is computed from its measured output. This gives a value of the input which is smaller than the actual by the amount of the stray load loss in the generator, i. e.:

$$W_g'' + L_g'' = W_g'' \tag{2}$$

Fig. 2. Curves of stray load losses illustrating division between machines



where W_g'' is the computed value of the generator input, W_g'' is the actual value, and L_g is the stray load loss in the generator. The difference between W_g' and W_g'' is equal to the belt loss L_b, i. e.:

$$W_g' - W_g'' = L_b \tag{3}$$

Solving eq 1, 2, and 3 for $L_m = L_g$ there results:

$$(L_m + L_g) = W_m' - W_g'' - L_b$$

The problem is now reduced to the accurate division of the stray load losses between the 2 machines.

Division of the Stray Load Losses Between the Machines

Stray load losses in both machines, determined in the manner described above, are given on Fig. 2 (curve A) as a function of the arithmetical sum of the stator currents in both machines. Point a on the curve corresponds to the sum of the no-load currents in the 2 machines. According to the method of determining the iron loss the entire input to each machine acting separately as a motor at no load is classified as: stator copper loss, stator iron loss, and friction and windage loss, no part of the input being assigned to the stray load loss. Yet if the stray load loss is considered as a function of current, some of it must occur at no load due to the exciting current. This value of the stray loss at no load can be found by extrapolating curve A of Fig. 2 until it intersects the zero current ordinate (point b). Thus the amount 0-b previously classified as a part of iron loss should be properly referred to the stray load loss, which raises the stray loss curve into position B.

Division of the stray load loss may be accomplished by 2 methods: graphical and numerical.

Graphical Method

Denoting by $F(I_m + I_g)$ the experimental curve B, and by k the current ratio I_m/I_g (I_m being the motor current and I_g, the generator current), the problem can be stated analytically as follows:

$$F(I_m + I_g) = f(I_m) + f(I_g)$$

or:

$$F\big(I_g(1 + k)\big) = f(kI_g) + f(I_g) \tag{4}$$

also:

$$F(0) = 0; \text{ and } f(0) = 0$$

Here $f(I)$ is the required function, i. e., stray load loss in either machine in terms of the stator current. Though an analytical solution of eq 4 can be found in

terms of $F(I_m + I_s)$ and its derivatives (see Appendix), it is of little practical value because of its complexity. This is augmented by the fact that $F(I_m + I_s)$ is not readily obtainable from the experimental curve. In order to see how a graphical solution can be effected we shall note that the solution of eq 4 depends upon the value of k. We shall note, also, that values of k from zero to one cover the entire field in which the solution can exist, as all other values of k (outside of $0>k>1$) are merely reciprocals of those within this interval, and it does not matter which way we take the ratio of currents I_m/I_s as $f(I_m)$ and $f(I_s)$ are in fact one and the same function. Thus values of $k = 0$ and $k = 1$ give us the limiting values of $f(I)$. For $k = 0$, eq 4 gives:

$$F(I_s) = f(0) + f(I_s)$$

Since $f(0) = 0$, for this case the experimental curve B, Fig. 2, is the solution. The other limiting case is obtained for $k = 1$:

$$F(2I_s) = 2f(I_s)$$

Hence:

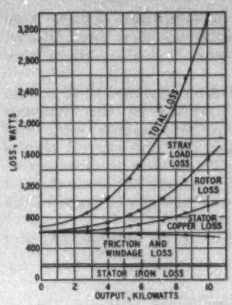
$$f(I_s) = {}^1/_2\, F(2I_s)$$

i. e., $f(I)$ can be obtained by plotting one-half of the ordinate of curve B against one-half of its abscissa. Curve C, Fig. 2, is obtained in this way. It represents the higher limit of the required function $f(I)$. We know now that the required function should lie within the 2 limits represented by curves B and C. To determine the location of $f(I)$ more accurately, curve C is used as the first approximation, and on the basis of this curve and the current ratio k (as determined from the I_m/I_s curve, plotted as a function of $I_m + I_s$), the curve of total stray loss in both machines is constructed (curve D). Naturally, as should be expected, the curve thus obtained lies above the experimental curve, which shows that a correction should be introduced into curve C. By taking the amount of error from curve E (*e. g.*: *c-e*), and subtracting one-half of it from curve C at half of the abscissa of curve D (*e. g.*: *c-c*) we obtain a second approximation for $f(I)$, which is slightly closer than C to the true location of $f(I)$, and lies below it (curve C'). If now we draw curve E exactly between curves C and C', we will be within draftsman's accuracy of the exact location of $f(I)$, as can be checked by reconstruction of the total stray load loss curve on the basis of curve E and I_m/I_s ratio.

Curves C' and D are drawn on Fig. 2 merely for the purpose of illustration. These curves are not at all necessary for the determination of curve E, as the process of determination of the error (*e. g.*: *e-e*) can be done numerically for a few values of abscissa $(I_m + I_s)$, and one-fourth of the error may be subtracted directly from C to obtain E.

Numerical Method

The shape of the stray load loss curve (curve E, Fig. 2) resembles that of a parabola of the second degree, which suggests a possibility of dividing the total stray load loss between the machines in proportion to the square of the current. An analysis of



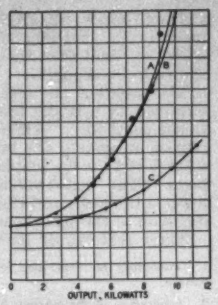


Fig. 3 (left). Separate losses in the motor as determined by the loading-back test

Fig. 4 (right). Comparison of total motor losses as determined by different methods

Curve A. Loss by brake test
Curve B. Loss by loading-back test
Curve C. Loss by conventional efficiency method

the curve shows that the latter does not satisfy exactly a simple equation of the form:

$$L = K I^n$$

where L is the stray load loss, I is the line current, and K and n are constants. Actually, both K and n vary as follows in the particular case of the machines used: for the lower part of the curve $K = 4.57$, $n = 1.525$; for the upper part $K = 1.21$, $n = 2.03$. Nevertheless, the division of the total stray load loss in proportion to the square of the current gives a fairly accurate result. The applicability of this method of stray load loss division for practical purposes can be determined by several tests of different types of motors.

Determination of Belt Loss

In order to determine the loss in the belt it may be assumed that it consists of 2 components: (1) loss due to the slip of the belt, which varies with the load, and can be determined from the expression:

$$\text{Belt slip loss} = \frac{\text{Motor output} \times \text{belt slip (rpm)}}{\text{Motor speed (rpm)}}$$

and: (2) the loss due to belt adhesion, internal friction, windage, increased bearing friction due to tension in the belt, etc. This group of belt losses is assumed to be constant, which is a fair assumption as the tension in the belt is the only factor affecting this loss that may change with load. This constant belt loss is determined for each load point by measuring the watts input to the motor with the generator belted to it, but not electrically connected. From the data obtained, the constant belt loss is found as the difference between the motor input and motor copper loss, stator iron loss, rotor loss, motor friction and windage loss, and the generator friction and windage loss. As the load on the motor is very small in this case, the conventional method of motor

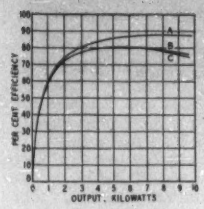


Fig. 5. Comparison of motor efficiencies determined by different methods

Curve *A*. Conventional efficiency

Curve *B*. Efficiency by loading-back test

Curve *C*. Efficiency by brake test

loss determination (as described in the A.I.E.E. Standards) gives a sufficiently accurate result. The loss due to the belt slip can be neglected; in fact, no belt slip could be detected with the generator not connected to the line.

The belt slip, necessary in order to compute the variable part of the belt loss, was determined from the actual pulley ratio, and the actual speed of the motor and the generator, which, in turn, was determined by means of a synchronously driven stroboscope.

Assumptions Investigated

In the initial computations by this method the motor rotor losses are calculated from the expression:

$$\text{Rotor loss} = \frac{\text{Stator output} \times \text{rotor slip (rpm)}}{\text{Synchronous speed (rpm)}}$$

in which the stator output is taken as the motor input less the sum of stator copper loss based upon its d-c resistance and the stator iron loss. That portion of the stray load losses which occurs in the stator is neglected in this calculation because it has not as yet been determined. This procedure gives a value for the rotor loss which is slightly higher than its true value. However, this error in the motor calculations is partly compensated for by the fact that the value of rotor loss used for the generator is too low, as a result of neglecting to add the stray load losses of this machine to its output in obtaining a value for the stator input.

Also, it has been indicated above that the belt slip loss may be slightly wrong due to a small error in the value used for the motor output employed in its calculation.

In order to obtain an idea of the magnitude of the error in the stray load losses resulting from the above approximations, after the stray load losses were computed the procedure of loss computation was repeated on the basis of ascribing all the stray load losses of each machine to its stator. New values of stray load losses thus obtained were practically identical with the previous values for all but very low currents where the difference was small enough to be negligible.

It is well to point out that there are 2 assumptions involved in the test which may impair its accuracy. One is that the stray load loss is the same function of current in each of the motors. Though one of the machines is operated as a motor, and the other as a generator, there is hardly any good reason to think that this assumption may cause any appreciable degree of inaccuracy. The other assumption is that the variable part of the belt loss is due only to the belt slip. This may not be quite correct, as the tension in the belt may change with the load, causing a change in the bearing friction. However, even if it does change somewhat, the error due to assuming it constant cannot be appreciable, as the total amount of the belt loss, which is assumed to be constant, is very small.

Results

Three previously mentioned features of the test should be emphasized: possibility of the stray load loss determination, separation of losses, and high degree of accuracy.

Losses in the machine operated as a motor are given in Fig. 3. The total loss in the machine is separated into 5 components: (1) the stator no-load loss, which includes all the tooth-frequency loss occurring at no-load; (2) the stator d-c copper loss; (3) the stray load losses in the stator and rotor; (4) fundamental frequency rotor loss; and (5) the friction and windage loss. The points indicated on the curves by small circles are the actual experimentally determined values. Good agreement between the experimental points and the smooth curves connecting them serves as one of the indications of the accuracy of the test.

In order to show more positively the real worth of the test, a brake test of the motor was made with no attempt at refinements. The comparative values of losses as determined by the brake, loading-back, and the conventional method is shown in Fig. 4 as a function of the kilowatt output of the motor. The comparative efficiencies of the motor, as determined by the 3 methods, are shown in Fig. 5. As the 2 graphs indicate, there is a good agreement between the results of the brake test and loading-back test, whereas the value of the conventional loss is too low.

The application of the loading-back test of various induction motors becomes very simple and convenient once the losses in one of the machines of the test have been accurately determined.

Emphasis should be placed upon the fact that this particular test was made on only one type of induction motor. Consequently the results obtained cannot be taken to indicate the amount of the various losses on induction motors in general. The test was made purely for the purpose of establishing the worth of this method of determining the values of the various losses in induction motors.

Appendix—Analytical Solution of the Division of the Stray Load Loss Between the 2 Motors

Statement of the Problem

Denoting the motor current by $I_m = x$, and the generator current by $I_g = y$, we have the following conditions:

$$F(x + y) = f(x) + f(y) \tag{5}$$
$$x = ky$$
$$F(0) = 0$$
$$f(0) = 0$$

k is known, being the ratio of currents in the 2 machines
$F(x + y)$ is known being the experimental curve B, Fig. 2
$f(x)$ or $f(y)$ is to be found

SOLUTION

Equation 5 can be written as:

$$F\big(y(1 + k)\big) = f(ky) + f(y)$$

Differentiating this expression with respect to y, taking k as a constant:

$$(1 + k)F'\big(y(1 + k)\big) = kf'(ky) + f'(y)$$

When $y = 0$, this gives:

$$(1 + k)F'(0) = (1 + k)f'(0)$$

i. e.:

$$F'(0) = f'(0),$$

because,

$$f'(ky) = f'(0) = f'(y)$$

Differentiating eq 5 twice with respect to y:

$$(1 + k)^2F''\big(y(1 + k)\big) = k^2f''(ky) + f''(y)$$

For $y = 0$, this gives:

$$(1 + k)^2F''(0) = (1 + k^2)f''(0)$$

Hence:

$$f''(0) = \frac{(1 + k)^2}{(1 + k^2)} F''(0)$$

Similarly:

$$f^{(n)}(0) = \frac{(1 + k)^n}{(1 + k^n)} F^{(n)}(0)$$

Expanding now $f(y)$ about $y = 0$, we have:

$$f(y) = f(0) + f'(0)y + f''(0)\frac{y^2}{1\cdot 2} + f'''(0)\frac{y^3}{1\cdot 2\cdot 3} + \ldots$$

$$= 0 + F'(0)y + \frac{(1 + k)^2F''(0)}{2!\,(1 + k^2)}y^2 + \ldots\ldots + \frac{(1 + k)^nF^{(n)}(0)}{n!\,(1 + k^n)}y^n + \ldots$$

References

1. NOTE SUR L'ESSAI DES MOTEURS ASYCHRONES, P. Meunier. *L'Eclairage Electrique*, v. 34, 1903, p. 228–31.

2. THE DISTRIBUTION OF MAGNETIC INDUCTION AND HYSTERESIS LOSS IN ARMATURES, W. M. Thornton. *Jl.* of I.E.E., 1906, v. 37, p. 125–37.

3. POLE FACE LOSSES, C. A. Adams, A. C. Lanier, C. C. Pope, and C. O. Schooley. A.I.E.E. TRANS., v. 28, 1909, p. 1133–56.

4. INDUCTION MOTOR LOAD LOSSES, H. G. Reist and A. E. Averrett. A.I.E.E. TRANS., v. 32, 1913, p. 423–8.

5. STRAY LOSSES IN INDUCTION MOTORS, A. M. Dudley. A.I.E.E. TRANS., v. 32, 1913, p. 429–34.

6. NOTES ON INDUCTION MOTOR LOSSES. R. W. Davis. A.I.E.E. TRANS., v. 32, 1913, p. 435–7.

7. THE UNSYMMETRICAL HYSTERESIS LOOP, J. D. Ball. A.I.E.E. TRANS., v. 34, 1915, p. 2,693–715.

8. A METHOD OF SEPARATING NO-LOAD LOSSES IN ELECTRICAL MACHINERY, C. J. Fechheimer. A.I.E.E. TRANS., v. 39, 1920, p. 291–9.

9. INDUCTION MOTOR CORE LOSSES, P. L. Alger and R. Eksergian. JL. of A.I.E.E., v. 39, 1920, p. 906–20.

10. TOOTH FREQUENCY IRON LOSSES IN SLIP RING INDUCTION MOTORS, D. B. Hoseason. *The Electrician*, v. 91, 1923, p. 240–2.

11. TOOTH PULSATION IN ROTATING MACHINERY, T. Spooner. A.I.E.E. TRANS., v. 43, 1924, p. 252–61.

12. SURFACE IRON LOSSES WITH REFERENCE TO LAMINATED MATERIALS, T. Spooner and I. F. Kinnard. A.I.E.E. TRANS., v. 43, 1924, p. 262–81.

13. SQUIRREL CAGE INDUCTION MOTOR CORE LOSSES, T. Spooner. A.I.E.E. TRANS., v. 44, 1925, p. 155–63.

14. NO-LOAD COPPER EDDY-CURRENT LOSSES, T. Spooner. A.I.E.E. TRANS., v. 45, 1926, p. 231–9.

15. A.I.E.E. STANDARDS, 1926.

16. MEASUREMENT OF STRAY LOAD LOSS IN POLYPHASE INDUCTION MOTORS, C. J. Koch. A.I.E.E. TRANS., v. 51, 1932, p. 756–63.

A Unique Oscillograph

An optical system designed to permit simultaneous viewing and photographing has been incorporated in a new portable oscillograph which is rugged in construction and weighs but 22 lb. It is particularly adapted for observing and photographing recurrent wave forms and certain types of transient phenomena. This oscillograph should find many fields of application where the refinements of present larger types are not required.

By
K. A. OPLINGER
ASSOCIATE A.I.E.E.

Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.

A NEW simplified, portable oscillograph has been developed which is comparable in size, simplicity, and ruggedness with the average electrical indicating instrument. The following outstanding features, most of them unique for a portable oscillograph of small size, are incorporated in this oscillograph:

1. Simultaneous viewing and photographing.
2. A continuous time axis furnished by a small revolving mirror the speed of which is variable.
3. A new type of galvanometer with electromagnetic damping and high frequency response.
4. An optical system which magnifies the galvanometer deflections and which gives a brilliant trace that can be observed in a brightly lighted room.
5. A simple method of taking photographs similar to an ordinary camera.
6. A large viewing screen for making tracings or for giving demonstrations to a group of persons.
7. Simplicity, compactness, and ruggedness comparable with the average electrical indicating instrument.

Specially prepared for ELECTRICAL ENGINEERING and based upon "A Portable Oscillograph With Unique Features" (No. 33-90) presented at the A.I.E.E. summer convention, Chicago, Ill., June 26–30, 1933.

Application

With this new oscillograph, wave forms which are recurrent can be both observed and photographed easily and accurately. Transient phenomena of short duration also can be observed and photographed. Since there is a spot of light on both film and viewing screen at all times, transient phenomena may be observed and photographed without a timing shutter. Although there is no device on the oscillograph for timing transient phenomena, the operator can tell when the transient occurs by watching the viewing screen. This procedure will be found satisfactory for many types of transients, especially those which are not of too short duration, and which do not have to be timed with great accuracy. It is expected that an instrument of this type will find many new applications for the oscillograph in general experimental and instructional work where size, ruggedness, and cost were limiting factors in previous designs.

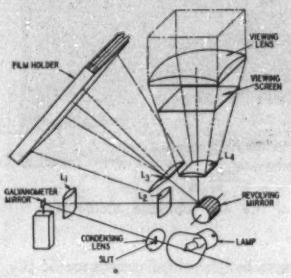


Fig. 1. Optical system of the new oscillograph which makes possible simultaneous viewing and photographing

The Optical System

The novel optical system, shown in Fig. 1, is one of the features which has made possible the design of this oscillograph. This optical system permits simultaneous viewing and photographing of wave forms and also gives an optical multiplication to the galvanometer deflections, thereby making it possible to obtain the equivalent of a long optical lever in a short space.

Referring to Fig. 1, the slit is illuminated by a standard 6-volt 32-cp automobile headlight lamp the filament of which is imaged on the galvanometer mirror by a small condensing lens. The lenses L_1 and L_2 are cylindrical with their axes at right angles to the axes of the cylindrical lenses L_3 and L_4. Optical multiplication is obtained by means of the lenses L_1 and L_2. The lens L_1 gives a reduced image of the slit directly in front of the lens L_2. This image, together with any motion imparted to it by the galvanometer mirror, is then enlarged by the lens L_2 on to the film. The size of the image on the film, in the vertical direction, is therefore fixed by the width of the slit and the over-all magnification of the lenses L_1 and L_2. The other dimension of the image is determined by the height of the slit and the magnification of the lenses L_3 or L_4 which focus on the film and screen, respectively.

Directly above the viewing screen is a spherical lens, so placed that it gives an enlarged virtual image which is comparable in size to the image on the film. Without this lens, the image does not appear equally bright at all points on the screen. The lens corrects for this and also gives greatly increased brilliancy which is sufficient for viewing even in a brightly lighted room.

To secure a continuous time axis, the number of faces on the revolving mirror, and the angles subtended by the film and viewing screen, have been chosen so that there is always a spot of light entering on both the film and screen just as the previous spot is leaving.

An inside view of the oscillograph is given in Fig. 2, showing the arrangement of the different parts of the optical system. The small revolving mirror is driven by the friction between a wheel on the mirror shaft and a face plate mounted on the end of the motor shaft. The speed of the mirror, and hence the timing on the screen, is varied by sliding the motor back and forth to change the driving radius. This adjustment is made on the oscillograph panel by the operator.

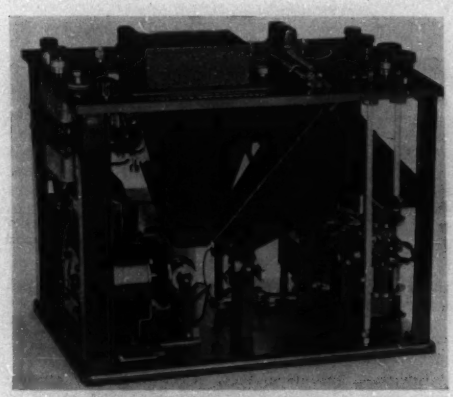


Fig. 2. Inside view of the new portable oscillograph

Rugged Galvanometer With Large Mirror

A galvanometer of very rugged construction has been designed especially for the oscillograph. This galvanometer, shown in Fig. 3, is of the moving iron type with a balanced armature form of construction. Although galvanometers of this type are not new to the art, this is the first time they have been successfully applied to the oscillograph. In place of the

vibrator ribbon as used in the moving coil galvanometer, this new galvanometer has a stiff torsional stem which supports the armature and furnishes the necessary restoring force to keep the armature centered in the air gap. In Fig. 4 is shown the armature and its support which is firmly clamped at one end in the galvanometer frame. The frequency range of the galvanometer may be extended simply by increasing the torsional stiffness of this support. In contrast to other types of galvanometers, the moving iron type becomes more rugged as the frequency range is increased.

The size of the galvanometer mirror in any oscillograph optical system is an important factor contributing to the brightness of the spot since the mirror will act as an aperture stop to decrease the illumination. With the galvanometer described, it is possible to make the mirror quite large and thereby obtain a very bright spot. The mirror shown in Fig. 4 is 1/8 x 5/32 in. and has approximately 15 times the area of an ordinary oscillograph galvanometer mirror.

Fig. 3. Moving iron type of galvanometer used in the new oscillograph

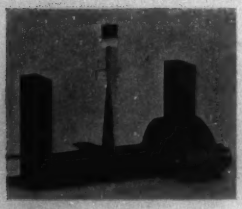


Fig. 4. Galvanometer armature and support

Damping Without Oil

In most galvanometers, it is necessary to use some form of mechanical damping, such as oil or rubber, but with the moving iron type it has been possible to get sufficient electromagnetic damping.

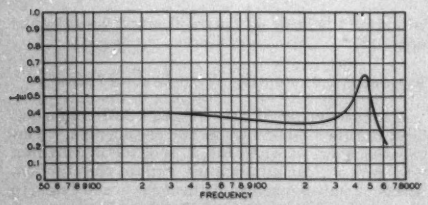


Fig. 5. Galvanometer frequency response

If a strong magnetic field is used, the motion of the armature at resonance will generate a back-voltage which will oppose the applied voltage to prevent any large deflections. The effectiveness of this back-voltage is determined by the total resistance of the circuit.

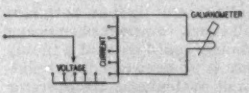


Fig. 6. Diagram of galvanometer circuit

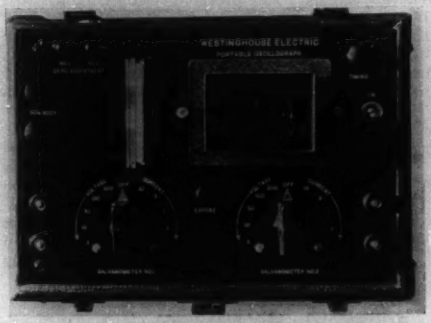


Fig. 7. Panel of the new portable oscillograph

A typical response curve for the galvanometer used in the oscillograph is shown in Fig. 5. Although the damping obtainable with electromagnetic systems as used in the galvanometer is somewhat less than the desired value, it should be emphasized that it is practically independent of temperature, and the frequency response characteristic is therefore more satisfactory for a wide range of temperatures than that of an oil damped galvanometer.

In order to use a single galvanometer for making both current and voltage measurements, the circuit shown in Fig. 6 was devised for use in the oscillograph. This circuit makes the galvanometer response independent of the resistance of the external circuit and also provides a simple arrangement for making tap connections on the shunt and multiplier resistors. When making current measurements, a small resistance having a number of taps is permanently shunted across the galvanometer. The taps give the desired current range and the value of the shunt is such as to give the desired frequency response. It can be shown that this response is the same for any tap position. For making voltage measurements, another resistor is connected in series with the current circuit. This latter resistance has taps to cover the voltage steps, and is arranged so that on the lowest voltage tap, there is still sufficient resistance to give essentially a constant current to the shunted galvanometer circuit.

Compact and Light-Weight Design

The inside view of the oscillograph as shown in Fig. 2 gives an idea of the compact design. The over-all dimensions are 8 x $11^1/_2$ x 11 in. and the total weight is approximately 22 lb. The instrument is entirely self-contained and may be operated from a 110-volt 60-cycle lighting circuit without auxiliary attachments.

A top view of the panel, Fig. 7, shows how few controls are necessary to operate the oscillograph. Each galvanometer has a single switch for selecting the desired multiplier or shunt resistor. The values marked on the panel give the approximate d-c voltages and currents for a deflection of one inch. Both galvanometers may be used for measurements of potentials up to 250 volts or currents up to 10 amp without the use of external resistors. The control switches have a stop to prevent the operator from accidentally switching to the current side when connected to a voltage circuit. However, no damage will result to the instrument if this mistake is made, since both the resistors and galvanometers are protected by fuses.

Both film and viewing screen are in position for use at all times. When it is desired to take a photograph of any recurrent phenomenon, it is only necessary to press the "expose" button near the center of the panel. This button opens a shutter to the camera, and at the same time, places an overvoltage on the oscillograph lamp. Provision has been made to use either a standard cut film holder or pack with $2^1/_4$ x $3^1/_4$ in. film in a manner similar to that of an ordinary camera.

Although this oscillograph is a research development product, it will be made available in the near future in a form that will differ only in minor details from the instrument described.

Two Applications of Nonlinear Circuits

Design of a feeder voltage regulator having no moving parts, and a method of improving alternator stability are discussed in this article. Both schemes utilize nonlinear inductive circuits, and were developed by the authors while they were undergraduate students.

By
T. M. AUSTIN
ASSOCIATE A.I.E.E.

F. W. COOPER
ASSOCIATE A.I.E.E.

Both formerly of University of Colorado, Boulder, Colo.

THE principle of nonlinear inductive circuits, in which the current is not directly proportional to the applied voltage, has been known for a long time, but has been applied commercially only comparatively recently. It was suggested to the authors that further investigation of the phenomenon of nonlinear inductive impedance might be of value. Accordingly, it was decided to examine the possibilities of applying the characteristics of such circuits to the following practical problems:

1. The design of a feeder voltage regulator having no moving parts.
2. The improvement of synchronous machine stability.

No claim is made to the discovery of any radically new principle, and the authors regard their work on the subject merely as an attempt to contribute something to the knowledge of possible new applications of an already established principle. The experiments have disclosed the fact that the nonlinear inductive circuit can be applied to the above problems with some degree of success. The authors do not presume to estimate the commercial value of these 2 schemes, but believe that some further development of the ideas may be found practicable in the future.

Essentially full text of a paper "The Application of Inductive Nonlinear Circuits to Some Electrical Engineering Problems," presented before an A.I.E.E. joint meeting of the Denver (Colo.) Section and the University of Colorado Branch, at Denver, Colo., April 20, 1932. This paper, written while the authors were seniors in electrical engineering at the University of Colorado, was awarded the Institute's 1932 national prize for Branch paper. *Not published in pamphlet form.*

I—A Voltage Regulator Having No Moving Parts

A feeder voltage regulator has been developed in a college laboratory that has a number of advantages over existing types of voltage regulators. In the most recent of several stages through which this development has passed, the voltage regulator makes use of the inductive nonlinear circuit of the 3-legged reactor, and is controlled by gas or mercury vapor hot cathode electronic tubes. The characteristics of this regulator as regards load voltage, regulator efficiency, and effect on line power factor, are comparable to those of other types of regulators. The regulator also has the advantages that there are no moving parts, relays are not required, hunting is

eliminated, operation is noiseless, and the regulator probably would be cheaper to manufacture than existing types of induction regulators.

The regulator was developed from the fundamental characteristics of an iron-cored reactor which has a changing voltage-current relation as saturation is approached. With a reactor composed of a single coil wound on an iron core, as soon as the core begins to saturate the effective impedance of the reactor decreases with increasing current. The similar effect occurs with 2 coils mounted on a closed iron core. This case is analogous to that of a 2-winding transformer. The impedance of the primary decreases with increasing secondary current. This reduction takes place regardless of whether the secondary current is alternating current induced from the primary coil, or is direct current applied to the secondary coil.

This principle has been applied commercially in what is known as the "3-legged" reactor, shown diagrammatically in Fig. 1. With the outer coils wound so that their magnetomotive forces balance each other, a small amount of direct current in the central coil may control a much greater amount of a-c power in the outer coils. This arrangement has been used in modern theater lighting control equipment, in relays, and as an amplifier. As will be shown later in this article, the same principle is used in the new regulator.

Manually Controlled Regulator

One of the earlier arrangements of the voltage regulator, although not by any means the first, is that shown in Fig. 2. This circuit consisted of a booster-connected transformer supplying power to the motor through a step-down transformer and the reactive line. The saturable reactor was connected

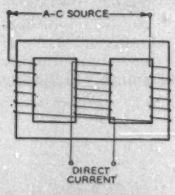


Fig. 1 (above). Schematic diagram of d-c controlled reactor

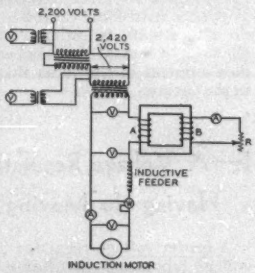
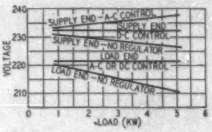


Fig. 2 (right). Booster transformer and saturable reactor regulating load voltage

in series with the secondary of the step-down transformer to reduce the boosted voltage to 220 volts at the motor terminals at no load. The voltage at the terminals of the 10-hp single-phase 220-volt induction motor was to be maintained constant by a change in the reactance of the reactor, as follows: As the motor was loaded, it drew a heavier and heavier current through the reactor and the reactive feeder, thereby producing considerable voltage drop between the supply end of the line and the load. This was compensated for, however, by reducing the impedance of the coil A through the medium of an increased current through the secondary coil B. As the load current increased, the resistance R was varied by hand, so as to permit more current to flow in B, which, as has just been pointed out, would reduce the voltage drop in A and offset the drop through the feeder. The voltage drop in the reactor requires the use of the booster transformer, which may be given a permanent setting.

This form of regulation was entirely successful, as is shown by the curves of Figs. 3 and 4, which give the results of regulation using both alternating and direct current in coil B. The circuit has the disadvantage, however, of requiring hand operation of the rheostat R; moreover, the over-all power factor



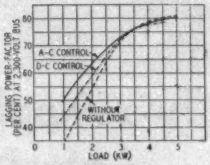


Fig. 3 (left). Manually operated reactor regulating voltage at the end of a reactive feeder

Fig. 4 (right). Over-all power factors obtained with and without reactor-regulator in circuit

of the system is slightly impaired at the higher loads. Oscillograms of the source voltage, the load voltage, and the load current were taken at no load, half load, and full load; these oscillograms show that practically no distortion of the wave form is caused by the use of such a regulator.

Automatic Regulator Developed

Attention was next given to the possibility of employing some form of vacuum tube control of the direct current in the secondary, or control, circuit of the reactor. Since a current of the order of 2 or 3 amp had to be handled, use of the ordinary type of vacuum tube was out of the question, and it was decided to experiment with a gas or mercury vapor filled hot cathode electronic tube. To this end, the circuit shown in Fig. 5 was established. Essentially, it consists of a booster-connected 2,200 to 220-volt, single-phase transformer taking power from a 2,300-volt line. The boosted voltage is then stepped down through another 2,200 to 220-volt transformer which supplies power through the regulating reactor and the reactive line to the load. The control coil B of the reactor is connected across the supply end of the feeder, in series with the rheostat R and the plate circuit of the tube, which in this case was a type *FG-67* thyratron tube. After considerable experi-

mentation with various values of grid bias on the tube and with various settings of the rheostat R, it was possible to effect entirely automatic regulation of the load voltage from no load to full load. The operation of the circuit was made to depend upon the

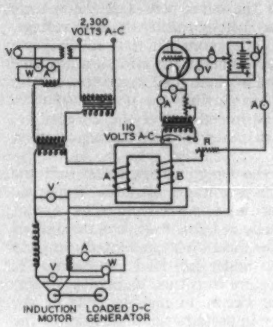


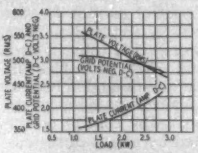
Fig. 5. Reactor controlled by electron tubes, automatically regulating load voltage

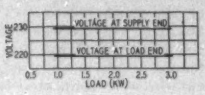
variation in the induced voltage of coil B occasioned by variation in the load current flowing through the primary coil A.

The voltage at the supply end of the feeder was connected in series with coil B in order to obtain sufficient operating voltage for the plate circuit of the tube. In this manner, a range in plate voltage of from 560 volts at no load to 460 volts at full load was obtained. It should be noted that the tube had an inverse voltage-current characteristic in this particular circuit, the plate current apparently increasing with decreasing plate voltage. Another point worthy of note is that, despite the application of a constant negative potential to the grid of the tube, the grid voltage actually became less negative as the plate current increased. This change in grid voltage is assumed to have been caused by a voltage drop within the tube from grid to filament, produced by the plate current. Since the tube exhibited some slight grid-potential plate-current control, this decrease in negative potential tended to increase the plate current and to assist the regulation. The results obtained with this system were plotted, and are shown in Figs. 6 and 7. They indicate that a satisfactory voltage regulator might be evolved in which the disadvantages of moving parts and contacts would be absent, and in which there would be no time-lag or hunting.

Three-Legged Reactor Applied

Attention was next given to an arrangement in which the booster and regulator would be combined in a single unit. For this purpose the 3-legged core of an old 13,200 to 220-volt, 3-phase transformer was used, and circuits were established as shown in the upper left hand corner of Fig. 8, except that in the early development the middle leg of the main reactor, instead of being connected to an auxiliary reactor and the tube circuits, was connected directly to a variable rheostat which shunted this middle coil. The booster consisted of the high voltage coil on one outer leg and the low voltage coil of the other outer leg. The low voltage coil of the central leg was used as the control coil, and the regulating current was adjusted by manual operation of the rheostat. The regulating effect produced here differs somewhat in its origin from that in the single-core reactor used





Figs. 6 (left) and 7 (right). Curves obtained with the reactor scheme shown in Fig. 5, automatically regulating voltage at the end of a reactive feeder

previously. In the other type of reactor, the reluctivity of the iron core was varied by varying the amount of current in the secondary coil. In the new system, however, the passage of additional current through the regulating coil on the center leg not only increases the flux density in the outer legs, but also decreases the amount of leakage flux from the outer legs passing through the center leg. The system appeared to have such good possibilities that it was decided to attempt to make it automatic. Before developing the electronic tube control, shown in Fig. 8, automatic control was secured by a water rheostat connected in the circuit of the center leg

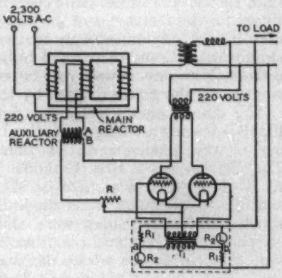


Fig. 8. Three-legged reactor controlled by electronic tubes, regulating load voltage

of the reactor, and to which direct current was applied. With this arrangement, the setting of the water rheostat was controlled by a solenoid in the feeder circuit. The plunger of this solenoid rotated a lever arm which changed the setting of the water rheostat, thereby changing the amount of current flowing in the control circuit of the reactor. This regulator had a somewhat rising characteristic, but any desired characteristic could have been obtained

by changing the design of the solenoid and water rheostat.

More Satisfactory Equipment Evolved

It was next decided to apply electronic tube control to the 3-legged regulator, as shown in Fig. 8. In this combination the control current was not passed directly through the center coil of the reactor, but through coil B of an auxiliary reactor, the other coil of which was connected in series with the center coil of the main reactor. The control current for the auxiliary reactor was obtained by rectification from the load end of the line. For rectification, 2 electronic tubes were used, and their plate-filament circuits were connected to the line through a one-to-one ratio center-tapped transformer, in order to obtain full-wave rectification. The control of the tube plate current was effected by means of the circuit enclosed in the dotted rectangle at the lower right-hand corner of Fig. 8. The operation of the circuit is as follows: The tube plate current passes through the tube as an arc, the starting of which may be controlled by the grid. Once started, however, it cannot be further controlled by the potential on the grid, but may be stopped by reducing the anode voltage to zero, as is done periodically when an alternating potential is applied to the plate-filament circuit. Under such conditions, the tube operates with intermittent arc discharge, the average current of which is controlled by the grid voltage. The simplest method of operating a tube of this type is to impress alternating voltage on the anode and any desired voltage on the grid. The critical grid voltage which will start the discharge is a function of the instantaneous value of the anode voltage. As long as the grid voltage is more negative than this critical value, no current will flow in the plate circuit. Whenever the grid voltage becomes less negative than the critical value, plate current starts and continues for the remainder of the half cycle. Its value, once it starts, is limited only by the resistance of the circuit or load, and consists of pulses. The average current over any period will be equal to the area covered by the pulses divided by the time.

The circuit enclosed by the dotted rectangle in Fig. 8 is termed a voltage-sensitive bridge, and makes use of the phenomenon of nonlinear resistance. The bridge (see "Hot Cathode Thyratrons," by A. W. Hull, *Gen. Elec. Rev.*, v. 32, 1929, p. 213–23 and 390–9) was made up of dissimilar resistances, of which 2 opposite sides were slide-wire rheostats obeying Ohm's law, and the other 2 sides were tungsten filament lamps which deviate from that law, and whose equilibrium current varies as the square root of the applied voltage. Since the resistances follow different laws, evidently there can be only one value of terminal voltage which will allow the points a and b to have the same potential, and hence allow no current to flow through the primary transformer T_1. This voltage is defined as normal voltage. At this voltage the tubes are so nearly balanced that it is not certain whether they will operate or not; actually they operate about half the time. When they do operate, they feed more direct current through the coil B of the auxiliary reactor, thereby decreasing the impedance of the secondary coil A, which decrease in impedance permits more current to flow through the center coil of the 3-legged reactor. This increase in current in the center coil, as pointed out in previous discussions of this reactor, reduces the impedances of the outer coils and the voltage drop through them, thereby raising the load voltage. The transformer T_1 is so connected that any decrease in the load voltage will make the grids less negative during the half cycles when their respective anodes are positive, thereby allowing the plate current to flow and reduce the impedance of the 3-legged reactor, which in turn raises the load voltage, as just explained.

It is seen from the foregoing discussion that the attempt to produce a voltage regulator having no moving parts has been successful. The circuit operated satisfactorily at light loads, but the limited capacity of the tubes available prevented complete tests of the system under full load conditions. It was necessary therefore to return to manual operation of the control circuit in making tests of the efficiency and other important characteristics of the 3-legged regulator, but this in no way invalidates the possibilities of the system. Manual operation of the regulator was accomplished by connecting the coil B to a d-c generator, and varying the current by a rheostat in this circuit.

The curves of Fig 9 and 10 show the important characteristics of the 3-legged voltage regulator. It is seen that they are comparable to those of other types of regulators, and in addition the circuit has the following important advantages:

1. Absence of moving parts.
2. Relays are not required.
3. Hunting is eliminated.
4. Noiseless in operation.
5. Probably would be cheaper to manufacture than existing types of induction regulators.

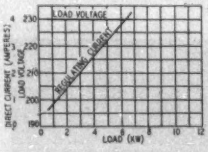
II—The Improvement of Synchronous Machine Stability

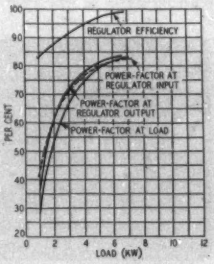
Much has been written in the past few years on the subject of power system stability, and many proposals have been made which aim to keep an alternator synchronized with its load when the power limit of the system has been approached.

It will be remembered that when a synchronous motor is being loaded from an infinite bus, the rotor of the machine drops back behind its true synchronous position by an angle depending upon the value of the load, the internal reactance of the machine, and the field excitation. Finally, when the load has reached a high enough value, the angular displacement is increased to its critical value, and the machine drops out of synchronism, even though the supply voltage is maintained constant. The critical load at which the machine drops out of step can be materially increased by increasing the field excitation.

Similarly, a synchronous generator can be caused to pull out of step with its load, if the power available to drive the generator is sufficient. The amount of load which a generator will carry successfully without falling out of step with the system is also dependent upon the internal reactance of the machine, and upon its field excitation.

Generator power limit or system stability problems do not necessarily arise during the normal operation of a system; however, an emergency may result from the automatic switching out of a generating unit, or from the tripping out of an entire power plant. Such an occurrence throws additional loads on the remaining generators of the system, so that any one of them may possibly be forced to operate at or very close to its maximum power limit. If the load imposed should happen to exceed the power limit of such a machine, it will fall out of step with the rest of the already heavily loaded machines, with the result that they also will drop their loads, and the whole system will break down.



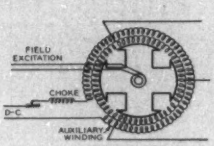


Figs. 9 (above) and 10 (right). Characteristics of 3-legged reactor as a voltage regulator

A Method of Increasing Stability

If there were some method by which the power limit of a synchronous alternator could be temporarily increased so as to carry it over the emergency, the stability of the power system could be materially improved. It is a recognized fact that to increase the power limit of a generator, the excitation must be increased, but at the same time the voltage must be kept constant. This has the effect of operating the machine higher up on the saturation curve. Several methods have been proposed to bring about the desired effect. It has been suggested, for instance, that the alternator terminals be shunted with large reactors. This has the effect of lowering the power factor on the generator, so that the field current must be increased in order to maintain normal voltage. In this way the machine is forced to operate higher on the saturation curve, and its power limit is materially increased. It is seen that this has the effect of apparently increasing the air-gap of the generator, or of stiffening the coupling. This proposal is sound, and tests in the laboratory confirm the theory. However, no one as yet has tried to build such a reactor for, say, a 50,000-kva alternator.

It might be thought that an ordinary vibrating type generator voltage regulator would take care of the matter of increased excitation; however, should the power factor of the system rise, the voltage of the alternator also would rise, owing to the magnetizing effect of the armature reaction. Thus the regulator would remain inoperative during such an emergency.



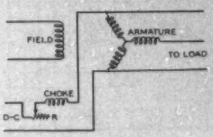


Fig. 11 (left). Alternator with an auxiliary d-c winding on the stator

Fig. 12 (right). Alternator stator connected to receive d-c component

Some engineers have advocated the use of high speed excitation systems which will, in any event, raise the field current of the alternator very rapidly. This is accomplished by causing a relay to shunt across the contacts of an ordinary vibrating type voltage regulator, thereby raising the field current very quickly, regardless of the voltage. This scheme and others that function somewhat in the same manner possess the disadvantage of causing the alternator voltage to rise along with the field excitation. When the system voltage rises, the load also rises, thereby increasing the load on the affected machine, and very little has been gained.

It may be emphasized, that in order to raise the load limit of a generator, the field excitation must be increased, but the terminal voltage must remain constant. This is, indeed, not a new principle; it has been repeatedly stressed in the writings of men who are recognized authorities on the subject of stability. The actual application of the principle, however, is not easy.

Application of the Nonlinear Circuit

The characteristics of the nonlinear inductive circuit make it readily adaptable to the solution of this problem. Referring to Fig. 11, let us suppose that an alternator is equipped with an auxiliary stator winding through which varying amounts of direct current may be passed. In series with this auxiliary winding is a heavy choke coil which will prevent the passage of any alternating currents which may be induced in it. Ordinarily, there is no current flowing in the auxiliary winding, but when an emergency arises and the load increases close to the critical value, a relay will act to force direct current through the auxiliary winding. The presence of this direct current will lower the reactance of the main stator winding by increasing the degree of saturation of the core, and at the same time the field current will have to be increased in order to maintain the flux necessary for constant terminal voltage. The net effect of

this operation is equivalent to an increase in the air-gap of the machine, so that a stiffer generator, with a correspondingly higher power limit, results.

It was not necessary to have a generator with an auxiliary winding in order to investigate the merits of the above theory. By connecting an alternator as

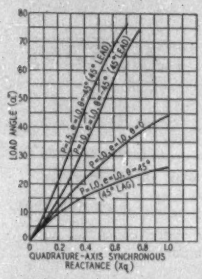


Fig. 13 (above). Theoretical curve for an alternator, obtained from the equation of tan α given in the article. Values of parameters are "per unit"

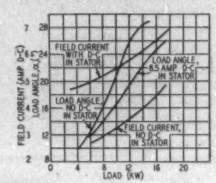


Fig. 14 (above). Curves showing the effect of a d-c stator component upon the load-angle vs. load characteristics of a 3-phase 15-kva 230-volt 60-cycle 6-pole alternator. Corresponding field current curves when operating at 192 volts, also are shown

shown in Fig. 12, a d-c component was passed through 2 phases of the Y-connected stator winding. This arrangement was tried out with satisfactory results, which will be further discussed later in this paper.

Theory Supporting These Views

From the vector diagram of a loaded alternator having salient poles (see p. 939 of "Synchronous Machines," by R. E. Doherty and C. A. Nickle, A.I.E.E. Trans., v. 45, 1926, p. 912–42) the following equation may be derived

$$\tan \alpha = \frac{Px_q}{e^2 + Px_q \tan \theta}$$

where

α = electrical angle by which the terminal voltage of the machine lags behind the quadrature axis; it is termed the load-angle, or torque-angle, and is a measure of the displacement of the rotor from its true synchronous position, i. e., the displacement of the pole from the phase axis

P = total electric power, expressed as a fraction of the normal, or "rated" power of the machine

x_q = quadrature-axis synchronous reactance, expressed as a fraction of the normal reactance of the machine per phase; where normal phase reactance is defined as the ratio of rated phase voltage to rated phase current

e = terminal voltage, expressed as a fraction of the normal terminal voltage (i. e., "rated terminal voltage")

θ = power-factor angle, the angle by which the phase current is displaced from the phase voltage

In this equation, the quantities are defined in what is known as the "per unit" notation, rather than being expressed in percentages, or in absolute quantities, such as ohms. Such procedure makes for considerable simplification in computations based upon equations relating to these various machine constants. Hereinafter, unless otherwise stated, all quantities dealt with are per phase and per unit. As an example of the use of the per unit notation, consider some of the constants of the alternator used in these experiments, and which was rated 15 kva 230 volts, 37.6 amp per phase.

Normal phase voltage = 133 volts = 1.0 per unit
Normal phase current = 37.6 amp = 1.0 per unit
Normal phase resistance = $\frac{133}{37.6}$ = 3.53 ohms = 1.0 per unit

The equation for tan α given above indicates clearly how the magnitude of the load angle depends upon the 3 factors: load, power factor, and quadrature-axis synchronous reactance, assuming the voltage to be maintained constant. Since the effect of x_q in the numerator of the above fraction is much greater than its effect in the denominator, anything that could be done to decrease x_q presumably would decrease the load angle α thereby increasing the stability of the machine and raising the power limit. This fact is demonstrated rather strikingly by the theoretical curves of Fig. 13, in which α is plotted against x_q for various values of θ and P, e being maintained constant at 1.0.

Alternator operating with no d-c component in stator winding

Alternator operating with 8 amp direct current in 2 phases of stator winding

Fig. 15. Oscillograms of terminal voltage of alternator, operating at 160 volts

Tests on an Actual Machine

Experimental verification of the above theory was next sought, and it was decided to measure the direct and quadrature synchronous reactances of the 15-kva 230-volt 6-pole alternator, by means of the slip method, both with and without direct current

flowing in the stator. Oscillograms were taken of line voltage and phase current with the machine rotating at slightly less than synchronous speed. The values of direct and quadrature synchronous reactances under the 2 conditions were as follows:

No Direct Current in Stator

Direct-axis synchronous reactance, x_d = 2.88 ohms = 0.82 per unit
Quadrature-axis synchronous reactance, x_q = 1.90 ohms = 0.54 per unit

With 8.5 Amp Direct Current in 2 Phases of the Stator Winding

Direct-axis synchronous reactance, x_d = 2.32 ohms = 0.66 per unit
Quadrature-axis synchronous reactance, x_q = 1.67 ohms = 0.47 per unit

While the proportionate reduction in x_q was not as great as that in x_d, nevertheless, it was deemed sufficient to justify the next experiment, an investigation of the effect of the direct current upon the load-angle α with a view to substantiating the theoretical deductions.

The next test consisted of a load run of the same alternator at a terminal voltage of 192 volts (0.835 per unit), with observations of the load angle being made by means of a glow tube stroboscope shining

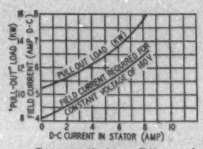
Alternator operating with no direct current in stator

Alternator operating with 8.5 amp direct current in 2 phases of stator

Fig. 16. Oscillograms of terminal voltage, armature current, and field current when loaded

on a marked disk attached to the shaft of the machine and a circular scale mounted on the frame. The use of a terminal voltage of 192 was necessitated by the fact that the stroboscope used had to be operated from the terminals of the machine under test and at a voltage of 110 volts. To obtain these conditions, the voltage from line to neutral on the machine was adjusted to 110 volts and the stroboscope connected thereto. This resulted, of course, in a terminal voltage of 192 volts.

At first the machine was loaded in the ordinary manner, and observations were made of the following quantities for each load: load in kilowatts, terminal



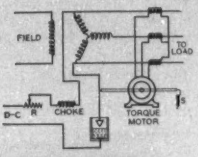


Fig. 17 (left). Effect of a d-c stator component upon the pull-out load of alternator operating at 160 volts

Fig. 18 (right). Automatic scheme for feeding direct current into the stator of an unstable alternator

voltage (constant at 192 volts), field current, and load angle. The procedure was then repeated with a direct current of 8.5 amp flowing through 2 phases of the stator winding. A comparison of the results of the 2 tests may be made upon reference to Fig. 14. It is seen that for the same given load, the torque angle was considerably less when direct current was present in the stator than when the machine was operating in the ordinary way. It should also be noted that there was a marked increase in the field current for the same terminal voltage, which, it will be remembered, was the desideratum for increased stability.

It might be thought that the direct current in the stator would distort the voltage wave, or cause such unbalance in the stator as to produce heavy induced currents in the field circuit. The oscillograms of the terminal voltage of all 3 phases, both with and without direct current, shown in Fig. 15 indicate but slight distortion in the voltage wave; while those of phase voltage, phase current, and field current in Fig. 16 (taken at a slight overload), show that only a slight a-c ripple is produced in the field circuit. This latter fact is all the more noteworthy because the machine used has no damper winding on the field structure.

As further proof of the efficacy of the method, the pull-out load of the machine was measured for various amounts of direct current in the stator, ranging from 0 to 8 amp. Here, again, it was impracticable to operate at normal voltage, because the d-c motor driving the alternator was incapable of carrying the loads involved without overheating. It was decided, therefore, to operate at 160 volts. The results of this test are shown in the curves of Fig. 17, in which pull-out load and field current required for constant voltage are plotted against stator direct current. It may be seen that with no direct current in the stator the load limit was 10.48 kw and that a field current of 4.1 amp was needed to maintain 160 volts at this load. When the d-c component in the stator was raised to 8 amp, however, the load limit rose to 15.6 kw, and the corre-

sponding field current to 6.5 amp; an increase in pull-out load of 48.6 per cent and an increase in field current of 58.5 per cent.

Automatic Control Applied

An arrangement was then set up by means of which it was hoped to apply the direct current to the stator automatically whenever the need for it might arise. In Fig. 18 is shown the loaded alternator with 3 Y-connected current transformers in the lines. The secondaries of these transformers were connected to the stator of a small 3-phase induction motor. The greater the load current, the greater would be the torque on the rotor of the induction motor. This torque acted in a counter-clockwise direction against the pull of the spring *S*. As the load increased, the induction motor would turn and dip the upper contact of the water rheostat into the water, thereby allowing direct current to flow into the stator of the alternator. The application of the direct current increased the degree of saturation of the stator core and tended to reduce the terminal voltage, but a vibrating type regulator (not shown) would act immediately to bring up the field current above normal for that voltage, so that the alternator would be in an over-excited state without any rise in voltage having taken place. The apparatus operated satisfactorily, and was, of course, so adjusted that no direct current was applied until the machine was dangerously near to its load limit. Only at such a time would the upper contact dip into the water rheostat to produce the desired effect. It may be noted that the system is effective regardless of the power factor, and regardless of any unbalance in the load.

Electrical Figures on Plates in Air

A recent investigation into the behavior of Lichtenberg figures and streamers extending out from an electrode resting on a glass plate coated on the opposite side with tin foil is reported in this paper. The new data offered throw considerable light on the formation and characteristics of these interesting figures.

By
J. GIBSON PLEASANTS
ASSOCIATE A.I.E.E.
Calif. Inst. of Tech., Pasadena

THE 2 SETS OF PHENOMENA known as Lichtenberg figures and Toepler's "Gleitfunken" or "spreading discharges" are closely related in that they originate in the same manner and the latter is only a further developed form of the former. Both phenomena have been studied extensively and various explanations of them have been offered, [1,2,3,4,5] but the new data offered in this paper throw considerable light on the formation and characteristics of these interesting figures. This work was undertaken at the instigation of Professor Matthias of the Berlin Institute of Technology, and because in a search of the literature relating to Lichtenberg and Toepler figures (some of which is reviewed in this paper) no very satisfactory explanation was found for the relation between the sizes of the positive and negative figures, the relation of the velocities of growth of the 2, and the increase in size of the figures as a function of time. Completion of the experimental work was made possible by a stipend from the "Verein Deutscher Ingenieure."

Summarized briefly, the more important findings of these experiments are as follows: Lichtenberg figures and streamers going out from an electrode resting on a glass plate coated on the other side with tin foil grow with an average radial speed of 20 to 315 km per second, or even more. The instantaneous speed of growth decreases with increasing size of the figure. The speed is dependent, for a given voltage surge, on the dielectric constant and thickness of the plate. Any variation of these that increases the capacitance per unit area of the plate causes an increase in the speed of growth and *vice versa*. A given variation of the dielectric constant or thickness of the plate produces a greater change in the speed of growth of negative figures than in that of positive figures. The per cent variation in speed of growth for figures of either polarity, resulting from a given variation of the plate constants, decreases with increasing magnitude of the applied voltage surge. The maximum current intake (for 2 figures in parallel) has been observed to be 45 amp at 60 kv (maximum value of voltage surge) and 120 amp at 85 kv. In one case the effective capacitance of 2 figures in parallel varied from an initial value of practically zero to about 8,000 cm in 3×10^{-7} sec, causing a reduction in the maximum value of the applied voltage wave of 25 per cent; the reduction in the rate of rise of the voltage for the same case was 30 per cent. The behavior of the figures supports the theory that the movement of electrons alone is principally responsible for their formation.

Full text of a paper recommended for publication by the A.I.E.E. committee on electrophysics. Manuscript submitted April 28, 1933; released for publication Sept. 28, 1933. *Not published in pamphlet form.*

1. For references, see bibliography at end of paper.

Review of the General Behavior of Lichtenberg and Toepler Figures

Brush Discharge and Streamer Discharge. Toepler has differentiated between 2 stages of the figures, which he calls "Gleitkorona" and "Gleitfunkenkorona," or "Polbueschel" and "Gleitbueschel," respectively. Equally descriptive English names are "brush discharge" and "streamer discharge." Lichtenberg figures belong to the first class. The true streamer discharges, which belong in the second class, appear under the influence of more powerful voltage surges.

The following characteristics of these figures can be investigated: (1) length attained, (2) speed of growth, and (3) current drawn. Using the familiar arrangement of a small electrode resting upon a glass plate coated widely underneath with metal forming the other electrode, these properties are found to vary with the voltage applied, the thickness of the glass, and the dielectric constant of the glass.

According to Toepler's results the size attained by the figures in the first stage depends only on the voltage wave, i. e., on the polarity, steepness of front, maximum value, and, to a degree, on the steepness of the tail. No difference was noticeable in this stage "for plates of the most widely varied thicknesses." The voltage of transition from the first to the second stage, however, is dependent on the thickness of the plate. This critical voltage is expressed as a constant times the square root of the thickness, the constant being somewhat different for the 2 polarities. As long as the discharge remains in the first stage, that of Lichtenberg figures, the radius of the positive figure is about twice that of the negative for a given voltage wave, and the figures are symmetrical.

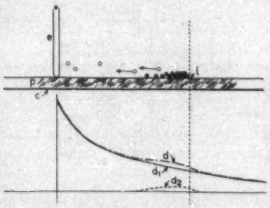


Fig. 1. Formation of surface charge and distortion of original voltage distribution with growth of electrical figure

As the voltage of the surge is increased, the discharges go over to the streamer state, in which glowing branched channels appear to be going out from the electrode. The appearance of these channels causes the figure to lose its symmetry, and gives it an unbalanced flower-like shape. Toepler's researches revealed that the maximum radial length attained by the figures in this stage depends not only on the form, size, and polarity of the voltage wave, but also on the capacitance per unit area between the 2 surfaces of the plate according to the following relation: Maximum radial length = a constant × (unit capacitance)^2. In this stage, as the figures become larger and larger, the difference in the size of the positive and negative figures approaches zero.

Mechanism of the Spreading Discharges

Capacitor Chain Theory. In order to explain this phenomenon of a discharge along the surface of the glass, Toepler first proposed the concept of a series of neighboring elementary capacitors formed by elementary areas of the upper surface and the coating of the lower surface. From this point of view the process of growth of a figure is as follows; A voltage wave reaching the electrode raises its potential high above that of the upper plate of the first elementary capacitor (i. e., of the neighboring surface) so that an arcover occurs between the electrode and the first capacitor. The latter is charged through the spark, and, as soon as its voltage is high enough, arcs over to the second capacitor. This second capacitor in turn is charged and arcs to the third, which then is charged, etc. By the use of a formula derived by Binder[6] on the basis of the differential concept just outlined, Jezek[6] was able to confirm by calculation his measurements on the velocity and current intake of streamer discharges along glass tubes filled with mercury.

Expanding Ring Surface Charge Theory. A truer idea of the process also was suggested by Toepler in the paper referred to, in which the production and movement of ions and electrons, and their influence on the original voltage distribution along the glass, are taken into consideration. Staack[5] also supports his theoretical discussion on this conception, which, however, must be modified in the light of the results of recent work done by Erwin Marx[7] and C. E. Magnusson.[4] These modifications will be dealt with later.

Referring to Fig. 1, a sudden application of voltage to the electrode *e* causes ionization of the air immediately surrounding its tip. Particles of opposite polarity are attracted to the electrode. Par-

Fig. 2. Right half of positive figure and left half of negative figure made under identical settings of "firing" gap and "cut-off" gap (actual size)

ticles of the same polarity experience a force away from the electrode and against the surface of the glass, so that they form a ring-shaped surface charge. The potential distribution d_2 along the plate due to this surface charge combines with the original distribution d_1 to form a new potential distribution d. This raises the gradient along the plate at the point i enough to cause ionization, the surface charge expands, and the process continues until the gradient at the outer rim of the surface charge becomes less than that necessary to ionize air.

Results of Previous Experiments

Jezek[6] determined simultaneously by spark gap methods the maximum rate of voltage rise and the maximum current intake. Using the current measurements in a formula in which the velocity of growth appears as a function of current intake, voltage, and capacitance per unit length between the 2 surfaces of the tubes used, he determined the probable values of velocity. He found the velocity to be directly proportional to the voltage. His tubes had values of capacitance per unit length ranging between 4 and 9 cm, and for one of them a voltage of 64 kv maximum value caused a maximum speed of growth of 5,000 km per second. The observed maximum current was not directly proportional to the maximum voltage, as it increased from 57 to 125 amp for maximum voltages of 26.4 and 45 kv, respectively.

According to the measurements of Mueller-Hillebrand[8] the velocity of growth of Lichtenberg figures produced by voltages between 2.5 and 18 kv can reach a value as high as 500 km per second.

P. O. Pedersen[2] has determined an expression for the radius of the figure as a function of time in the form: $r = R(1 - e^{-\alpha t})$ in which r = radius at any instant and R = radius finally attained. From

Fig. 3. Test plate mounting; surge generator in background

this the velocity is $v = \alpha R e^{-\alpha t} = \alpha(R - r) = v_0 - \alpha r$. For atmospheric pressure, v_0, the initial velocity, was found to be 700 km per second for positive, and 300 for negative figures. The empirical constant α was given as about 2.5×10^9 for positive and 1.9×10^9 for negative figures (for r in cm).

In his 1921 article Toepler quoted measured or estimated values of speed of growth in air that varied from 3,560 to 55 km per second.

While the present paper relates only to the rate of growth of these figures in air it may be of interest to note here that Staack[5] found for one value of voltage velocities of growth on plates in transformer oil of 18 km per second for positive figures and 9 for negative figures which were constant throughout the entire development of the figure.

Discussion of Previous Results

Range of Velocities Observed; Polarity Difference. The preceding material presents 2 features of interest: (1) observed velocities of growth covering a very broad range, the smallest differing by more than one order of magnitude from the largest; and (2) the difference in the speeds of growth of positive and negative figures, and the practical disappearance of the difference when the figures become very large. The fact that the results of Toepler, Pedersen, and Staack (in his work under oil) show continually in the first stage velocities of growth for positive figures approximately 2 times the velocities for negative figures is very disturbing. If such a simple ratio really exists it should be exactly determinable experimentally and justifiable theoretically. If not, it should be recognized as an accident.

Explanation of Wide Velocity Range. The wide difference in the values of speed of growth observed

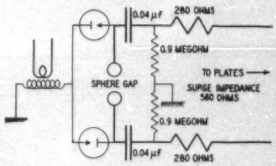


Fig. 4. Diagram of connections of surge generator

by different experimenters probably may be traced to variations in the several experimental conditions such as, for instance, the thickness of the plate, the dielectric constant of the plate, the form of the voltage wave used, etc. As shown by Toepler, the length attained by streamer discharges is a function of the capacitance per unit area of the plate. The original object of the work described here was to investigate the dependence of the speed of growth of the figures on the thickness and dielectric constant of the glass. The results include data showing an increase of (average) speed of growth in the ratio of 1.84 to 1 for positive figures and 2.98 to 1 for negative figures when the thickness of the plate was decreased in the ratio of 1.63 to 1 with no change in the dielectric constant of the plate. (The fact that this effect is greater for negative figures than for positive ones is of significance in the theory of formation of the figures, and will be discussed later.) Decreasing the thickness of the plate in the ratio of 1.98 to 1 caused an increase in the velocity of growth of as much as 2.51 to 1 for positive figures and 3.97 to 1 for nega-

tive figures. These figures show in a convincing way that observed velocities very easily might differ by one order of magnitude or more, when, as in the case of Jezek's tubes and the plates used in these experiments, the ratios of thickness vary between 6 to 1 and 11 to 1.

Experimental Procedure of Present Work

Glass plates were used for the tests described in this paper. As quickly as possible after the application of a voltage surge to the plate it was sprinkled with a mixture of red oxide of lead and sulphur. As these 2 powders together are dusted on the plate, the lead oxide takes on a positive charge and the sulphur a negative one. Thus if a plate that had just been exposed to a negative surge was sprinkled with the mixture, the red oxide of lead was attracted to the negative ring surface-charge left on the glass, thus marking the limits the figure had reached.

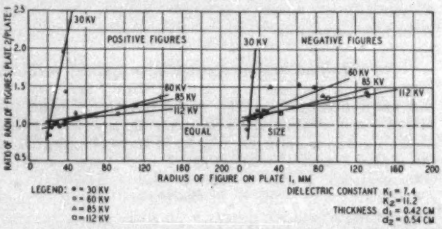


Fig. 5. Comparison of plates 1 and 2: variation of figure size with dielectric constant, thickness approximately the same

Similarly the limits of the positive figure were marked with the yellow sulphur. To prepare the plate for recording another figure it is only necessary to sweep off the powder and remove any remaining surface-charge by rubbing with the hand, finishing the rubbing with a clean dry cloth to leave the surface perfect. Photographs of typical figures recorded in this way are reproduced in Fig. 2. In one respect, this method of recording is preferable to the photographic plate method: It shows the final position of the charges on the plate, whereas the photographic plate gives a trace of their entire motion.

In making the tests, 4 glass plates were used; 2 of them had a dielectric constant of about 7, the other 2 of about 11. One plate of each of these pairs was about 5 mm thick, the other about 1 cm. The plates always were tested 2 at a time, in different combinations of 2 plates in parallel for each test. This was done to eliminate undesired variables from the test conditions. With the plates in parallel it was certain that exactly the same voltage wave was impressed on both plates, and any difference in the resulting figures was bound to be due alone to differences in the physical properties of the plates. A needle gap was connected in parallel with the plates, its spacing being used to regulate the duration of the voltage on the plates. As is well known, if a voltage little more than just sufficient to cause arcover of a needle gap (on d-c test) is impressed upon the gap very suddenly, an interval of time will elapse before the discharge actually occurs; this is because ionization does not occur over the entire gap at the same

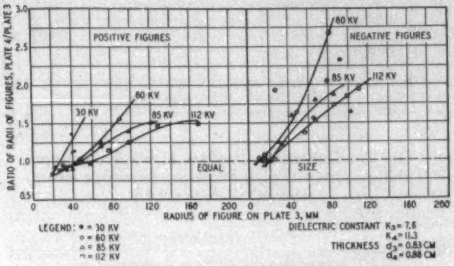


Fig. 6. Comparison of plates 3 and 4: variation of figure size with dielectric constant, thickness approximately the same

time, but begins near the points and spreads toward the middle. If the maximum value of the surge voltage applied to a needle gap is appreciably above the d-c arcover voltage, the time lag is very short, and, as it proved, of the right duration to allow the electrical figures to attain a convenient size.

Figure 3 shows clearly the arrangement of plates, electrodes, and needle gap; in addition 2 negative figures may be seen. The figures are in the second stage, no longer round and symmetrical, but with somewhat scalloped rims due to the formation of streamers. Figure 4 shows the diagram of connections for the surge generator used in the tests. The connection to the plates was made over an indoor transmission line with a surge impedance of 560 ohms. To eliminate oscillations from reflected waves a noninductive resistance of 280 ohms was included in each side of the line at the surge generator.

Test Routine. The thin plate with the low dielectric constant was called No. 1, the thin plate with the high dielectric constant No. 2, and the thick plates with the low and high dielectric constants Nos. 3 and 4, respectively. Tests were made on parallel combinations of Nos. 1 and 2, 3 and 4, 1 and 3, and 2 and 4. Surges having maximum values of 30, 60, 85, and 112 kv were used. For any series of tests at one voltage the needle gap was set at 0.5, 1.0, 1.5, 2.0 cm, etc. After each surge the electrical figures formed were measured and their sizes recorded. As soon as the figures had entered the second stage and had become unsymmetrical, the *greatest* radius was recorded in each case.

Sometimes the measurements for duplicate tests were quite consistent, but more often they were not. Obviously consistent data were possible only when

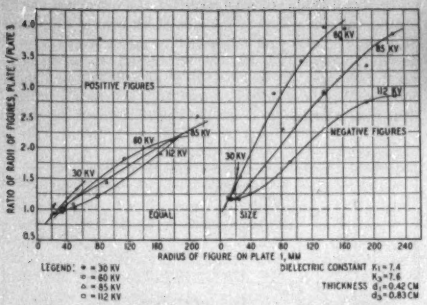


Fig. 7. Comparison of plates 1 and 3: variation of figure size with plate thickness, dielectric constant approximately the same

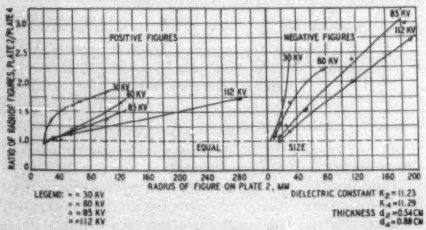


Fig. 8. Comparison of plates 2 and 4: variation of figure size with plate thickness, dielectric constant approximately the same

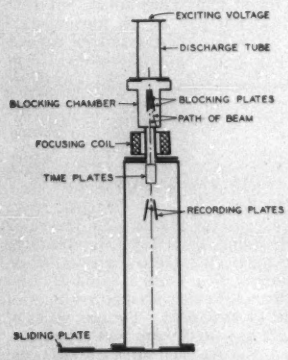


Fig. 9. Cathode ray oscillograph of the type developed at the Berlin Institute of Technology, which was used in these tests

under fixed conditions identical figures could be obtained in several tests. For this, the nature of development of the figures must be such as to produce identical figures under identical conditions, and the time lag of the "cut-off" needle gap must remain accurately the same for the same voltage and spacing.

Fig. 10. Oscillogram of voltage on test plates

Sine wave is for timing; its wave length is 111 m, period 3.7×10^{-7} sec

It is probable that neither of these conditions was satisfied.

Each measurement was repeated 3 or more times, until a good average was available or until, through the trend of the readings, a probable value became evident. The rule of always measuring the greatest radius of the figure was not entirely satisfactory, because successive figures formed under the same voltage and needle gap settings were often of very different shapes. Perhaps a more reliable guide would have been the area of the figure.

Results Obtained

Data obtained are presented in graphical form in Figs. 5 to 8, inclusive. Figure 5 shows the ratio of the radii attained in the same length of time on plates 1 and 2 plotted as ordinate against the radius of the figure on plate 1. Figure 6 shows similar data for plates 3 and 4, while Figs. 7 and 8 are for plate combinations 1 and 3, and 2 and 4, respectively. An attempt was made to fit the curves as well as possible to the available points. In some cases, such as the 60-kv curve of Fig. 6 for negative figures, the scattering of the points was so severe as to render a justifiable choice of curve practically impossible. In other curves, such as the positive curves of the same set, and the negative curves of Fig. 7, the data seem reasonably unequivocal.

Remembering that each point gives the ratio of the radii of 2 figures formed in the same length of time, it is clear that it also represents the ratio of the average velocities of growth (up to that point of time) of the 2 figures. The effect grows with the size of the figures in every case, since the curves have a positive slope. The velocity of growth was greater for the plate with the greater dielectric constant or the smaller thickness, i. e., with the greater capacitance per unit area between surfaces. This finding agrees with the work of Toepler and others. Detailed study makes apparent 1 or 2 other features of interest.

For a given size of figure, the ratio of the greater average velocity to the smaller average velocity decreases with increasing surge voltage, as shown by the decreasing steepness with increasing voltage for all curves. Therefore, the effect of varying the dielectric constant or plate thickness decreases in importance with increasing voltage, for a given size of figure.

A second point of interest is the polarity difference apparent in the curves. Each negative curve is steeper than the corresponding positive one, so that higher values of the velocity ratio are observed for negative figures than for positive ones. The nega-

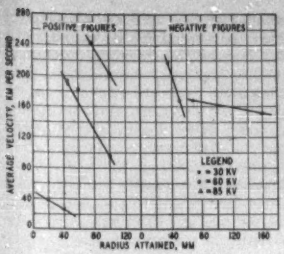
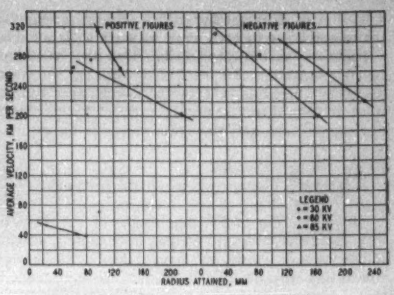


Fig. 11 (left). Growth velocities of electrical figures on plate 1 versus radius attained, for different voltages

Fig. 12 (right). Growth velocities of electrical figures on plate 2 versus radius attained, for different voltages



tive figures are therefore more sensitive to variations in the plate constants.

Experiments With Cathode Ray Oscillograph

For this part of the work, a cathode ray oscillograph was used to make records of the voltage applied to the test plates (see Fig. 9). The time of duration of the voltage surges on the plates, and the actual average speed of growth of the figures thus could be determined. Here again 2 plates were tested simultaneously. Most of the tests were made with the 60-kv maximum surge. A few were made at 30 kv, and a few at 85 kv; at the latter voltage the induced disturbances due to the necessary proximity of the oscillograph and the surge generator were so great as to preclude any attempt to work at 112 kv. One of the surge voltage records is shown in Fig. 10. Although not entirely free from disturbances, the length of time from voltage rise to voltage cut off can be determined accurately.

Most of the tests were made on plates 1 and 2 in parallel, and the data presented apply to them. On Fig. 11, the average velocity of growth of figures on plate 1 is plotted as ordinate against the radius of the figure. There are not enough points to determine significant curves, but straight lines are drawn through points taken at the same voltage to indicate that the average velocity decreases with increasing size of the figure. Similar data for plate 2 is plotted in Fig. 12. The velocities recorded are seen to be greater for higher voltages, as is to be expected, and lie in the range of from 20 to 315 km per second.

Effect of Polarity Difference

The data given cannot be used for a strict comparison of the relative velocities of positive and negative figures, as the voltage values given are the voltages for which the firing gap of the surge generator was set, i. e., the maximum voltage that would have appeared on the *open* transmission line. The presence of the test plates on the line, and of the rapidly increasing effective capacitance of the figures growing on them, caused some reduction in the steepness of the wave front and in the maximum value attained by the voltage wave. This reduction was greater for positive figures, because of their (already known) greater initial speed of growth, than for the negative ones.

To verify this, a 3-curve oscillogram was made with a 60-kv wave applied to the line. The first curve was for the open line, the second was with the test plates connected to record negative figures, and the third with the plates connected for positive figures. Measurements of the curves showed that whereas with open line the 60-kv wave had a maximum rate of rise of approximately 850 $\times$ 10^6 kv per second, with

Fig. 13. Oscillogram showing reduction of traveling wave of voltage caused by formation of electrical figure

Upper trace shows voltage (60 kv) on open line; lower trace, voltage appearing on plates 1 and 2 during formation of positive figures. Sine wave is for timing

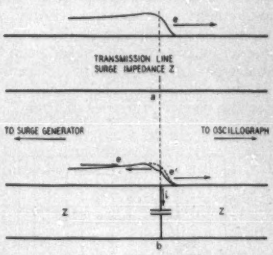


Fig. 14. Effect of lumped capacitance on traveling wave

the negative figures the steepness was reduced to 520 $\times$ 10^6 kv per second and the maximum value attained to 44.2 kv; with the positive figures the 2 values were 236 $\times$ 10^6 kv per second and 31.6 kv. A similar oscillogram for the 85-kv wave showed a maximum value for positive figures of only 47.6

kv. For a given setting of the firing gap, therefore, the negative figures were formed with a higher actual voltage on the electrode than the positive figures. Notwithstanding this favorable condition for greater negative velocities, the positive velocities recorded were greater than the negative ones for the same firing gap voltage and the same radius of figure.

Current Intake and Effective Capacitance of the Figures

The reduction of the magnitude of the traveling wave of voltage from its open line value caused by the current drawn by the figures may be used to calculate this current. Such calculations were made for the 2 voltage curves shown on the oscillogram in Fig. 13. The conditions in the 2 cases are made clear schematically in Fig. 14. For the open line, a voltage wave of instantaneous value e travels along the line from the surge generator to the oscillograph, as in Fig. 14a. If the test plates are across the line the voltage enters their point of connection with the same instantaneous value, e, emerging from this point with the reduced value e' due to the current i entering the plates. For such a connection the instantaneous value of the current taken by the plates can be calculated by the formula $i = 2(e - e')/Z$, in which Z is the surge impedance of the line.

The voltage waves from Fig. 13 are reproduced in the drawing of Fig. 15 with voltage and time calibration, together with the current taken by the plates, calculated by the preceding formula. The curve in Fig. 16 shows the instantaneous value of the effective capacitance of the figures, calculated from the i and e' curves of Fig. 15, as a function of time.

Discussion of the Theory of Formation of Streamer Discharges

Figures Formed by Movement of Electrons Alone. By means of experiments in which Lichtenberg figures were formed under the influence of a perpendicular magnetic field, Magnusson[4] has proved that both positive and negative figures are formed by the movement of negative charges. Since electrons would move much faster than any complex ions that might be present, the outer boundary of the figure, and thus its size, must be determined by the motion of the electrons. The velocity of growth observed for the electrical figures of from 2×10^6 to 3×10^7 cm per second could not be attained by positive ions for the field strengths involved, at atmospheric pressure. (Rogowski gives the velocity of charges moving in a field of 30 kv per centimeter at room temperature and atmospheric pressure as between 10^7 and 10^8 cm per second for electrons, and 10^5 cm per second for positive ions; *Arch. f. Elek.*, v. 16, 1926, p. 502.) Therefore, the explanation of the manner of growth of these figures as given in the fore part of this paper under heading "Mechanism of the Spreading Discharges" must be revised to the extent that the leading part in the movement of charge for the figures of both polarities be assigned to the negative charges, the positive ions being regarded as fixed.

The Polarity Difference. In the formation of the positive figures the ring-shaped surface charge is formed by the withdrawal of the electrons from the freshly ionized district, the positive ions remaining practically fixed in their positions on the plate. The expansion of the ring is effected similarly: As electrons are attracted to the electrode, the ring-shaped area in which a positive charge predominates widens. For the positive figure, at a stage of considerable development, the probable conditions are those shown in Fig. 17. The negative figure, however, grows by the movement of the electrons out along the plate, the ring formed by the negative surface charge truly expanding in this case. Fig. 18 illustrates this.

The radical difference in the formation of the positive and negative figures, therefore, is this: In the former the electrons move freely back and slightly up from the rim of the figure, impelled by the high gradient there; in the latter the electrons must move out along the plate against which they are driven, their movement impeded by repeated collisions with the plate.

Any exact analysis of the relation between the electron velocity and the speed of growth of the positive figure is difficult to make. It is the author's hypothesis, however, that the positive figure grows with a speed approximately equal to that of the electrons in the high gradient at the rim of the figure. Regarding the problem as a differential one, suppose that ionization has just taken place in the elementary area of radial extent δr. The theory that the prerequisite for ionization in the next greater elementary ring be the removal of the newly formed electrons over the distance δr is a tenable one. Under this hypothesis the difference in speed of growth of the positive and negative figures becomes the difference in speed of electrons moving (1) freely in a high field, and (2) in a field of about the same value that has a

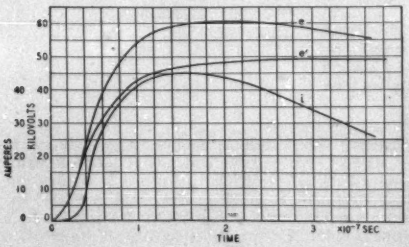
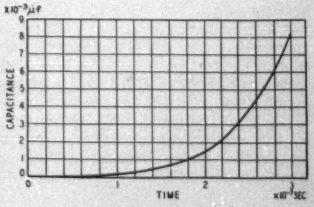


Fig. 15 (left). Voltage-time and current-time characteristics of electrical figures

e, e', and i. See Fig. 14

Fig. 16 (right). Capacitance-time characteristic of electrical figures



component impelling them against the plate. That this retarding force is of such a value as to have produced in the experiments of some authors a ratio of size and velocity of the 2 sorts of figures of 2 to 1, must be regarded as a coincidence. The hindering effect due to impact against the plate can be said to vary with the magnitude of the vertical component of the field. The fact that for large figures the velocity of growth (average) and the size of the negative figure approach those of the positive can be traced to the decrease of the vertical component of the field with increasing distance from the electrode.

Effect of Varying Unit Capacitance of Plate. The speed of growth of the figures thus depends directly on the field strength at the rim. The original voltage distribution along the plate influences the manner and rate of growth of the surface charge, and thus, indirectly as well as directly, influences also the field strength at the rim. Variations in the dielectric constant or thickness of the plate are significant because of their effect on the original voltage distribution and on the superposed potential of the growing surface charge.

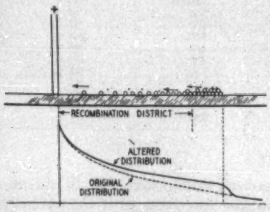


Fig. 17. Probable conditions during formation of positive figure showing effect on voltage distribution

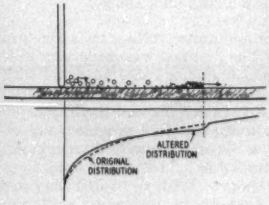


Fig. 18. Probable conditions during formation of negative figure showing effect on voltage distribution

Increasing the dielectric constant and reducing the thickness of the plate both result in the bunching of the lines of force toward the center, around the electrode. The gradient and its component along the plate is increased in the region directly around the electrode, with the result that they are diminished farther out. The curves of original voltage distribution along the plate for a (hypothetical) plate of dielectric constant 1, and for one of a higher dielectric constant, are shown in Fig. 19. A reduction of the thickness of the plate may be thought of as producing the same result.

The greater velocities and sizes of figures on plates with higher values of capacitance per unit area between the surfaces is to be attributed to the more intense ionization in the region around the electrode directly at the start. A surface charge of higher density which is able to propagate itself along the plate with greater rapidity is set up at once. The growth of the figure is expedited further, with the plate having greater unit capacitance, by the bunching of the lines going out from the surface charge in its progress across the plate, and the resulting increase of the gradient at its rim.

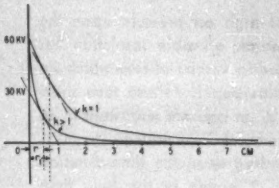


Fig. 19. Effect of an increase in dielectric constant of plate on voltage distribution

At some distance out from the electrode, the lines of force leaving it enter the plate almost vertically. This vertical gradient causes the retarding of the movement of the electrons by impact against the plate in the case of the negative figure. The reduction in this gradient caused by the bunching of the lines at the center upon an increase in the unit capacitance of the plate permits the negative surface charge to move across the plate with fewer collisions with the plate. This explains the greater response of the negative figures to an increase in the unit capacitance.

Effect of an Increase in the Applied Voltage. The decrease in the ratio of growth speeds on plates with different dielectric constants or different thicknesses with increasing voltage applied is explainable through the decrease in significance of the space charge—everything considered for a given radius of figure attained. The growth of the space charge on the plate, and its furtherance of the formation of the figure, is a cumulative process. A given difference in velocity and amount of space charge at any stage of the simultaneous development of figures on 2 plates in parallel is magnified with farther growth. An extension of the region in which ionization can take place without help from the space charge, by producing a higher initial gradient along the plate, cancels some of this magnification and reduces the difference in the figures.

Bibliography

1. M. Toepler, *Archiv fuer Elektrotechnik*, v. 10, 1921, p. 157.
2. P. O. Pedersen, *Annalen der Physik*, 4th Series, v. 69, 1922, p. 205.
3. K. Przibram, *Elektrotechnik und Maschinenbau*, v. 41, 1923, p. 97.
4. C. E. Magnusson, A.I.E.E. Trans., v. 49, 1930, p. 1384.
5. H. Staack, *Archiv fuer Elektrotechnik*, v. 25, 1931, p. 607.
6. Die Wanderwellenvorgaenge auf Experimenteller Grundlage., L. Binder, published by Springer, Berlin, p. 52.
7. Erwin Marx, *Archiv fuer Elektrotechnik*, v. 20, 1928, p. 589; v. 24, 1930, p. 61.
8. Mueller-Hillebrand, *Siemenszeitschrift*, No. 819, 1927, p. 547, 605.

Effect of Oil Pressure on Insulation Strength

The effect of high oil pressure upon the electrical strength of cable insulation has been subjected to a series of tests which are reported in this paper. These tests show that an increase in pressure will result in an increase in the breakdown voltage, the magnitude depending upon the time duration of the test. Although in the long time tests breakdown voltage was doubled by pressure increased from 1 to 6 atmospheres, no improvement was secured with impulse tests by a pressure increase up to 11 atmospheres.

By
JOHN A. SCOTT
ASSOCIATE A.I.E.E.

General Elec. Co.
Schenectady, N. Y.

IMPROVEMENT in cables, which combine liquid and solid dielectrics, has come largely through the study and control of gaseous electrical phenomena. This is because through circumstances of use in the field, gases enter the cable structure and the resulting electrical discharges in these gas layers cause deterioration ultimately leading to failure.

The steps in improvement have led successively first to the abandonment of the heavy solids or petrolatums as treating materials and then to the oil filled cable, where the possibility of entrapped and dissolved gases is reduced to the minimum possible.

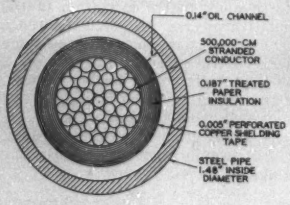


Fig. 1. Cross sectional view of 500,000-cir-mil single-conductor cable tested in steel pipe

Granting, however, that some residual gas remains, its effect should be reduced if it is subjected to high pressure, for it is a well-known fact that the breakdown voltage of a gas increases with the pressure almost linearly. Furthermore Koch[1] has shown that the dielectric strength of liquids shows a similar effect but that of solids does not. In order to study the combined dielectric (oil and paper) tests have, therefore, been run to investigate the effect of high oil pressures on (1) the long time or endurance dielectric strength; (2) the short time dielectric strength; and (3) the impulse voltage strength of treated paper insulation. The first 2 of these tests have been previously reported.[5]

Table I—First Long Time Voltage Test

Kilovolts	Average Stress, Volts Per Mil	Hours
75.0	400	300
85.0	450	307
93.5	500	383
103.0	550	326
112.0	600	163
121.5	650	160
131.0	700	6

Table II—Second Long Time Voltage Test

Kilovolts	Average Stress, Volts Per Mil	Hours (Held)
37.5	200	25.0
46.7	250	53.0
56.1	300	24.0
65.5	350	42.0
74.8	400	168.0
84.1	450	168.0
93.5	500	165.0
103.0	550	165.0
112.0	600	165.0
122.0	650	225.0
131.0	700	192.0
140.0	750	1.4

Long Time Voltage Tests on Cables

Two long time or endurance voltage tests were run on actual cables. The first test was made on a 10-ft length of 2/0 single-conductor cable insulated with 0.187 in. of oil treated paper. The treating oil was a heavy cable oil of viscosity 580 sec Saybolt at 60 deg C. Porcelain terminals were provided and oil pressure supplied by a small motor-driven pump automatically controlled to hold 80 lb per sq in. pressure above atmospheric. With the small diameter of the cable and a lead sheath thickness of 0.125 in., the lead sheath withstood this pressure without appreciable stretching during the test. A long time step-up voltage test was applied holding each step for 2 weeks, as shown in Table I. The life at the last step was 6 hr.

Tested at atmospheric pressure, the life of similar cable is of the order of 20 to 200 hr at 350 volts per mil. There is therefore approximately a doubling of the long time breakdown voltage when the oil pressure is increased from atmospheric pressure to a pressure of 80 lb per sq in. above atmospheric.

Since any application of high pressure to cables in service necessarily would prevent the use of a simple lead sheath, the second test was run on a 45-ft length

Full text of "The Effect of High Oil Pressure Upon the Electrical Strength of Cable Insulation" (No. 33-65) presented at the A.I.E.E. summer convention, Chicago, Ill., June 26–30, 1933.

1. For all numbered references see list at end of paper.

Table III—Short Time Voltage Test

Pressure, Lb–Sq In. Gauge	Dielectric Strength (Volts Per Mil) Rapidly Applied Voltage	Minute Step-Up
0	1,280	970
25	1,600	1,400
55	1,790	
60	1,670	
65		1,650
112	2,010	1,870
172	2,190	1,990

Table IV—Impulse Breakdown Voltage With 1-10 μsec Impulse Wave

Pressure, Lb/Sq In. Gauge	Kilovolts Electrode No. 1	2	3	4	5	6	7	8	9	Average	Volts Per Mil
0	52.5	55.0	50.0	47.5	55.0	50.0	52.5	50.0	47.5	51.0	3,400
30	50.0	52.5	47.5	52.5	52.5	50.0	50.0	47.5	47.5	50.0	3,340
60	47.5	50.0	52.5	52.5	52.5	52.5	52.5	47.5	52.5	51.0	3,400
90	52.5	55.0	50.0	45.0	47.5	52.5	50.0	55.0	50.0	50.8	3,380
120	47.5	47.5	50.0	50.0	50.0	50.0	52.5	52.5	50.0	50.0	3,340
180	57.5	52.5	52.5	52.5	52.5	55.0	57.5	52.5	57.5	54.2	3,620

of cable, without lead sheath but provided with a 5-mil copper spiral shielding tape. This cable was drawn, untreated, into a length of steel pipe and provided with porcelain terminals. The physical dimensions are shown in Fig. 1.

The cable was vacuum treated after installation and filled with the oil normally used on oil filled cable. The oil had a viscosity of 100 sec Saybolt at 100 deg F. Voltage was applied and held according to the schedule in Table II. Failure occurred at 750 volts per mil. Again the result was a dielectric strength double that to be obtained at atmospheric pressure.

Short Time Tests on Treated Paper Sheets

The short time dielectric strength tests were made on sheets of treated cable paper, and were carried out over a range of pressures. A small pressure tank was constructed in which sheets of paper (total thickness 0.015 in.) after previous treatment in oil, could be placed and tested under pressure up to 200 lb per sq in. Tests were made between 2-in. diam disk electrodes, with edges rounded to a $^1/_8$-in. radius (A.S.T.M. electrodes). Two series of runs have been made so far; first, a rapidly applied test in which the voltage was raised uniformly at 0.5 kv per sec until failure, and second, a minute step-up test starting at 40 per cent of the rapidly applied breakdown and increasing the voltage in 1 kv steps each held for 1 min until failure. The results, expressed in volts per mil for these tests are given in Table III. (The values given are the averages of 10 individual tests.)

Impulse Tests on Treated Paper Sheets

The impulse voltage tests were made on the same type and thickness of treated paper samples, using the same electrode and equipment, as were the short time tests described above. A 1–10 testing wave was used, i. e., one which obtained its crest value in 1 μsec and diminished to ½ crest value in 10 μsec. The tests were conducted by starting with an impulse wave of 37.5-kv crest and increasing this value 2.5 kv between successive applications until a breakdown was indicated by a surge crest ammeter.[2,3,4] The results of these tests are shown in Table IV.

Conclusions

These tests indicate that at power frequencies and under long time application of voltage there is a considerable increase in endurance strength of oil treated insulation at pressures of several atmospheres. Under impulse stresses, however, practically no benefit is derived from increased pressure. The effect of pressure on dielectric strength is greater the longer the time of voltage application, being negligible for the impulse voltage tests of only a few microseconds duration and a maximum for the long time endurance test. This is shown in Fig. 2.

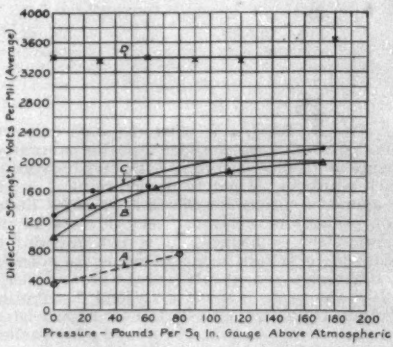


Fig. 2. Summary of test results

A. Long time test on cable
B. Minute step-up voltage test on oil treated paper sheets
C. Rapidly applied voltage test on oil treated paper sheets
D. Impulse voltage test on oil treated paper sheets

Credit is given to G. M. J. Mackay for suggesting this work and to J. B. Felter, J. A. Weh, B. H. Thompson and H. P. Kuehni, members of the General Engineering Laboratory staff for obtaining the data herein reported.

References

1. The Dielectric Strength of Liquids, Semi-Solids, and Solids as Influenced by Pressure, F. Koch. *E.T.Z.*, v. 36, 1915, p. 85–8 and 99–102.

2. The Surge Crest Ammeter, C. M. Foust and H. P. Kuehni. *Gen. Elec. Rev.*, v. 35, 1932, p. 644–8.

3. Impulse Testing Technique, C. M. Foust and H. P. Kuehni. *Gen. Elec. Rev.*, v. 35, 1932, p. 358–66.

4. Laboratory Measurements of Impulse Voltages, J. C. Dowell and C. F. Foust. A.I.E.E. Trans., v. 52, 1933, p. 537–43.

5. Report of the committee on electrical insulation of the division of the engineering and industrial research, National Research Council, December 1931.

Theory of Primary Networks—Part I

A study of voltage regulation and load distribution is given in this section of the author's work on power system primary networks, solutions of practical operating problems under both normal and abnormal conditions being given. Simple equations are presented to enable the distribution engineer to determine the proper settings of compensators and contact-making voltmeters, and other practical problems are discussed and answered.

By
F. M. STARR
ASSOCIATE A.I.E.E.

General Elec. Co.,
Schenectady, N. Y.

PRIMARY networks used in power system distribution are considered in this paper from the point of view of operating engineers responsible for such networks, all practical conditions of steady state operation being considered. Previous literature on primary networks has been devoted largely to comparative economics. It is not intended to rediscuss these factors here, but rather to consider the actual design and operation of the network itself. Part I of the paper is devoted to load distribution and voltage regulation, and Part II (to appear later) will be concerned with short-circuit and relay studies.

The material presented in the present section consists of:

1. A discussion of emergency load distribution, with charts showing the distribution of load in a network under various emergency conditions, and with analyses showing the influence on emergency load distribution of such factors as automatic regulation, power factor, impedance of the 4-kv ties, etc.

2. A discussion and analysis of normal network operation and design as influenced by such factors as voltage regulation, circulating currents, and unbalanced load.

As an aid to the analytical work in this paper, an exact mathematical analysis of the regulated network was developed, and is given in general form in the Appendix. Although this method of analysis is applied here to primary networks, it is perfectly general and should be useful in analyzing any network having a multiplicity of regulated feed points.

The particular questions which it has seemed advisable to study in the present section of the paper are as follows:

1. When a transmission line feeding a primary network is taken out of service, how does the load carried by this line distribute among the network units remaining in service?

2. Quantitatively, what advantage in load distribution is gained by staggering the network loads on a given transmission feeder over concentrating adjacent loads on a given feeder?

3. What effect does the automatic regulating equipment (tap-changers or induction regulators) on the network transformers have on the distribution of load under normal and abnormal conditions?

4. Can the compensator used in conjunction with the regulating equipment be adjusted to limit circulating currents (due to differences in tap positions on the network transformers as well as to differences in the angles of the impressed primary voltages) to a desirable minimum, to aid in uniformly distributing a normally unbalanced load, and at the same time to give adequate over-compounding during peak load?

5. What maximum angular difference between supply voltages on the various primary feeders is permissible?

6. What procedure should be used in adjusting the compensator to give optimum performance?

These various factors have been studied analytically and by actual tests on networks in operation. In addition a number of calculating-board studies have been made. The conclusions arrived at here as a result of these studies, and the quantitative data obtained are thought to be quite reliable and should prove useful in the design and operation of primary networks.

Load Distribution Under Emergency Conditions

An important factor which affects the design of a primary network is the load distribution under conditions of both normal and emergency operation. It is desirable that the network be designed so as to permit all of the network transformers to share the load as uniformly as possible. No trouble usually is experienced in obtaining good load distribution under normal operating conditions providing adequate 4-kv ties are incorporated in the design. In some rare cases where the load density is extremely light, it may be desirable to use high reactance transformers to insure uniform load division.

More important than the problem of normal load distribution in network design is that of emergency load distribution. In order that a primary network may be designed to have adequate reserve capacity under the emergency condition of a transmission line which feeds the network being out of service, it is necessary to know how the load carried by that feeder divides among the network units remaining in service.

A variety of networks differing in size and construction have been studied with this problem in mind, and in the light of these studies the fundamental principles of emergency load distribution have been established. Primary networks may be very small, as for example those shown in Figs. 1*A* and 1*B*, or they may be quite large similar to that shown in Fig. 2. It is necessary to consider both the large and the small network to determine the limiting factors in load distribution.

Initially, networks are usually very small, only 3 or 4 units being tied together. The 2 networks shown in Figs. 1*A* and 1*B* are typical initial layouts and are very similar to 2 networks which are in

Full text of "Theory of Primary Networks, Part I—A Study of Voltage Regulation and Load Distribution on Primary Networks" (No. 33-85) presented at the A.I.E.E. summer convention, Chicago, Ill., June 26–30, 1933.

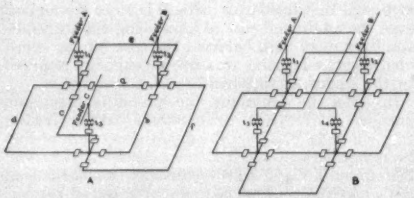
operation at the present time. The network shown in Fig. 1*A* is a symmetrical layout of 3 units, each being supplied by a separate transmission feeder. If feeder *C* is taken out of service the load carried by unit 3 distributes uniformly between units 1 and 2 owing to the symmetry. Even though all of the 4-kv ties are not of equal impedance, the load division still will be fairly uniform if the units are all thoroughly tied together.

To illustrate this fact, load data on an actual network in operation are given in Table I. This table shows that in spite of the normal unbalance in load and the poorly linked network, fairly good emergency load distribution is obtained.

Table I—Load Data on an Actual Network

Feeder Out	Load on t_1.	Load on t_2.	Load on t_3.
	73	63	80
A	0	95	121
B	90	0	126
C	103	113	0

Above loads are in per cent of normal. The above data were taken on a network similar to Fig. 1*A* but with ties *e* and *f* open. The transformer reactances were 5.5 per cent, and the 4-kv ties had impedances as follows: $a = (4.54 + j2.56)$, $b = (3.64 + j2.06)$, $c = (4.15 + j1.87)$, and $d = (12.30 + j10.70)$.



A. 3-unit network B. 4-unit network

Fig. 1. Typical small sized primary networks. These are characteristic of initial layouts

Now consider the network shown in Fig. 1*B*. This network of 4 units is fed by 2 lines, units 1 and 4 being supplied by feeder *A*, and units 2 and 3 being supplied by feeder *B*. If feeder *B* is out of service the load carried by units 2 and 3 will distribute uniformly between units 1 and 4 owing to the symmetrical layout. If each of the 4 points were fed by a separate line the emergency capacity of the network would be greater by the capacity of one unit than that of the layout as shown. Under this condition, if one of the units, say unit 4, were out of service, units 2 and 3 would each take approximately 35 per cent of its load and unit 1 would take the remaining 30 per cent. (These values are based upon the assumption that the 4 internal ties are 4-per cent overhead lines, the 4 external ties are 7-per cent overhead lines, and the transformers have 6-per cent reactance.)

Experience has shown that networks of a size up to about 8 units may always be laid out in such a manner that the load carried by any feeder will distribute uniformly between the units remaining in service when that feeder is out of service. In larger networks the units adjacent to the transformers out of service will absorb more of the load than the more remote units. In order to determine the emergency load distribution in an extensive network, the layout shown in Fig. 2 was studied. An extensive calculating board study has been made on this particular layout, the results of part of which are shown in chart form in Figs. 3, 4, 5, and 6. By exercising some care, these results may be applied directly in designing any large sized network (assuming of course that the network is not too loosely tied together).

The curves of Fig. 3 show how a normal 100 per cent load carried by transformer 23 would distribute among the remaining units if transformer 23 were taken out of service. Thus, assuming the impedance of the network main to be 4 per cent (1,500-kva 4-kv base), it may be noted from the curves of Fig. 3 that the 4 units immediately surrounding unit 23, i. e., units 16, 22, 24, and 30, each take 7.3 per cent of the load originally carried by unit 23 (only the curve for unit 16 is plotted in Fig. 3 since the other 3 are identical to it owing to symmetry). Other units more remote from unit 23 take correspondingly smaller percentages of the total load.

A set of curves similar to those of Fig. 3 are shown in Fig. 4 for transformer 39 out of service. It may be noted that the distribution in this case does not differ greatly from that obtaining in the above case with unit 23 out. For example, from Fig. 4, units 32 and 38 each take 7.8 per cent of the load carried by unit

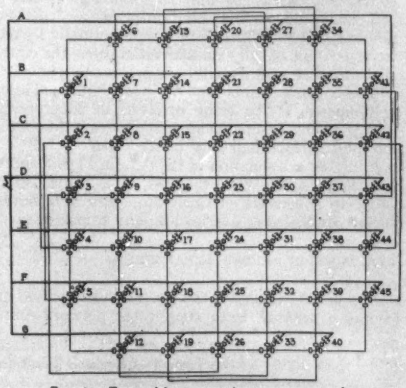


Fig. 2. Typical large sized primary network

This network was studied in regard to the various aspects of emergency load division

39 as compared with the 7.3 per cent of the load carried by unit 23 taken by units 16, 22, 24, and 30 in the above case. Space does not permit the printing of charts for other key transformer positions. However, the 2 sets of curves shown in Figs. 3 and 4 represent the 2 extreme current distributions for any one transformer out of service, all other outages giving distributions intermediate to these. Therefore, it should be fairly easy to estimate emergency

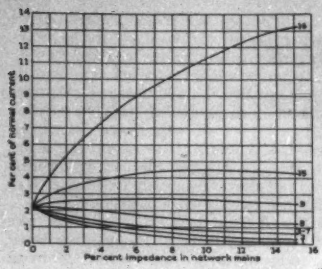


Fig. 3. Showing how the load normally carried by unit 23 in Fig. 2 distributes among the units remaining in service when 23 is out

Transformer reactance 6 per cent. Percentage values on 1,500-kva 4.3-kv base

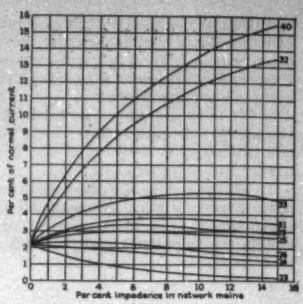


Fig. 4. Showing how the load normally carried by unit 39 in Fig. 2 distributes among the units remaining in service when 39 is out

Transformer reactance 6 per cent. Percentage values on 1,500-kva 4.3-kv base

load distributions for any large network with reasonable accuracy from the data in charts of Figs. 3 and 4.

In a network of the size shown in Fig. 2, each transmission line would feed from 2 to 5 network units, the number depending upon certain economic factors. In order to obtain the most uniform division of load under emergency conditions, it is desirable that the network units supplied by any one feeder be non-adjacent to each other, i. e., staggered. For example, suppose units 11, 23, and 39 to be supplied by a common feeder. If this feeder were taken out of service unit 24 would receive the most severe overload. In this case, again assuming 4 per cent network mains, unit 24 will receive 7.3 per cent of the load carried by unit 23 (from Fig. 3) and it will receive 1.8 per cent each of the loads carried by units 11 and 39. If each unit were normally loaded to 90 per cent of full load kilovoltamperes, the emergency load on unit 24 will be approximately 0.9 (100 + 7.4 + 1.8 + 1.8) or 99.9 per cent of full-load kilovoltamperes. (The error involved in superposing the several load components arithmetically to obtain the total is small and may be neglected.)

A further examination of the data in Figs. 3 and 4 will demonstrate that the loss of a transmission feeder in a network of fairly large size need never impose an excessive overload on any transformer.

Transmission Feeder Arrangement

As pointed out above, the conventional method of feeding a network is to stagger the network units connected to any one feeder. For example, units 6, 22, 38, and 26 in Fig. 2 might be fed by one feeder, units 7, 23, 39, and 19 by another, etc. An alternative method would be to feed a group of adjacent network units from a single transmission line. The network in Fig. 2 is shown with this type of transmission layout. It is recognized that this sort of layout imposes a greater emergency overload burden on certain parts of the network when a transmission feeder goes out of service. However, it has been suggested that this latter method is more economical since the additional cost of interlacing the transmission lines more than balances the cost for the somewhat increased reserve transformer capacity required for the second arrangement.

In order to determine the probable maximum emergency overloads in networks whose feeders supply a series of adjacent units, the network of Fig. 2 was studied with the feeder arrangement as shown. The curves of Fig. 5 show the distribution of the load carried by feeder A when feeder A is out of service. Similarly the curves of Fig. 6 show the distribution for feeder D out of service. (Note that all loads are given in percentages of the normal load for any one transformer.) It may be noted that the maximum overload on any unit for line A out of service (assuming 4-per cent impedance mains) is 31.5 per cent on unit 21 (see curve 21, Fig. 5), and for line D out of service it is 27 per cent on unit 24 (see curve 24, Fig. 6).

Since many utility engineers follow the practice of

Table II—Calculated Results for Various Circuit Conditions in Fig. 7

Case No.	a	b	c	E_i	E_2	e_1	e_2	I_1	I_2	I_L	I_1'	I_2'
1	$0 + j6$	$5 + j0$	$95 + j31$	108.45	93.54	$100/-3.08°$	$100/0°$	1.67	1.077	0.957	0.575	0.432
2	$0 + j6$	$0 + j5$	$95 + j31$	102.29	100.00	$100/-2.02°$	$100/-1.10°$	0.70	0.321	0.985	0.637	0.348
3	$0 + j6$	$2.3 + j5.1$	$95 + j31$	103.00	99.20	$100/-2.05°$	$100/-1.01°$	0.779	0.324	0.964	0.633	0.335
4	$0 + j6$	$4.4 + j1.4$	$95 + j31$	105.73	96.27	$100/-2.41°$	$100/-0.681°$	1.690	0.653	0.958	0.585	0.408
5	$0 + j6$	$2.3 + j5.1$	$90 + j43.6$	103.60	99.25	$100/-1.92°$	$100/-0.947°$	0.820	0.303	0.959	0.630	0.334
6	$0 + j6$	$4.4 + j1.4$	$90 + j43.6$	106.19	96.48	$100/-2.27°$	$100/-0.642°$	1.225	0.616	0.957	0.584	0.407
7	$0 + j6$	$2.3 + j5.1$	$80 + j60$	104.32	99.35	$100/-1.68°$	$100/-0.830°$	0.679	0.265	0.952	0.625	0.331
8	$0 + j6$	$4.4 + j1.4$	$80 + j60$	106.69	96.87	$100/-2.02°$	$100/-0.568°$	1.260	0.548	0.958	0.585	0.408

The above data apply to Fig 7
Impedance and voltage values are in per cent
Current values are in times normal
Currents I_1 and I_2 occur with regulation and I_1' and I_2' are the corresponding currents without regulation
The network tie impedance $(2.3 + j5.1)$ is that of one mile of standard 4/0 overhead line; and the time impedance, $(4.4 + j1.4)$, is that of one mile of 1/0 under ground 3-conductor cable

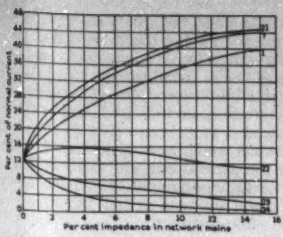


Fig. 5. Showing how the load normally carried by feeder *A* in Fig. 2 distributes among the units remaining in service when *A* is out

Transformer reactance 6 per cent. Percentage values 1,500-kva 4.3-kv base

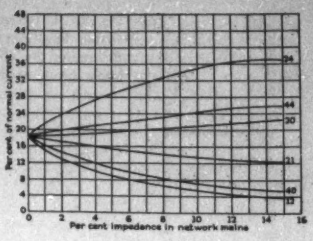


Fig. 6. Showing how the load normally carried by feeder *D* in Fig. 2 distributes among the units remaining in service when *D* is out

Transformer reactance 6 per cent. Percentage values on 1,500-kva 4.3 kv base

allowing 25 per cent or more short-time overloads on substation transformers under emergency conditions, it appears that the feeder arrangement shown in Fig. 2 may not be objectionable from the point of view of overloads and it may be highly desirable from the point of view of economy. Naturally the overloads on any particular transformer on a network considerably smaller than the one in Fig. 2 are apt to be greater, and more reserve transformer capacity will need to be provided. However, it should be borne in mind that, for small networks, this problem of feeder arrangement is not important since each of the units in a small network will be supplied usually by a separate line.

Effect of Regulators on Emergency Load Division

The foregoing studies and accompanying charts are the result of calculating-board studies on fairly well designed networks. In addition to these operating characteristics under optimum conditions, the relative effects on network operation of certain irregularities in design are important. It is important to know under what conditions the automatic regulators on the network transformers affect the emergency load division, to know quantitatively what this effect may be, and to know how this effect varies with power factor, impedance of the 4-kv ties, etc.

Voltage regulation on a primary network is maintained by means of automatic tap-changing equipment on the network transformer, or in some cases by means of induction regulators. In conjunction with a contact-making voltmeter and a line-drop compensator, these regulating equipments tend to hold 100 per cent voltage at some point in the secondary distribution system. The action of the regulator, in effect, is to change the magnitude of the voltage impressed on the transformer without affecting its phase angle. Furthermore, the operation of the contact-making voltmeter and compensator is to hold a constant magnitude of voltage at the load without regard to the angle of that voltage.

It is evident that this regulator action may in some cases influence the emergency load distribution in the network. The question may be asked, for example, if network unit 23 in Fig. 2 is taken out of service, what difference is there in the distribution of this load among the remaining units with and without automatic regulation? It may be shown (see below) that in closely linked well designed networks the load distribution is substantially the same with or without regulation. It may be shown further that the greater the inherent unbalance due to the inherent impedance characteristics of the network, the greater will be the effect of the automatic regulators to change the distribution. Thus, if feeder *C* in Fig. 1*A* is out, its load will divide uniformly between units 1 and 2 whether regulators and compensators are provided or not. Similarly the emergency load distribution in the large network shown in Fig. 2 will not change much if the units are unregulated.

In order to study the effect of regulator action on emergency load distribution it was necessary to go to an extreme case in which this action was accentuated. For this purpose the simple 3-unit network shown in elementary form in Fig. 7 was used. The impedance links *a* represent the network transformers and the

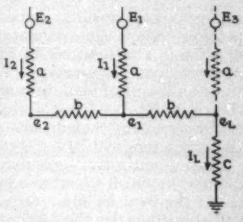


Fig. 7. Impedance diagram representing the simple 3-unit network studied to determine the fundamental effects of bus regulators on emergency load division

The distribution of load *C* between units 1 and 2 has been studied for various circuit constants; refer to Table II

connected transmission lines (the latter are usually negligible). The links *b* represent the 4-kv network mains or ties. (In this case only a single tie between units is used in order to simulate the most extreme case of a loosely linked network.) The links *c* represent 100 per cent loads. The problem is to determine how the load normally carried by unit 3 divides between units 1 and 2 when unit 3 is out of service. To simplify the analysis the loads carried by units 1 and 2 have been omitted since their effects may be superposed later if desired. The method used is the exact analytical one developed in the Appendix. The calculated results for the various circuit conditions studied are tabulated in Table II. To simplify the analysis it was assumed that voltage magnitude was held at the bus rather than at some point near the load. Since the loads themselves do

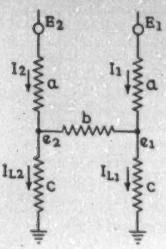


Fig. 8. Diagram representing the simple 2-unit network studied to determine the effect of bus regulators on a normally unbalanced load

not change this assumption is legitimate for the present purpose.

From the data of Table II the following pertinent facts may be observed:

1. For highly reactive network ties, such as overhead lines, the distribution of load 3 between units 1 and 2 is substantially the same with and without regulation. This fact apparently is equally true for all reasonable load power factors. Since the network studied is an extremely loosely linked one, it may be concluded from the above that the load distribution in all networks with overhead ties is not influenced greatly by the action of the regulators.

2. For highly resistive network ties, such as underground cables, the distribution of load 3 between units 1 and 2 is much more unbalanced with automatic regulation than without. This unbalance is less pronounced at lower load power factors.

3. The action of the regulator in cases 1, 4, 6, and 8 is to cause heavy circulating currents to flow from the adjacent unit to the remote unit as indicated by the magnitude of voltages E_1 and E_2. Since all of the "E" voltages are in phase, these circulating currents are highly reactive and the components of power current are relatively small. The actual division of power currents between units 1 and 2 is about the same with or without regulation.

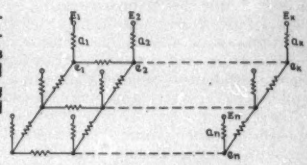
The above results demonstrate the maximum possible effect that regulation may have on load division. The network in Fig. 7, of course, would never be found in practice. The other extreme, from the standpoint of load division, is the 3-unit network shown in Fig. 1*A*. In this case uniform load division under emergency conditions always will obtain and the regulators will have no effect whatever.

The quantitative criterion that determines the manner in which a load at a given point in a network (i. e., the load on some transformer not in service) will distribute to the various points of feed is the range of variation in the transfer impedances from the point of load to the respective points of feed. A load at a given point will distribute directly as the transfer admittances to the various points of feed. In a closely linked network the variation in transfer admittance between one pair of feed points and any other pair of feed points is small, which means that a closely linked network insures a maximum uniformity in load division regardless of whether the network ties are cables or overhead lines. Furthermore, the differences in transfer admittances between feed points are less for a large network than for a small one (with the exception of certain symmetrical layouts), which indicates that a large network may have better operating characteristics from the standpoint of load division. It should be noted further that not only does the criterion of minimum differences in transfer admittances insure inherently a minimum of load unbalance, but this same criterion minimizes any tendency for the regulator action to set up circulating currents. To illustrate in a simple manner, refer to Fig. 7 and to case 4 in Table II. If the transfer admittances from the point of load e_L to the 2 sources, E_1 and E_2, had been equal, not only would I_1 and I_2 have been equal, but their circulating components would have been zero.

It may be stated in general that any effect which tends to improve load division under any emergency operating condition will also tend to limit circulating currents under the same condition.

The above conclusions are borne out in actual operating experience. In one particular case the transfer admittances between load points and various feed points do not differ by more than 10 per cent. Even though the network ties are highly resistive

Fig. 9. Diagram representing the elements of the general network having *n* regulated feed points



cables, the load carried by any transformer under normal conditions distributes practically uniformly when that transformer is out of service. The unit receiving the maximum portion of the redistributed load receives only 25 per cent more of this load than the unit receiving the minimum portion. Circulating currents are practicably negligible.

Normal Network Operation

The foregoing analysis and discussion have been confined to the design and operation of the network as affected by emergency operating conditions. The following discussion is concerned with normal network operation.

Optimum network performance requires that:

1. The regulators function to maintain approximately 100 per cent voltage at some point in the secondary distribution system.

2. All circulating currents be reduced to a minimum.

3. The distribution of load in the network feeders be maintained as uniform as possible.

The chief instrument in operating the network to these requirements is the line-drop compensator. The following analysis will demonstrate how the compensator should be adjusted for various circuit constants to achieve these results.

Voltage Regulation

Consider a single network unit, which may be designated as unit k, at any point in a network. The circuit constants associated with this unit are related by the following equations, which, though approxi-

mate, are nevertheless quite accurate and well suited to the present purpose. These relations are sufficiently well known as to require no proof. They are not vector but algebraic relations.

$$E_k = e_b + a_k I_t \sin \theta_t \tag{1}$$

$$\beta = \frac{2 I_t a_k \cos \theta_t}{e_b + E_k} \tag{2}$$

$$e_b = I_L (R \cos \theta_L + X \sin \theta_L) + 100 \tag{3}$$

$$e_{c.v.} = e_b - I_t (r \cos \theta_t - x \sin \theta_t) = 100 \tag{4}$$

where

E_k = voltage impressed on transformer k in per cent
e_b = network unit bus voltage and reference vector
β = angle in radians between E_k and e_b
a_k = transformer reactance in per cent
I_t = magnitude of transformer current in times normal
θ_t = power factor angle of I_t with respect to e_b
I_L = magnitude of load current in times normal
θ_L = power factor angle of I_L with respect to e_b. (Positive for lagging I_L and negative for leading I_L)
$e_{c.v.}$ = voltage impressed on contact-making voltmeter
r = resistance setting of the compensator
x = reactance setting of the compensator
R = apparent resistance in distribution system to load center
X = apparent reactance in distribution system to load center

The vector relations of the above quantities are shown diagrammatically in Fig. 11. If there is no circulating current, $I_t = I_L$. Otherwise $I_t = I_L + I_c$ (vectorially), where I_c is the circulating current

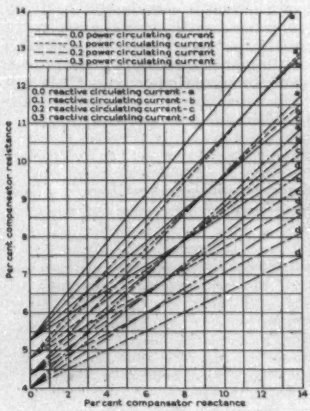


Fig. 10. Curves useful in determining the correct compensator settings to maintain good regulation on a primary network

Curves given for various amounts of power and reactive circulating current in the transformer. A 100-per cent 0.95-power factor load was assumed. Currents are in per unit values

from E_k into the network owing to any cause whatever. Since voltages at the load center should be ideally 100 per cent, and since $e_{c.v.}$ is likewise 100 per cent, the following algebraic equation expressing the condition of perfect network regulation follows from eqs 3 and 4 above:

$$(I_{cP} + I_{LP})\, r - (I_{cR} + I_{LR})\, x = I_{LP} R + I_{LR} X \tag{5}$$

where the added subscript P indicates power component of current, and the added subscript R indicates reactive component of current (both referred to e_b). In eq 5, the reactive components of current are positive or negative accordingly as they are lagging or leading. If for any reason the left-hand member of this equation is less than the right-hand member, the voltage at the load will be too low.

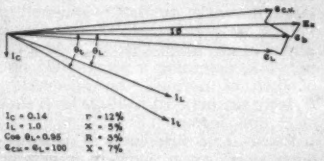
Equation 5 may be found particularly useful in determining the compensator setting best suited to good voltage regulation on the network. It is to be used on conjunction with eqs 6 to 9 given below. In Fig. 10 is a family of curves representing eq 5 for an assumed load current of 100 per cent, 0.95 power factor, and for R = 3 per cent and X = 7 per cent (all resistances and reactances being in per cent on a 1,500-kva 4.3-kv base). These load and circuit constants were chosen because they are fairly representative of a large number of cases.

As stated above, if eq 5 is satisfied by the compensator settings, good regulation will result. Note, however, that, if 100 per cent voltage is held at full load, the voltage at light load will be somewhat less than 100 per cent owing to the decreased power factor that inherently accompanies a light load condition.

Circulating Currents

In regard to the functions of the compensator, next in importance to voltage regulation is the limitation of circulating currents. As is well known and as is evident from eqs 4 and 5, this is accomplished by means of inverse reactance compensation. If any current flowing in the network unit transformer be resolved into power and reactive components, I_P and I_R, the effect of that current on bus voltage, by virtue of the compensator action, is to add rI_P and to subtract xI_R volts. The effects of all other components of voltage are negligible. That is, the reactance compensation is effective in changing transformer taps only when reactive current is flowing, and the resistance compensation is effective in changing transformer taps only when power current is flowing. Since load current usually is of high power factor, the over-compounding during peak loads is determined chiefly by the amount of resistance compensation. Also, since circulating currents usually are highly reactive, their suppression depends chiefly upon the amount of reactance compensation.

Fig. 11. Vector relations of the quantities defined in eqs 1 to 4



Both power circulating currents and reactive circulating currents are discussed below.

Circulating currents due to differences in tap positions of the network transformer regulators always are highly reactive. If transformer k has an impressed voltage n taps above or below the voltage level of the network, and if each tap gives an incre-

ment change in E_k of ΔE_k, the circulating current into the network will be:

$$I_{CR} = \Delta E_k D_{kk} n \tag{6}$$

where D_{kk} is the driving point admittance (reciprocal of driving point impedance) from transformer k into the network. Since D_{kk} is highly reactive, I_{CR} will be highly reactive and will tend to change the magnitude of e_k by the amount $\Delta E_k D_{kk} x n$ (a voltage increase if I_{CR} is leading and a decrease if I_{CR} is lagging). One tap change should not produce a change in bus voltage greater than the contact-making voltmeter voltage band in order that pumping and instability of the tap changers may be avoided, i. e.,

$$\Delta E_k D_{kk} x < \text{contact-making voltmeter band } (\doteq 0.5 \text{ per cent}) \tag{7a}$$

Furthermore, 2 tap changes should produce a change in bus voltage greater than the contact-making voltmeter band to insure that reactive circulating currents shall be limited to a value not more than that corresponding to a single tap change, i. e.,

$$2\,\Delta E_k D_{kk} x > \text{contact-making voltmeter band} \tag{7b}$$

Unlike circulating reactive currents, circulating power currents usually are caused by phase-angle differences in impressed transmission voltages. If E_k is shifted δ deg from the voltage level of the network, the times normal circulating current will be

$$I_{CP} = 1.75\, D_{kk} \delta \text{ deg} \tag{8}$$

This current, being an in-phase power current, will tend to produce a voltage change in e_k of magnitude $1.75\, r D_{kk} \delta$ deg. This change in voltage impressed on the contact-making voltmeter will cause a tap change which in turn causes a reactive circulating current to flow. This reactive current will prevent more than a single tap change from occurring due to phase-angle differences provided

$$\Delta E_k D_{kk} x > 1.75\, D_{kk} r \delta \text{ deg} \tag{9}$$

The question arises as to how much circulating current owing to a difference in impressed-voltage phase-angle is permissible. This, of course, depends upon the degree to which the network transformers are loaded. In general, a circulating current of from 0.10 to 0.15 of normal load current should not be objectionable. Since D_{kk} varies from 0.12 in large networks to 0.065 in small networks (these values are the inverse of percentage driving point impedances, 1,500-kva 4-kv base), in the average network, assuming a permissible circulating current of 0.15 of normal, the allowable phase shift of E_k from the network voltage level should not be more than one degree.

Phase-angle differences in impressed voltages were determined on a particular network which is in operation. The maximum divergence from the average was found to be 0.98 deg at the time of full-load. The resulting power circulating currents were less than 0.10 of normal and not objectionable.

Problem

To illustrate the proper procedure in setting a network compensator, and to summarize the above analysis, the following example is given:

A network unit in a small sized network is supplied by a feeder whose voltage leads the network level by 0.5 deg. The driving point impedance from the transformer into the network is 9.2 per cent, or $D_{kk} = 1/9.2$. The contact-making voltmeter band is 1.0 per cent volts, and the regulator taps are 1.25 per cent volts each. What is the correct compensator setting?

From eq 8, the power circulating current due to 0.5-deg voltage phase displacement is 0.095 of normal. A reactive circulating current corresponding to one tap change (which is, from eq 6, 0.136 of normal in this case) should be assumed since the power circulating current is sufficient to cause at least one tap change. From eq 7*a* and 7*b* the compensator reactance x should be less than 7.35 per cent and greater than 3.63 per cent. For a first trial, let $x = 6$ per cent. Then (assuming average circuit conditions, i. e., 0.95 power factor, $R = 3$ and $X = 7$) from eq 5 or from Fig. 10, the value of r is found to be 7.4 per cent, which value fails to satisfy eq 9. However, if $x = 5$ per cent, $r = 6.9$ per cent, which value satisfies eqs 5, 7, and 9 and is satisfactory.

Unbalanced Load

It is highly desirable that a network have characteristics such that a normally unbalanced load will distribute uniformly among the various points of feed. The natural impedance characteristics of a network promote uniform distribution of load whether the network be regulated or not. This fact is borne out in the calculating board studies illustrated in Figs. 3, 4, 5, and 6.

Table III—Circuit Constants and Calculated Data for Fig. 8

Quantity Measured	Case 1	Case 2
a	$j6$	$j6$
b	$2.3 + j5.1$	$4.4 + j1.4$
c_1	$1.1\ (95 + j31)$	$1.1\ (95 + j31)$
c_2	$0.9\ (95 + j31)$	$0.9\ (95 + j31)$
E_1	101.68	101.08
E_2	102.85	103.40
e_1	$100.0\ \angle -3.12°$	$100.0\ \angle -3.04°$
e_2	$100.0\ \angle -3.27°$	$100.0\ \angle -3.35°$
I_1	$0.952\ \angle -17.2°$	$0.902\ \angle -11.4°$
I_2	$1.063\ \angle -26.4°$	$1.129\ \angle -30.2°$
I_1'	$0.982\ \angle -20.8°$	$0.996\ \angle -19.8°$
I_2'	$1.028\ \angle -23.3°$	$1.013\ \angle -23.8°$
I_{L1}	$0.910\ \angle -18.2°$	$0.910\ \angle -18.2°$
I_{L2}	$1.100\ \angle -18.2°$	$1.100\ \angle -18.2°$
I_L	$2.010\ \angle -18.2°$	$2.010\ \angle -18.2°$

The above data apply to Fig. 8. Impedance and voltage values are in per cent. Current values are in times normal. Currents I_1, I_2, and I_L occur with bus regulation, and currents I_1' and I_2' are the corresponding currents without regulation. The circuit constants are similar to those studied in Fig. 7 and Table II.

In order to study the problem of distribution of unbalanced loads, the simple 2-unit network shown in Fig. 8 was analyzed. The circuit constants and calculated data applying to this figure are summarized in Table III. It may be noted that 2 0.95-

power factor loads (load 1 being 10 per cent above normal and load 2 being 10 per cent below normal) were assumed. The distribution of loads was calculated assuming bus regulation (i. e., $e_1 = e_2 = 100$), and then assuming no regulation at all at the network busses (this latter case being equivalent to regulation at the generating station). The layout was studied assuming the network tie to be a highly reactive overhead line (case 1), and assuming it to be a highly resistive underground cable (case 2). An examination of the data in Table III will substantiate the following facts and conclusions.

The distribution of the load between the 2 network transformers is somewhat better without bus regulation than with, particularly so when the 4-kv tie is underground cable.

Thus, bus regulation alone, without compensation, cannot be said to improve load division. However, suppose that compensation of the type described above be incorporated in the network units of Fig. 8. In case 1 in which the network tie is a highly reactive overhead line, a power circulating current flows from unit 1 which is underloaded to unit 2 which is overloaded. This power circulating current helps to balance the load in the manner already indicated, but its effect on the compensator is to cause E_1 to increase and E_2 to decrease slightly, whereas the opposite effect is desired if a more equitable division of load is secured. Actually, the magnitude of the power circulating current in this case is so small that it would not result in any tap change at all.

Now consider case 2 in which the network tie is the highly resistive underground cable. Here the circulating current is highly reactive. This reactive current, in itself, has little effect in balancing the load. However, its action on the compensator, in contrast with the corresponding action of case 1, is to cause E_2 to increase and E_1 to decrease, which action has a beneficial effect in balancing the loads. It should be noted furthermore, that, whereas the circulating current in case 1 is small in magnitude, the circulating current in case 2 is of appreciable magnitude and will result in an actual change of taps.

The above analysis leads to the conclusion, then, that for networks inherently endowed with unbalanced loads, the resistance compensation should be somewhat smaller when the ties are overhead lines than when they are cables. Networks having overhead ties have a greater inherent tendency to balance loads than do networks with cable ties. Networks with cable ties, on the other hand, are able better to improve load division by virtue of the effect of the inverse reactance compensation.

Appendix—Analysis of the Regulated Network

A simplified impedance diagram of a primary network that is intended to represent any network having n points of feed is given in Fig. 9. The transformers feeding the grid are represented by impedances a_1, a_2, etc. These transformer impedance links are intended to include the impedances of the transmission lines feeding them, which, however, usually are negligible. The "E" voltages are the voltages impressed on the various transformers, and their magnitudes will vary from 100 per cent depending upon the tap positions of their respective load ratio control equipments. The "e" voltages are the bus voltages of the respective network units. It will be assumed here that the E voltages are all in phase, and that the e voltages are all equal in magnitude and equal to some value, say 100 per cent volts. Loads are not shown in Fig. 9 since the following analysis applies without respect to the manner in which the network is loaded.

The currents flowing into the general network of Fig. 9 at the various points of feed will be:

$$\begin{aligned} I_1 &= D_{11}E_1 + D_{12}E_2 + \ldots + D_{1n}E_n \\ I_2 &= D_{21}E_1 + D_{22}E_2 + \ldots + D_{2n}E_n \\ &\cdot \\ &\cdot \\ I_n &= D_{n1}E_1 + D_{n2}E_2 + \ldots + D_{nn}E_n \end{aligned} \tag{10}$$

where $D_{11}, D_{22} \ldots D_{nn}$ are the driving point admittances from feed points $1, 2 \ldots n$, respectively, and coefficients of the form D_{jk} are transfer admittances (between points j and k). These coefficients are the characteristic admittances of the network and may be determined readily by measurement or calculation. (See reference 6 at end of paper.)

In addition to eq 10 the following vector relations are evident:

$$\begin{aligned} e_1 + a_1I_1 &= E_1 \\ e_2 + a_2I_2 &= E_2 \\ &\cdot \\ &\cdot \\ e_n + a_nI_n &= E_n \end{aligned} \tag{11}$$

In addition to eqs 10 and 11 the conditions of the problem specify that all of the E voltages are in phase but of unknown magnitude, and that all of the e voltages are equal to 100 per cent volts but of unknown phase angle.

If in eq 10 above, the jth equation be multiplied through by a_j, and the kth equation be multiplied through by a_k, and so on, and then if the term a_kI_k on the left of each equation be replaced by $E_k - e_k$, there results:

$$\begin{aligned} -e_1 &= (D_{11}a_1 - 1)E_1 + (D_{12}a_1)E_2 + \ldots + (D_{1n}a_1)E_n \\ -e_2 &= (D_{21}a_2)E_1 + (D_{22}a_2 - 1)E_2 + \ldots + (D_{2n}a_2)E_n \\ &\cdot \\ &\cdot \\ -e_n &= (D_{n1}a_n)E_1 + (D_{n2}a_n)E_2 + \ldots + (D_{nn}a_n - 1)E_n \end{aligned} \tag{12}$$

Let eq 12 be written as:

$$\begin{aligned} D_{11}'E_1 + D_{12}'E_2 + \ldots D_{1n}'E_n &= \varepsilon_1 \\ D_{21}'E_1 + D_{22}'E_2 + \ldots D_{2n}'E_n &= \varepsilon_2 \\ &\cdot \\ &\cdot \\ D_{n1}'E_1 + D_{n2}'E_2 + \ldots D_{nn}'E_n &= \varepsilon_n \end{aligned} \tag{13}$$

Let the real and imaginary components of the D' coefficients be $D_{jk}' = m_{jk} + jn_{jk}$. Since all of the E voltages are in phase the following algebraic relations may be written:

$$\begin{aligned} m_{11}E_1 + m_{12}E_2 + \ldots + m_{1n}E_n &= R(\varepsilon_1) \\ m_{21}E_1 + m_{22}E_2 + \ldots + m_{2n}E_n &= R(\varepsilon_2) \\ &\cdot \\ &\cdot \\ m_{n1}E_1 + m_{n2}E_2 + \ldots + m_{nn}E_n &= R(\varepsilon_n) \end{aligned} \tag{14}$$

where $R(\varepsilon_k)$ is the real part of ε_k (using E as the reference vector). Since $\varepsilon_k = E_k - a_kI_k$, and since a_kI_k is never greater than $0.07e_k$, it follows that $R(\varepsilon_k)$ will differ from the magnitude of ε_k by not more than $0.002\varepsilon_k$, and it is therefore proper to replace the right-hand members of eq 14 by ε. Equation 14 may be solved readily for the E voltages, by means of determinants or a simple calculating board set-up. Then the "I" currents may be determined from eq 10.

References

1. Fundamentals of the Medium Voltage Network, D. K. Blake. *Gen. Elec. Rev.*, v. 34, 1931, p. 210–7.

2. Network Promises Marked Economies, D. K. Blake. *Elec. World* v. 97, 1931, p. 492–6.

3. Voltage Control in Primary Network Systems, W. J. McLachlan. *Gen. Elec. Rev.*, v. 35, 1932, p. 325–8.

4. Year of Experience Solves Primary Network Problem, R. J. Salsbury and H. S. Moore. *Elec. World*, v. 100, 1932, p. 624–6.

5. Application of the Primary Network Unit, D. K. Blake. *Gen. Elec. Rev.*, v. 35, 1932, p. 302–10.

6. Equivalent Circuits—I, F. M. Starr. A.I.E.E. Trans., v. 51, 1932, p. 287–98.

Silicon Steel With A-C and D-C Excitation

Magnetic tests on silicon steel at 60 cycles with superposed d-c excitation are described in this article. The results, which are expressed in the form of curves, constitute an addition to existing data on this subject, and should be helpful to designers of apparatus in which combined alternating and direct magnetic fields exist.

By
R. F. EDGAR
ASSOCIATE A.I.E.E.

General Electric Co.
Schenectady, N. Y.

BOTH power transformers and instrument transformers may be subjected to d-c excitation in some applications. The d-c core-loss and excitation characteristics of the core material under such conditions are of importance, for they affect the rating of the power transformers and the accuracy of the instrument transformers. Combined alternating and direct magnetic fields are present also in other types of apparatus, affecting their performance by changing the characteristics of the magnetic circuits.

This article describes a series of a-c core-loss and excitation tests with superposed d-c excitation which recently were made on low-, medium-, and high-silicon sheet steel, and presents in detail the results for the first and third of these 3 materials. These tests constitute an addition to existing core-loss and excitation data (see bibliography) which will be helpful in designing apparatus where combined alternating and direct magnetic fields exist. They will assist also in predicting the performance of existing designs when subjected to similar conditions of magnetization. Both alternating and direct components of flux density were carried to high values, the maximum value of the sum of the 2 components being approximately 20,000 gausses. Corrections were made for distortion of the voltage wave form at high densities.

Full text of "Loss Characteristics of Silicon Steel at 60 Cycles With D-C Excitation" (No. 33-54) presented at the A.I.E.E. North Eastern District meeting, Schenectady, N. Y., May 10–12, 1933.

Briefly, the principal conclusions reached from the results of these tests are as follows:

1. In the range of alternating flux density below a certain value, which may be called the "critical" value, hysteresis loss tends first to rise, then to reach a maximum, and finally to decrease, as d-c excitation is superposed and the alternating component of flux density is held unchanged. Superposed d-c excitation decreases the hysteresis loss for any given alternating component of flux density in the range above the critical value.

2. The critical value of alternating flux density for silicon steel lies in the range 13,200 to 13,800 gausses (85 to 89 kilolines per sq in.).

3. The a-c excitation for any given alternating flux density is increased by superposed d-c excitation.

4. The d-c excitation for a given direct flux density in the low or moderate density range is decreased by a small amount of superposed a-c excitation, but is increased by larger amounts. The d-c excitation for a given direct flux density in the high density range is increased by superposed a-c excitation.

Diagrams of Fig. 1 illustrate the change in the cycle of magnetization that is caused by a direct component of exciting current. The flux wave and the corresponding hysteresis loop are shifted from their symmetrical positions by a direct component of flux density. The shape of the hysteresis loop is changed; in general, its area, which represents the hysteresis loss per cycle, also is changed, although the amplitude of pulsation (vertical length) remains the same.

Eddy current loss, being a function of the effective value of the induced voltage, is not affected by the direct component of flux density, if, as assumed in Fig. 1, the amplitude and form of the flux and voltage waves remain unchanged. The assumption regarding the form of the voltage wave, however, is only approximately correct. Changes in the exciting current wave form and amplitude will react upon the impedance in the magnetizing circuit to distort the wave form of the induced voltage, so that the eddy current loss will be changed somewhat.

The change in the exciting current is associated with the change in the shape of the hysteresis loop. The general slope of the loop is decreased, so that the same pulsation of flux density (vertical length) requires a much greater pulsation of exciting current (horizontal length). Thus, in Fig. 1, the amplitude of the exciting current pulsation (x_2, x_1) is much greater for the displaced than for the symmetrical flux wave, although the amplitude of flux pulsation (a_2, a_1) is the same for both. There is, of course, a small component of exciting current due to eddy current loss, which is neglected in Fig. 1.

The converse effect, that of superposed a-c excitation on d-c excitation is illustrated by the diagrams of Fig. 2. The 2 flux waves have the same direct components of flux density (d_1, d_2) but different alternating components (a_1, a_2). The direct components of exciting current (y_1, y_2) are quite different.

Changes in the shape of the hysteresis loop illustrated in Figs. 1 and 2, have been shown in detail previously by other investigators (see bibliography).

Methods of Test

Tests were made on 20-lb laminated ring samples 9.45 in. outside diameter by 6.3 in. inside diameter.

The rings were wound with uniformly distributed primary and secondary windings of 200 turns each, the primary being outside of the secondary.

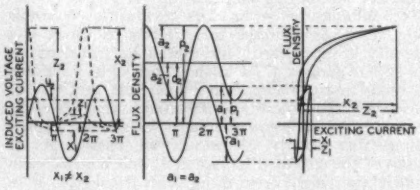
Apparatus and circuits used are shown in Fig. 3, which makes clear the method of supplying the combined alternating and direct current to the primary winding of the sample. The core loss was measured with an astatic reflecting dynamometer wattmeter. The secondary voltage was measured with both a flux voltmeter[8,9] (for all numbered references see bibliography) reading average rectified voltage times 1.111, and an rms voltmeter, thus allowing both the alternating flux density and the secondary copper loss to be determined correctly for a distorted voltage wave form. The use of the 2 voltmeters also allowed the eddy current loss to be corrected for a distorted voltage wave form, in separating the 2 components of the total core loss.

The direct flux density was measured with an overdamped ballistic galvanometer connected to a single-turn coil on the sample, deflections being read as the direct current was reversed. Several reversals were made each time before recording the deflection. A high-reactance choke coil was connected in series with the galvanometer to insure negligible alternating current and negligible loss in that circuit. The galvanometer was calibrated by means of a standard mutual inductor, and its sensitivity was adjusted by a shunt resistance.

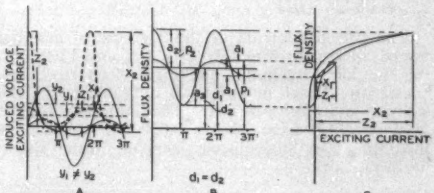
In making the tests, the flux voltmeter reading, and consequently the alternating flux density, was held constant at each desired value while the direct current was varied in steps over as great a range as the current carrying capacity of the primary winding permitted. The sample was demagnetized each time before proceeding to the next value of alternating flux density. Considerable time was allowed between readings with no power on, in order to minimize heating of the sample and consequent error in the calculation of the eddy current loss.

In separating the total core loss into hysteresis and eddy current components, the percentage of eddy current loss with no d-c excitation was taken from the results of numerous separation tests previously made on the same material, and it was assumed that the eddy current loss was not affected by superposed d-c excitation except as the voltage wave form was changed. At high densities, where a difference in the readings of the 2 voltmeters indicated a distortion of the voltage wave form, the calculated eddy current component was multiplied by the square of the ratio of the rms voltage to the flux voltmeter voltage before subtracting it from the total core loss. This correction was necessary because the calculated eddy current loss was for a sine wave form of voltage, and therefore somewhat less than that actually existing with the distorted voltage wave.

Excitation tests were made in a similar manner, except that the total rms current and the direct current were measured, instead of the power in watts. An rms ammeter and a d-c ammeter were connected in series with the primary winding, and the wattmeter and the rms voltmeter were switched out of



Subscript 1 refers to conditions with no d-c excitation
Subscript 2 refers to conditions with d-c excitation



Subscript 1 refers to conditions with a small flux pulsation
Subscript 2 refers to conditions with a large flux pulsation

Figs. 1 (left) and 2 (right). Wave forms of induced voltage, flux density, and exciting current, with corresponding hysteresis loops showing (left) the effect of superposed d-c excitation and (right) the effect of varying flux pulsation on the direct component of excitation

a Alternating flux density (1/2 total pulsation)
d Direct flux density (average over a complete cycle)
p Peak flux density (maximum in each cycle)
x Amplitude of exciting current pulsation
y Direct component of exciting current (average current)
z Peak value of exciting current

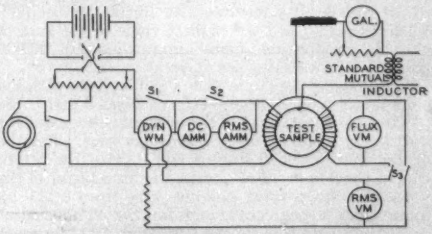
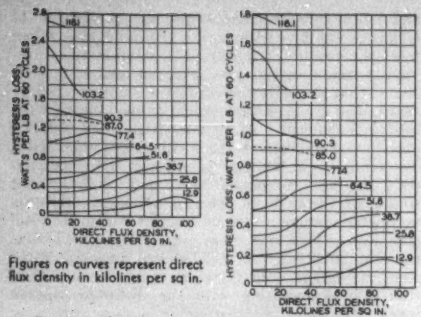


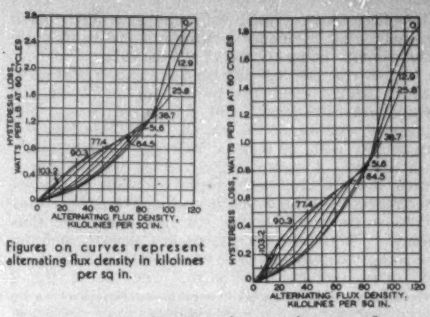
Fig. 3. Circuit diagram for core loss and excitation tests with superposed d-c excitation

Core loss. S_1 open, S_2, S_3 closed
Excitation. S_1 closed, S_2, S_3 open



Figures on curves represent direct flux density in kilolines per sq in.

Figs. 4 and 5. Hysteresis loss vs. direct flux density with various alternating flux densities, for (left) low-silicon steel and (right) high-silicon steel



Figures on curves represent alternating flux density in kilolines per sq in.

Figs. 6 and 7. Hysteresis loss vs. alternating flux density with various direct flux densities, for (left) low-silicon steel and (right) high-silicon steel

the circuit. The a-c component of exciting current was determined from the equation

$$I_{a-c} = \sqrt{I_{total}^2 - I_{d-c}^2}$$

The silicon contents of the 3 grades of material tested were approximately $2^1/_2$, $3^1/_4$, and 4 per cent for the low-, medium-, and high-silicon steels, respectively. Each material was annealed before the samples were punched out. The low-silicon sample was punched from sheets 0.019 in. thick; the medium- and high-silicon samples, from sheets 0.014 in. thick.

Results

Results are presented graphically in Figs. 4 to 11, inclusive. Only the hysteresis component of core loss is given. Alternating flux density values refer to half the amplitude of flux pulsation, and direct flux density values to the average flux density over a complete cycle; a-c excitation values refer to the effective value of the alternating component, and d-c excitation values to the average current over a complete cycle.

The alternating flux density ranged from zero to 18,000 gausses (116.1 kilolines per sq in.) and the direct flux density from zero to 15,600 gausses (100 kilolines per sq in.) the highest value of the sum of the 2 components being approximately 20,000 gausses (129 kilolines per sq in.).

Throughout the range of flux density for which the solid-line a-c excitation curves of Figs. 8 and 9 are plotted, the form factor of the induced voltage did not vary from 1.111 by more than 1 per cent. For the dotted-line curves of Figs. 8 and 9, with the exception of the 2 uppermost curves, the form factor of the induced voltage wave did not vary from 1.111 by more than 4 per cent; and for the 2 uppermost dotted-line curves it did not vary from 1.111 by more than 9 per cent.

Curves for the medium-silicon steel (not included in this article) were similar in form to those for the other 2 grades.

Hysteresis Loss

Inspection of the curves of Figs. 4 and 5 shows that for alternating flux densities of 14,000 gausses (90.3 kilolines per sq in.) and greater, the hysteresis loss tends to decrease immediately as direct flux density is superposed; for alternating flux densities of 12,000 gausses (77.4 kilolines per sq in.) and less it tends first to increase to a maximum, and then to decrease. For these lower densities, the hysteresis loss did not fall below the value without superposed direct flux density. However, the final slopes of some of the curves (Figs. 4 and 5) indicate that such a reduction might occur if the direct flux density were carried high enough.

In the range between the 2 densities given in the preceding paragraph, there is an alternating flux density for which the initial tendency of the hysteresis loss is neither to increase nor to decrease. It may be called the "critical" value. For the low-, medium-, and high-silicon steels the critical values are approximately 13,500, 13,800, and 13,200 gausses (87, 89, 85 kilolines per sq in.), respectively. Two of these are illustrated by the dotted-line curves in Figs. 4 and 5. Values for the dotted-line curves were read from the curves of Figs. 6 and 7, the critical alternating flux density being approximately the density at which the curve for no direct flux density intersects that for 2,000 gausses (12.9 kilolines per sq in.).

Table 4 of a previous paper[2] by Holm shows a critical value of 13,450 gausses (86.7 kilolines per sq in.) for motor sheet steel. Table I of a paper by Chubb and Spooner[4] indicates a critical value of approximately 10,300 gausses (66.5 kilolines per sq in.) for silicon steel. Apparently none of the other investigators referred to carried the alternating component of flux density high enough to determine the critical value.

The critical value indicated by the tests of Chubb and Spooner is considerably lower than the others, all of which are nearly alike. Possibly this may be accounted for, at least in part, by the fact that the tests by Chubb and Spooner were made on a trans-

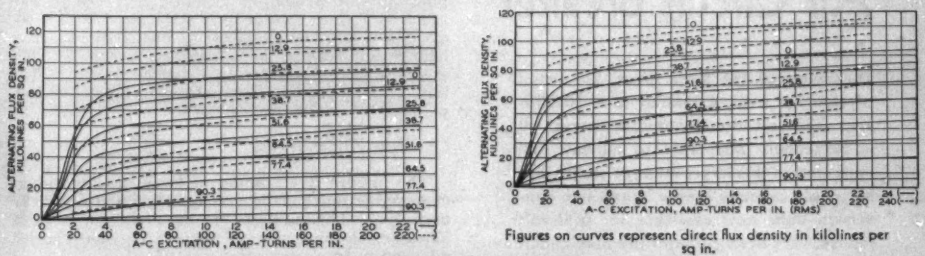
former rather than on a ring sample as were the present tests and those made by Holm.

These results may be used also to calculate approximately the hysteresis loss when alternating flux waves of 2 different frequencies are combined to form a flux wave with pulsations. The loss for each cycle of the pulsation during one low frequency cycle is found by taking an alternating flux density equal to half the amplitude of the pulsation and a direct flux density equal to the mean value of flux density during the pulsation. The losses for all the pulsations in one low frequency cycle then are added to give the pulsation loss per cycle. The symmetrical hysteresis loss for an alternating flux density equal to the maximum flux density during the cycle then is added to give the total hysteresis loss per low frequency cycle. This procedure assumes that the area of the minor hysteresis loops traced by the pulsations of flux is approximately the same as that of the minor loops of the same flux density range which have been repeated many times with a constant displacement, and that the area is the same whether the upper tips of the minor loops be on the normal induction curve or on the boundary of a large symmetrical loop. A previous paper by Spooner[5] shows that these are approximately true although the first minor loop is somewhat larger than succeeding ones, and the area varies slightly with horizontal displacement of the loop even though the vertical displacement is constant. The minor loops also may affect slightly the area of the symmetrical loop. Unfortunately, no data appear to be available to determine the extent of this effect.

Excitation

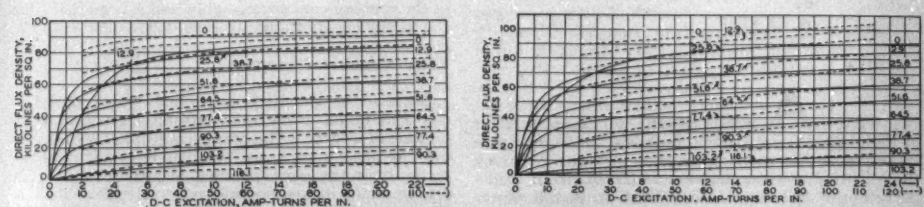
The first group of excitation curves (Figs. 8 and 9) shows that for any given alternating flux density superposed d-c excitation increases the required a-c excitation. The solid-line curves of Figs. 8 and 9 represent the rms excitation corresponding to a sine wave of induced voltage, since, for the range they cover, the form factor of the induced voltage was within 1 per cent of 1.111. The values of excitation given in the dotted-line curves, for which the wave form became somewhat distorted, are higher than would have been obtained with a sinusoidal voltage wave.

The second group of excitation curves (Figs. 10 and 11) shows the effect of superposed a-c excitation on direct flux density and d-c excitation. In the range from zero to 11,200 gausses (72 kilolines per sq in.) approximately, depending on the material, the direct flux density for a given value of d-c excitation is somewhat increased by small amounts of superposed alternating flux density; larger amounts decrease it. Neither the exact extent of the direct flux density range nor the value of the alternating component giving the greatest increase of direct flux density could be determined because of lack of data for alternating flux densities between zero and 2,000 gausses (12.9 kilolines per sq in.). Direct flux densi-



Figures on curves represent direct flux density in kilolines per sq in.

Figs. 8 and 9. Alternating flux density vs. a-c excitation with various direct flux densities, for (left) low-silicon steel and (right) high-silicon steel



Figs. 10 and 11. Direct flux density vs. d-c excitation with various alternating flux densities, for (left) low-silicon steel and (right) high-silicon steel

Figures on curves represent alternating flux density in kilolines per sq in.

ties above this range are not increased at all by superposed a-c excitation, but are decreased immediately.

BIBLIOGRAPHY

1. HYSTERESIS LOSS IN IRON, TAKEN THROUGH UNSYMMETRICAL CYCLES OF CONSTANT AMPLITUDE, M. Rosenbaum. *Journal Inst. of Elec. Engrs.* (London), v. 48, 1912, p. 534–45.

2. UNTERSUCHUNGEN UBER MAGNETISCHE HYSTERESIS, F. Holm. *Zeit. des Ver. Deut. Ing.*, v. 56, 1912, p. 1746–51.

3. THE UNSYMMETRICAL HYSTERESIS LOOP, J. D. Ball. A.I.E.E. TRANS., v. 34, 1915, p. 2695–715.

4. THE EFFECT OF DISPLACED MAGNETIC PULSATIONS ON THE HYSTERESIS LOSS OF SHEET STEELS, L. W. Chubb and Thomas Spooner. A.I.E.E. TRANS., v. 34, 1915, p. 2671–92.

5. TOOTH-FREQUENCY LOSSES IN ROTATING MACHINES, Thomas Spooner. A.I.E.E. JOURNAL, Sept. 1921, p. 751.

6. MAGNETIC PROPERTIES OF SHEET STEEL UNDER SUPERPOSED ALTERNATING FIELD AND UNSYMMETRICAL HYSTERESIS LOSSES, Y. Niwa and Y. Asami. *Researches of Electrotechnical Laboratory No. 124* (Tokyo), June 1923.

7. FURTHER STUDY ON THE MAGNETIC PROPERTIES OF SHEET STEEL UNDER SUPERPOSED ALTERNATING FIELD AND UNSYMMETRICAL HYSTERESIS LOSSES, Y. Niwa, J. Matuya, and J. Sugiura. *Researches of Electrotechnical Laboratory No. 144* (Tokyo), May 1924.

8. A FLUX VOLTMETER FOR MAGNETIC TESTS, G. Camilli. A.I.E.E. TRANS., v. 45, 1926, p. 721.

9. MEASURING CORE LOSS AT HIGH DENSITIES, B. M. Smith and C. Concordia. ELEC. ENG., Jan. 1932, p. 36–8.

A New High Speed Air Circuit Breaker

The range of the high speed air circuit breaker has been extended to a 10,000-amp 750-volt d-c continuous rating. It is particularly adaptable to railway systems, and in this larger rating, a single unit has ample capacity for the largest size conversion units now available for 600-volt service. A description of the new circuit breaker is given in this article.

By
A. O. KEEP
ASSOCIATE A.I.E.E.

General Elec. Co., Erie, Pa.

A HIGH SPEED air circuit breaker of high capacity in a single unit was made desirable by recent developments in railway systems. Among these factors was the decision of the board of transportation of the city of New York to install power conversion units of 3,000 kw and 4,000 kw rating on the Eighth Avenue Subway project in that city. A comparable rating in a single unit circuit breaker was desired. The previous maximum rating of high speed circuit breakers had been 4,000 amp and although for higher machine ratings a few installations had been made with 2 to 3 circuit breakers in parallel, the number of conversion units to be installed on the New York City system made the development of a larger single breaker unit desirable.

The new circuit breaker, known as type *JR-36* and illustrated in Figs. 1 and 2, is rated 750 volts direct current, 10,000 amp, continuously. This rating provides ample capacity for the largest size conversion units available at present for 600-volt railway service.

INTERRUPTING CAPACITY

Since the high speed circuit breaker limits the current peak to a fraction of the theoretical sustained value which the short circuit would reach if not opened, it has been customary to specify interrupting capacity in terms of initial rate of current rise, theoretical sustained value of current (or an equivalent total resistance of the short circuit external to the conversion unit), and time from tripping point to actual maximum current as limited by the operation of the high speed circuit breaker.

With the new high speed circuit breaker, the peak of the short-circuit current will occur in 0.007 sec on a short circuit having an initial rate of rise of 14×10^6 amp per sec and a theoretical sustained value of 200,000 amp. Time is measured from tripping point to maximum current. A typical oscillogram of a short circuit on a 625-volt 4,000-kw 60-cycle synchronous converter protected by the new high speed breaker is reproduced in Fig. 3. The external circuit resistance is 0.000694 ohm. The initial rate of rise is approximately 5.75×10^6 amp per sec.

GENERAL DESCRIPTION

The present day practice of truck mounted interchangeable units made a compact design especially desirable. The supports are on 20 x 25 in. centers. The over-all dimensions of 24 x $57^3/_8$ x 48 in. are well adapted to truck mounting.

The welded frame is fabricated entirely from bar and plate stock with machined surfaces to receive the subassemblies. The frame is at the potential of the moving contact assembly and is insulated from the mounting subframe by 4 molded insulators.

MAIN CIRCUIT ELEMENTS

Because of the high continuous rating especial care was taken to keep the current carrying parts to minimum length. This was accomplished by mounting the 2 $4^1/_2$x$4^1/_2$ in. positive terminal bars directly over the corresponding negative bars. This arrangement makes possible relatively short flexible shunts as the bridging member of the circuit. The moving contacts are made an integral part of the shunt ends and thus only 2 bolted connections are made in the main current carrying circuit of the

Especially prepared for ELECTRICAL ENGINEERING. *Not published in pamphlet form.*

breaker; i. e., shunts to lower bars and stationary contact member to the upper bars. The loop arrangement also increases the mechanical speed of opening on very heavy short circuit currents due to the electromagnetic force exerted on the contact arms which is in the direction to accelerate the contacts toward the fully open position.

The contact arms are fabricated from duralumin. The midpoints of the arms are connected by pull links of the same material to the main armature lever. Very light moving parts are essential if high mechanical speed is to be obtained without excessive

Fig. 1. The new high speed high capacity air circuit breaker equipped for relay tripping

accelerating forces. The lower ends of the arms are carried by bell cranks to which are attached the contact pressure springs. The outer ends of the bell cranks are provided with rollers bearing on the cross head of the hydraulic reset piston.

When separate relay tripping is used the negative bus connection is made directly to the lower bars. For inherent tripping the shunts for the twin series tripping coils are made an integral part of the lower bars with the outer shunt castings arranged for bus bar connection.

The leverage arrangement used is shown schematically in Fig. 4. The lift of the hydraulic piston during reclosure rotates the moving contact arms in a clockwise direction about the bumper *A* as a fulcrum until the holding magnet armature is closed. The retraction of the piston then allows the contact arms to rotate in a counter clockwise direction and close the circuit. This mechanism is completely trip free. Tip wear does not alter the main opening spring tension and consequently does not affect the calibration.

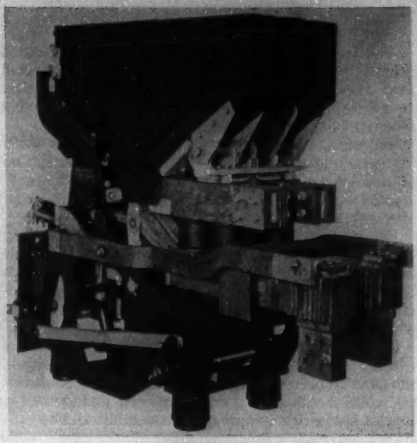


Fig. 2. The new high speed high capacity air circuit breaker equipped with inherent tripping

The 4 main contacts and 1 auxiliary arcing contact are carried on separate arms with separate contact pressure springs. The auxiliary contact arm is provided with a simple lost motion arrangement so as to make before and break after the main contacts. All arcing is confined to this auxiliary contact which is provided with renewable stationary and moving contact tips. The 4 main contacts are silver faced to obtain a low contact resistance and insure proper equalization to current division.

Reset Mechanism

Motor operation of the mechanism allows a lower demand on the operating battery than the solenoid type mechanism used on the smaller size circuit breakers. An entirely new type mechanism, based upon the use of hydraulic transmission, allows a mechanically simpler and more compact arrangement than any other mechanical arrangement heretofore used. The component parts, however, are conventional, standard devices which introduce no new or untried functions.

The driving motor is direct connected to a gear oil pump mounted at the side of the hydraulic cylinder. The motor drives through an insulated shaft and is mounted on an insulating base, and shielded from the main circuit breaker frame.

An automatic by-pass release valve is incorporated in the cylinder casting. This valve is held closed by pump pressure during the up stroke of the piston. When the hydraulic pump is stopped at the top of the stroke, pressure is released from this valve which opens, connecting the upper and lower ends of the cylinder and allowing the piston to return to the bottom position. The reclosing cycle is completed in approximately 4 sec.

Holding and Tripping Mechanism

The holding mechanism consists of a laminated armature carried on an armature lever fabricated from duralumin to which are attached the main opening springs. The armature spans the laminated pole tips of the d-c excited holding magnet.

Tripping is effected by the well-known flux shifting principle which allows an instantaneous release of the armature when current in the tripping coil, located between the pole tips, has reached the tripping value.

For polarized tripping on overcurrent or reverse current only, inherent trip is provided. In this case the tripping coil consists of 2 series single-turn coils each energized from separate shunts incorporated in the negative bus bars as previously described.

Checking calibration, after installation, on devices tripped directly by line currents of large magnitude has usually been difficult if at all feasible. A special low voltage calibrating coil has been included as a part of the series tripping coil assembly and is calibrated for each calibrated point of the series coil. A 12-volt automotive type storage battery, a small rheostat, and a direct reading ammeter constitute the only test apparatus needed to check the actual tripping point at any calibrated setting.

The excitation of the d-c holding magnet may be from any constant potential source. For machine breakers the excitation is usually taken from the machine bus. The effect of variable excitation on tripping point is shown in Fig. 5.

Fig. 3. Short circuit on a 625-volt 4,000-kw 60-cycle synchronous converter protected by the new high speed circuit breaker with inherent tripping set to trip at 4,500 amp

Curve *A*. 60-cycle timing wave
Curve *B*. Voltage across circuit breaker
Curve *C*. Current through circuit breaker

Discrimination

Reduction of tripping point on high rates of rise, by control of the ratio of inductance of the shunts to inductance of the series tripping coils, is obtained by the use of laminations on shunts and tripping coil leads. This arrangement gives the so-called discriminating effect whereby the effective tripping point is lowered under short-circuit conditions.

For machine reverse current protection a low tripping point is desirable since the maximum reverse fault current can be limited to a lower value. The polarized inherent tripping lends itself to a low tripping setting because it is inoperative on normal load current. Under this condition discrimination is not essential because the setting is independent of load current. On the form of circuit breaker with inherent tripping a minimum setting of 20 per cent of continuous rating may be obtained. This may be compared with previous practice of a minimum setting of 60 to 75 per cent.

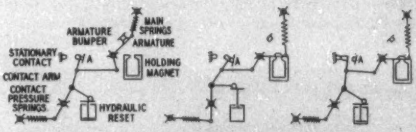


Fig. 4. Steps in the reclosing cycle of the new high speed circuit breaker, showing trip free operation

1. Open position
2. Armature closed, ready to trip. Contacts still fully open
3. Reset mechanism retracted. Contacts fully closed

With a very low tripping point for reverse current it becomes essential to provide no discrimination or a very small amount. Under steady state conditions the current divides between the series tripping coil and its shunt inversely as their respective resistances. Under transient conditions the division of current between the series tripping coil and its shunt is dependent upon both the inductance and resistance of the tripping coil and shunt. To maintain the same division of current under transient conditions as under steady state conditions the ratio of the inductances must equal numerically the ratio of the resistances of the parallel tripping coil and shunt. This may be indicated as follows (see Fig. 6):

Let

L_1 = inductance of trip coil
L_2 = inductance of shunt
R_1 = resistance of trip coil
R_2 = resistance of shunt

For all conditions the premise may be stated that

$$\frac{I_1}{I_2} = \frac{R_2}{R_1} \tag{1}$$

or

$$I_1R_1 = I_2R_2 \tag{2}$$

There may also be written

$$I_1R_1 + L_1\frac{dI_1}{dt} = I_2R_2 + L_2\frac{dI_2}{dt} \tag{3}$$

From eq 2

$$R_1\frac{dI_1}{dt} = R_2\frac{dI_2}{dt} \tag{4}$$

or

$$\frac{\frac{dI_1}{dt}}{\frac{dI_2}{dt}} = \frac{R_2}{R_1} \tag{4a}$$

Subtracting eq 2 from eq 3 and rearranging terms there results

$$\frac{L_2}{L_1} = \frac{\frac{dI_1}{dt}}{\frac{dI_2}{dt}} \tag{5}$$

Or, equating eq 4a and eq 5

$$\frac{L_2}{L_1} = \frac{R_2}{R_1} \tag{6}$$

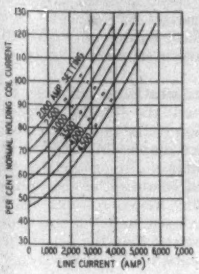
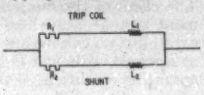


Fig. 5 (left). Characteristic curves showing effect of control voltage variations on tripping point

Fig. 6 (below). Diagram of tripping coil and shunt circuit



Accurate inductance values may best be obtained by calculation from oscillographic records of current rate of rise by the relation

$$L = \frac{E}{di/dt}$$

Where

E = applied voltage

$\frac{di}{dt}$ = initial rate of current rise in amperes per second

Where discrimination is desired the current in the tripping coil may be calculated from equations taking into account the external circuit inductance and resistance (see "High Speed Circuit Breaker in Railway Feeder Networks" by J. W. McNairy, TRANS. A.I.E.E., v. 45, 1926, p. 962–9).

High Speed Relay Tripping

For tripping on both overcurrent and reverse current the tripping coil is energized from the d-c control battery by the contacts of high speed relays arranged to trip from a separate shunt in the main circuit. This arrangement has not been used heretofore on d-c high speed circuit breakers and is only feasible now through the use of high speed relays developed for this purpose.

Each relay is in effect a miniature high speed circuit breaker tripping on the flux shifting principle. Reduction of tripping point by inductance ratio control is obtained in a similar manner. Discrimination may be separately controlled for each relay.

Due to the very small and light moving parts of the relay, very high speed contact closing operation is obtained and the over-all breaker rupturing time is not appreciably increased. An oscillogram of a short circuit on a 625-volt 3,000-kw 60-cycle synchronous converter protected by one of these high speed breakers equipped with relay trip is shown in Fig. 7. The external circuit resistance was 0.000562 ohm.

Blowout and Arc Chute Arrangement

To obtain high speed operation, fast arc rupturing is just as essential as quick release and high speed of the operating mechanism. A knowledge of the behavior and methods of control of the gas pressures generated during the arc rupturing process becomes of prime importance in opening the high currents encountered under maximum short-circuit conditions with high substation capacity. With intelligent direction this characteristic can be converted from a potential liability to a decided asset, and these forces utilized for rupturing by forcing the arc out into the chute at a higher rate than would be possible with the blowout magnet alone.

The main blowout magnet is energized by a semi-detached blowout coil which is inserted in the circuit, at the instant the arcing tips part, by transfer of the arc from the stationary contact face to the arcing horn. This arrangement facilitates the transfer of current to the arcing contact from the paralleled main contacts, without sacrifice of blowout effectiveness, by minimizing the change in inductance in the internal breaker circuits. A fully detached auxiliary blowout magnet, located in the upper part of the chute, is inserted in the circuit as the arc is forced upward.

Fig. 7. Short circuit on 625-volt 3,000-kw 60-cycle synchronous converter protected by the new high speed circuit breaker with relay tripping

Curve *A*. 60-cycle timing wave
Curve *B*. Voltage across circuit breaker
Curve *C*. Current through circuit breaker
Curve *D*. Circuit breaker tripping current
Curve *E*. Converter input, alternating current

The main arcing horns which act as the electrodes after the arc has been drawn and transferred, are made of a special non-magnetic nickel iron alloy having high specific resistance (150 microhms per cubic cm) and low permeability (approximately that of air). For the severe rupturing duty to which the high speed circuit breaker is subjected this material is well adapted and in comparison with the alloy

castings used under less severe conditions offers the advantages of reduction of energy in the arc stream and greater resistance to burning. The voltage drop in the main arcing horns may be 10 per cent or more of the total voltage across the contacts under maximum short circuit conditions.

Energy Consumption on Street Railways

Energy consumption on a street railway is affected by several variable factors; but because of their interrelation, it has been difficult to determine the separate effect of any one of these variables. A prolonged and detailed study on the railway property of the St. Louis (Mo.) Public Service Company, however, has resulted in the determination of relationships between energy consumption and weather conditions, passenger loading, and speed.

By
BENJAMIN F. THOMAS, JR.
MEMBER A.I.E.E.

Consulting Engineer
St. Louis, Mo.

ON ANY STREET RAILWAY operating under the same conditions of track layout, topography, and geographic location, and with the same equipment, the energy consumption per car mile of the system operated will vary with: (1) weather conditions; (2) number of passengers carried; (3) schedule speed operated; (4) density of vehicular traffic on the streets; (5) mechanical condition of the equipment; and (6) efficiency of operation of the motorman. Because of the interrelation of these variables, it has been difficult to separate the variation of energy consumption with each. It has been possible on several railways, however, to segregate some of these variables and to determine their relationships with the energy consumption. A prolonged and detailed study on the railway property on the St. Louis (Mo.) Public Service Company resulted in the determination of relationships between energy consumption and weather conditions, passenger loading, and speed.

Full text of a paper recommended for publication by the A.I.E.E. committee on transportation. Manuscript submitted Jan. 30, 1932; released for publication Sept. 11, 1933. *Not published in pamphlet form.*

It has been found that variations in the mean monthly temperature, used as a measure of the weather conditions, causes the energy consumption to increase as much as 10 to 15 per cent in midwinter over midsummer, when the cars have no electrical heating in them; and as much as 50 per cent increase when the cars are heated electrically. For each increase of 1 per cent in passengers carried, the energy increases 0.75 per cent; and for each 1 percent increase in scheduled speed (system average), the energy consumption increases 1.8 per cent. The methods used in deriving these figures are explained in detail, and the figures have been checked on other street railways.

Although the effects of the weather conditions, the number of passengers carried, the scheduled speed and the efficiency of operation of the motormen have been evaluated, it has been impossible accurately to show the effect of vehicular traffic on the streets. The effect of the mechanical condition of the equipment can be, and has been, shown for individual cars; but no evaluation has been made for a system as a whole, although it is patent that the better the operating conditions of the cars, the lower the energy consumption. The variation of the power demand is similar to the variation in energy consumption, but not by as great an amount.

Method of Procedure

Relationships given in this paper, deal with the energy consumption for a metropolitan street railway as a whole, not for individual cars. Practically all large systems operate cars of different types, weights, and motor equipments, on various lines or routes that have different characteristics. It is impossible in many cases to segregate the energy consumption by lines, and often to obtain quantitative values for the variables. The characteristics of an individual line vary and change much more rapidly than for the system as a whole, and the figures for the latter are more reliable and of more general usefulness.

The basic data upon which the information in this paper rests were obtained by the author in working on methods of reduction of energy consumption on the system of the St. Louis Public Service Company, St. Louis, Mo. This company operates about 1,500 cars over 460 miles of single track. The relationships have been checked by information obtained on other similar street railways in various localities in the northeastern part of the United States and are believed to be reliable and reasonably accurate. No claim for absolute accuracy is advanced because of the methods used and the insufficiency of the data obtainable. References to articles on this and allied subjects are given in the bibliography at the end of the paper.

Energy consumption data used in this study are for the system as a whole and represent the total energy purchased and generated by the company. The purchased energy was metered at the substation a-c bus bars before transformation, conversion, and distribution, so that these losses were included.

The generated energy was metered at the generator bus bars before conversion and distribution. Hence, the energy data included not only the actual energy used in the propulsion of the cars, but also the d-c distribution losses and the losses in the converters and their transformers. Included in this total energy originally was all energy used for other purposes, such as that used in the general and divisional repair shops, car shed lighting, electric heaters, compressors and lighting on the cars, that sold to other public utilities, and that used for all other purposes. Energy balances were computed, and all of this consumption was segregated carefully, either by metering where possible or by estimates, and was deducted from the gross figures; thus the net energy consumption of the street cars was obtained at the substation or generator bus bars.

This total consumption then was divided by the total car miles operated on the system, which data are kept by the statistical department of the company. Thus was obtained an over-all energy consumption in kilowatthours per car mile. No adjustment was, or could be, made for the different classes of equipment. The types of cars, however, remained practically the same throughout the years used in these studies. The consumption per car mile was calculated by months for 5 years. This entire study has been spread over a period of almost 10 years. Many curves were drawn and many trials made before the results presented were considered to be reliable.

Of the 6 factors causing variation in energy consumption as mentioned in the first part of this paper, certain years could be selected wherein some of these factors were nearly constant. For the 5 years between 1916 and 1921, the scheduled speed of operation was practically constant; the vehicular traffic was increasing somewhat, but not nearly at as fast a rate as in later years; the mechanical equipment, because of the regular routine of inspection and overhaul, was in approximately the same operating condition; and no effort during those years was made to increase the efficiency of the motormen. This left only 2 variables: weather conditions, and passengers carried.

With 2 unknown variables and 1 known factor, the equation was difficult to solve mathematically. It was done, however, by a "cut and try" method. First, the relationship between the energy consumption and the weather was established; then using the corrections thus obtained, the effect of the weather was eliminated, and the relationship between the energy and the passengers was determined. Both of these figures were in error; the first because the effect of the passengers was not eliminated, and the second because the factor for weather variation still was affected by the passengers. So another trial was made. Taking the relation between energy and passengers as originally established, the original energy figures were corrected for this variation after which the effect of the weather again was determined. This second curve took a logical shape, entirely different from the first as published in a previous article.[5] Again correcting the energy figures for weather variation, the effect of passengers was determined for a second time, and this curve also was much more logical. This whole process was repeated a third time, and by this successive elimination of each of the 2 variables, the final results are believed to be accurate.

5. For numbered references, see bibliography at end of paper.

Weather Conditions

In the beginning of the study it was noticed that the energy consumption per car mile was lowest in July, the month having the highest average temperature, and highest in the coldest months. The energy consumption for July therefore was taken as unity and the consumption for all other months in the same year was divided by that figure. This quotient was called the "temperature correction factor" and was expressed decimally. It has been plotted against the average monthly temperature, and is shown in Fig. 1. By means of this curve, the temperature correction factor may be found for any month corresponding to the average monthly temperature, and the energy consumption then may be reduced to a uniform basis, thus eliminating the effect of climatic changes.

The mean monthly temperature is used instead of rainfall, snow, or other variables, because it is the best and most available measure of the weather. The temperature of any month reflects the weather conditions, and the data clearly show the variation of the energy consumption with the mean temperature, whereas no relationship has been found for other conditions.

Figure 1 shows that as the temperature decreases the energy consumption increases, slowly in the warmer months and quite rapidly during the winter season. The curve becomes asymptotic at about 75 deg F, the usual mean temperature for the month of July. When the mean temperature falls to the freezing point, the energy consumption increases approximately 10 per cent over that in July, other factors remaining constant. This increase in energy results from: greater friction losses in bearings; unfavorable rail conditions due to the rains, snow, sleet, and frost that usually accompany the lower temperatures in this climate; higher winds, both

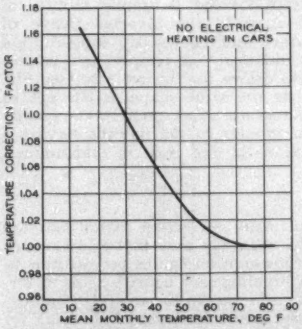


Fig. 1. Relation between energy consumption and weather conditions

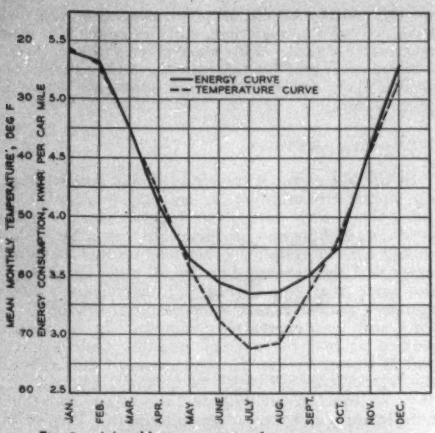


Fig. 2. Monthly comparison of energy consumption and mean temperature for a street railway in the northeastern United States

head winds and side winds, which cause greater head-on and side pressures; slower operation due to the bad conditions which causes lost time and inefficient operation in an effort to make up this time; slower movements of both passengers and crews due to the cold and to the heavier clothing worn; denser and more slowly moving vehicular traffic caused by the bad weather, and so forth. All of these items have an effect in varying degrees.

In this study, the energy used in electric heaters was subtracted from the totals, as only a few cars were equipped with this type of heater. In the colder climates and where all of the car heating is done by electricity, the effect of the heating plus the effect of the weather conditions so far overbalances the other variables that they may be neglected. This is shown very plainly in Fig. 2, the data for which were obtained on a street railway in the northeastern part of the country and represent averages for 5 years. Except for the 3 summer months of June, July, and August, the inverted curve of monthly temperature and the energy consumption curve are almost identical. A temperature correction curve also was drawn for this railway (see Fig. 3). This curve has the same shape as the one in Fig. 1, but the factors are much greater, the energy being 50 per cent greater in the months having a mean temperature of 32 deg than in midsummer.

Passengers

After the temperature correction factor was determined, it was a relatively easy matter to reduce all of the energy consumption figures per car mile to the same basis, by dividing each figure by this factor. With the effect of variations in the weather compensated, and with the schedule speed of the cars remaining approximately the same, the passengers per car mile were plotted against the energy consumption; the result is shown in Fig. 4. This curve has been checked against relationships obtained for other street railways, and in general is applicable although local conditions may affect the slope of the curve somewhat. The relationship between these 2 variables changes with the slope of the curve; the steeper the curve, the less effect the passenger load has on the energy consumption. The curve in Fig. 4 shows that for each 1-per cent increase in passengers carried the energy consumption increases 0.75 per cent. On other railways this increase in energy has been from 0.56 to 0.80 per cent.

The greatest element in the effect of an increase in the passengers carried is the number of car stops required per mile. In general, the more the passengers, the greater the number of stops, and the

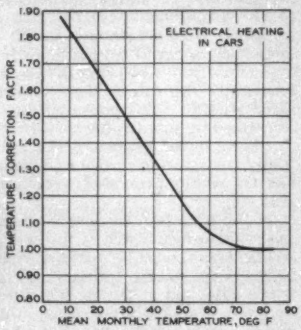


Fig. 3. Relation between energy consumption (including electrical heating) and weather conditions

greater the energy consumption. This has been shown repeatedly in previous papers and articles.[1,10] The reason is clear. For any given line, or system, the schedule speed has been set for average operation which anticipates a certain number of stops per mile, or per route, and a definite time has been set in which the motorman must make his run. As the loads increase beyond the average, greater time is required to load and to discharge passengers at each stop, and more stops are required. Each second that the motorman loses at a stop means that that much more time must be made up to prevent his falling behind schedule; and as he loses time, or, rather, as he endeavors to make up lost time, he increases the energy consumption of his car by driving it faster and coasting less. Any one who has operated a car knows this fact even without it having to be proved by the use of meters. The weight of the additional passengers has an effect, but this effect is small compared with the foregoing reason, even though the energy varies directly with the total weight. For example, assume a car weighing 42,500 lb net, and a passenger load of 50 at an average weight of 150 lb each. The total load is then 50,000 lb. If the passenger loading be doubled, the total weight of the car increases to 57,500 lb, an increase of only 15

per cent, whereas the actual energy consumption increases much more.

No claim is made that the curve in Fig. 4 represents the variation in passenger loading throughout the entire range on any one car. This relationship holds only for a system load, within the range usually encountered in month by month, or year by year, variations. An entirely different problem is presented, and new curves would have to be drawn from data not now available, in order to obtain the relationship with the energy consumption over the whole range from zero loading to a crowded car.

Speed

The term "speed" as used in this paper refers to the average monthly speed of the entire system. It is calculated by dividing the total car miles operated during any month by the total platform hours worked. It is not therefore the speed of any particular car, but is the average speed for the system. Included in the time are all stops, lay-overs, and delays occurring during normal or abnormal operation.

In the years during which the other data were developed, this scheduled speed was practically constant, varying less than 0.5 per cent from the average. In later years, efforts were made to speed up schedules, and to reduce the running time so as to reduce platform hours and to give better service. This increase in speed was not obtained by changing the equipment nor by the purchase of new cars, but

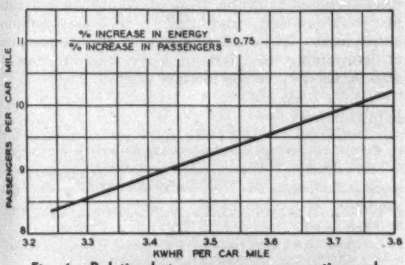


Fig. 4. Relation between energy consumption and passengers carried

by the elimination of waste time and by reducing the running time between time points. This latter caused faster acceleration and braking by making the motormen operate more rapidly. The total change in speed was a little more than 5 per cent, varying from 9.8 to 10.4 mph.

Figure 5 shows the relation between the change in speed and the change in energy consumption. Data for this curve were calculated in the same manner as for the previous ones. The actual energy consumption was divided by the temperature correction factor to reduce the energy to uniform weather conditions. Then the energy figures were adjusted to a uniform value for passengers per car mile, 9.24, which was the average loading for the first year. These adjusted energy figures then were plotted for each month against the average speed for the same month. It was determined in this manner that the energy consumption was increased 1.8 times the increase in speed. It must be borne in mind that this relationship is only for that part of the speed curve lying approximately between the limits of about 8 to 12 mph.

The curve of Fig. 5 was checked by drawing a speed time curve for one type of car on one particular line. Then taking that section of the speed time curve between 8 and 12 mph, the energy was calculated for this section and plotted against the speed. The result showed that the energy increase was double the speed increase. This was considered a good check, as no data from other systems were available.

Vehicular Traffic

No definite data could be obtained as to the relationship of energy to the density of street traffic. Without question traffic has some effect on the energy, because the car movements are retarded. Various methods were tried, but all failed because no apparent means of measuring the density of traffic seemed to be available. The vehicular registration shows only the increases by years, and are of no value here. An effort was made to determine the amount of gasoline consumed by months, but this could not be done. Although in St. Louis there is a gasoline tax, this is reported only by quarterly periods and frequently one period was heavily loaded with gasoline to be consumed in the next quarter, and *vice versa*. If the gasoline consumption could be determined accurately for any area, such as a city or metropolitan district, this would be a good measuring stick for the density of traffic.

However, it is not believed that the density of traffic has had nearly as great an effect upon energy consumption as has the weather, speed, or passengers, because, although traffic has increased tremendously

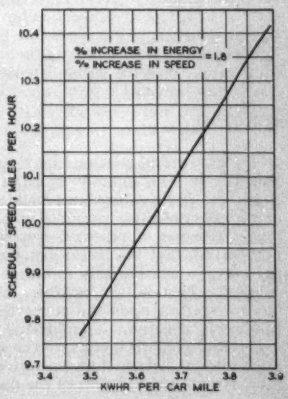


Fig. 5. Relation between energy consumption and schedule speed

in the past 10 years, the actual effect upon street car movements is limited to certain restricted areas which are small compared with the system as a whole. A second reason is that under normal conditions the traffic moves relatively rapidly and can clear the streets quickly. In bad weather, however, dense traffic or light traffic moves very slowly and has a habit of staying in the rails, probably with the idea that the rails will prevent skidding. At these times, the density has a very decided effect upon energy consumption, but a good part of this effect already is reflected in the factors for the weather conditions.

Condition of the Equipment

The physical condition of the equipment has a decided influence upon energy consumption. Cars with tight brakes or bearings use much more energy than necessary under better conditions. The energy consumption per mile will differ for cars of the same series, even though of the same weight and having the same equipment, all other conditions remaining the same. This is because the cars go through the shops periodically and are adjusted to take up wear, etc. Although efforts are made to adjust each car to a standard, it is a practical impossibility to adjust each car of any series so that all will be exactly alike. However, this variation of energy consumption is counterbalanced by the fact that a large number of cars of each series are averaged in all of the figures used, and as a result of the shop practice in use, the average condition of all cars will be approximately the same at all times.

Efficiency of the Motormen

By proper training and continued instruction, savings as great as 10 per cent or more in the total energy cost can be made. Operating men know this, and many articles published in the technical journals (see bibliography) bear out this assertion; but there is no measure by which to gauge the efficiency of a motorman, and consequently this efficiency cannot be plotted against the energy consumption. However, with the relationships that have been established in this study, it is quite possible to take the energy figures for a system and by reducing all of these figures to a common base, determine the effect of motorman instruction or of any other factor desired.

Power Demand

The figures and relationships that have been established have dealt entirely with the energy consumption. No mention has been made of power demand, or the effect of these variables upon the system peak load. Because of other studies, it is believed, but not proved, that the power demand will vary as will the energy, but that this variation will be somewhat smaller. That is, the weather, loading, and speed have less effect upon the power demand than upon the energy demand. Though it is possible to prove, it is rather difficult because of the complications that arise when it is desired to separate all of these figures for certain hourly periods of the day.

Discussion

As stated in the fore part of this paper, no claim is made for extreme accuracy of these figures. Too many variables are involved, and these variables are of such a nature that it is hard to evaluate them correctly. Care was used in the computation and plotting of the curves, but this, of course, does not change or improve the underlying inaccuracy of the basic figures.

The energy figures are metered and are the most accurate of all, probably within 0.5 per cent; but the necessary deductions made therefrom for energy used for purposes other than car propulsion are accurate only within 5 per cent. Data on the mean monthly temperature were obtained from the United States Weather Bureau, and should be accurate within less than 1 per cent. The number of passengers carried and the car miles operated depend upon reports turned in by the car crews, and are therefore more inaccurate than metered values, but are probably within 2 per cent of the true quantities. Hence, under the most unfavorable conditions with all of the errors additive, the maximum error should not exceed 8 per cent. It is believed that the relationships established are accurate within 5 to 8 per cent.

The data herein presented are of value to the street railway management, transportation officials, superintendents of power, the power companies, and all interested in the economics of street railways. By use of these relationships the effect of changing schedules to speed up the service, of handling more or less passengers, and of the weather conditions all can be predetermined, and the energy consumption anticipated. They also can be used for the purpose of determining the effect on energy consumption of any changed operating method desired.

Bibliography

1. Tests on the Lines of the Public Service Company of New Jersey. *Proc.* of the A.E.R.A., 1913, p. 319–55.

2. Economic Use of Energy for Car Purposes, D. D. Ewing. *Elec. Ry. Jl.*, March 27, 1920, p. 641–3.

3. Cutting Energy Costs in Seattle, S. E. Goodwin. *Elec. Ry. Jl.*, Dec. 18, 1920, p. 1233–5.

4. Substantial Energy Saving on the P.R.T. *Elec. Ry. Jl.*, Feb. 19, 1921, p. 355–6 and 360.

5. Energy Consumption Reduced in St. Louis, Benjamin F. Thomas, Jr. *Elec. Ry. Jl.*, Sept. 1, 1923, p. 321–4.

6. Coal Consumption Cut a Third in Three Years. *Elec. Ry. Jl.*, Dec. 22, 1923, p. 1054–5.

7. Benefits Derived From Power Conservation, F. Hollingsworth. *Elec. Traction*, Jan. 1924, p. 12.

8. Energy Consumption of Interurban Cars, *Elec. Ry. Jl.*, Feb. 2, 1924, p. 171–3.

9. Energy Saving Reduces Maintenance Costs in St. Louis, A. M. Brinkman. *Elec. Ry. Jl.*, July 18, 1925, p. 87–90.

10. Many Variables Affect Energy Consumption by Electric Railways, J. T. Lake. *Elec. Ry. Jl.*, Sept. 18, 1926, p. 449–51.

11. Car Improvements Bring Current Reduction. *Elec. Traction*, April 1929, p. 183–4.

12. Street Railway Power Economics on the Cincinnati System, J. A. Noertker. A.I.E.E. Trans., July 1929, p. 912–23.

13. Lubrication, With Particular Application to the Cars of the United Railways and Electric Company of Baltimore, W. B. D. Penniman. *Proc.* of the A.E.R.A., 1928, p. 449–72.

14. The Effects of Street Railway Equipment and Service Characteristics on Energy Consumption. T. F. Perkinsom and R. H. Sjoberg. *Proc.* of the A.E.R.A., 1931, p. 456–78.

Decrement Curves for Power Systems

A set of decrement curves useful in determining the magnitude of short-circuit currents on power systems has been calculated, based upon assumptions somewhat different from those used for previous decrement curves. These changes are intended to increase the usefulness of such curves and extend their range of application. Proper selection of oil circuit breakers and the determination of relay setting may be facilitated by the use of these curves.

By
CHARLES F. DALZIEL
ASSOCIATE A.I.E.E.

Univ. of California, Berkeley

IN recent years many advancements have been made in the technique of analyzing short circuits on power systems. The method of symmetrical compouents has been developed by which the magnitude of the initial and sustained short-circuit currents is readily obtained. The problem of determining the short-circuit currents for a definite time between these 2 extremes has been solved for some years past by the use of decrement curves.[1, 2, 3] Recently, considerable progress has been made in determining the behavior of synchronous machines during short circuits, and decrement curves considering these new developments have been published by W. C. Hahn and C. F. Wagner.[1] The curves presented herewith have been constructed along lines similar to the curves referred to above, the changes being those of application rather than fundamental assumptions.

The curves of Hahn and Wagner were constructed using the following basic assumptions:

1. The generators were assumed to be operating at rated voltage, frequency, and kilovoltamperes at 0.80 lagging power factor immediately preceding short circuit.

2. The short circuit was assumed to occur at the point of the voltage wave which corresponds to the maximum possible instantaneous current.

3. All resistance in the circuit including the resistance of the fault was neglected.

4. The actual system subjected to fault could be represented by a single equivalent generator of the same total kilovoltampere rating and external reactance.

5. No automatic voltage regulators were used.

6. The load was assumed to be located at the generator terminals, and the generator reactance was taken as 15 per cent. In cases where the total reactance to fault was less than 15 per cent, all the reactance was assumed to be in the generator.

7. All the machine electromotive forces were assumed to be in phase.

8. The short circuit was assumed to occur on an unloaded feeder.

9. The machine reactances and time constants were taken as representative of modern machines.

The present curves are based upon the same assumptions as the Hahn and Wagner curves with the following exceptions:

1a. The curves giving the maximum current assume that the generators are operating at rated voltage, frequency, and kilovoltamperes at 0.80 lagging power factor immediately preceding the short circuit.

1b. The curves giving the minimum current assume that the generators are operating at rated voltage, frequency, and no load, immediately preceding the short circuit.

2a. The curves giving the maximum current assume that the short circuit occurs at the point of the voltage wave which corresponds to the maximum possible current.

2b. The curves giving the minimum current assume that the short circuit occurs at the point of the voltage wave which corresponds to the minimum possible current.

3. The effect of resistance is considered in calculating the magnitude and rate of decay of the fault current. The impedance of the circuit external to the generator and load is assumed to have a ratio of resistance to reactance approximately equal to $^1/_3$. The impedance of the fault is assumed zero.

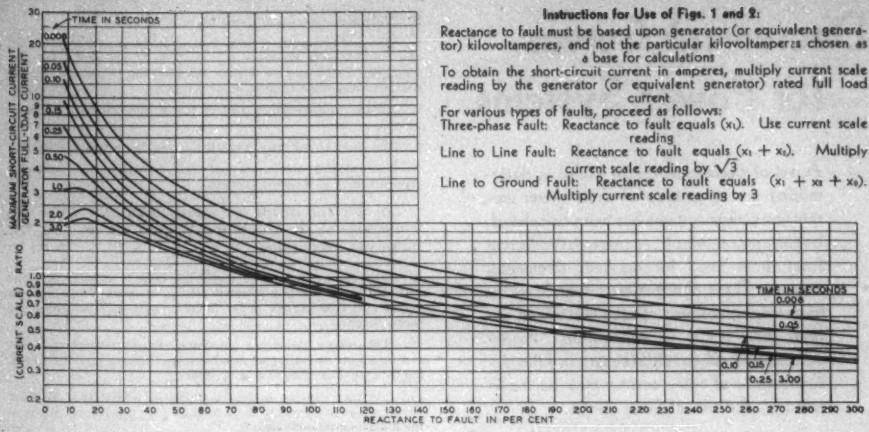
The following improvements should be noted. The extent of the curves and tables has been increased from the usual 100-per cent reactance to fault to 300-per cent reactance to fault. This makes possible the determination of currents for the 3 common types of faults (3 phase, line to line, and line to ground) up to a distance equal to approximately 100-per cent reactance from the generator. This is an increase in usefulness which should prove valuable from a practical standpoint. Resistance as well as reactance has been considered in computing both the initial currents and rates of current decay. Four decrement curves, and tables, are provided. The curves of Figs. 1 and 3 permit the determination of the maximum possible current corresponding to machines operating at normal full load excitation supplying a loaded system. The curves of Figs. 2 and 4 permit the determination of the minimum possible symmetrical current, corresponding to machines operating at no-load excitation. The 2 conditions determine the range of values to be expected, and permit an estimate of the probable currents for intermediate cases. One set, Figs. 1 and 2, is plotted in the conventional manner, and shows the effect of current decrement directly. The other, Figs. 3 and 4, has been arranged to expedite results obtained from calculating-table studies. For a complete discussion of terms used in this paper see reference 9.

Application of Decrement Curves

Under short-circuit conditions synchronous motors and condensers supply current to the fault during the transient period, and therefore all synchronous ma-

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution. Manuscript submitted April 3, 1933; released for publication Dec. 26, 1933. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.



Instructions for Use of Figs. 1 and 2:

Reactance to fault must be based upon generator (or equivalent generator) kilovoltamperes, and not the particular kilovoltamperes chosen as a base for calculations

To obtain the short-circuit current in amperes, multiply current scale reading by the generator (or equivalent generator) rated full load current

For various types of faults, proceed as follows:

Three-phase Fault: Reactance to fault equals (x_1). Use current scale reading

Line to Line Fault: Reactance to fault equals ($x_1 + x_2$). Multiply current scale reading by $\sqrt{3}$

Line to Ground Fault: Reactance to fault equals ($x_1 + x_2 + x_0$). Multiply current scale reading by 3

Fig. 1. Short-circuit decrement curves for power systems

Curves give root-mean-square maximum short-circuit current for various times after fault

Generators assumed operating at rated voltage, full load, 0.80 power factor, and without voltage regulators, immediately preceding short circuit

Curves are based on T_{do}' equal to 5 sec. For other values of T_{do}', multiply desired times by $5/T_{do}'$ to get proper time to use on curves

chines on a system are treated as generators during the initial period of a short circuit. It is important that the machines be represented by their subtransient reactances. The actual system must be reduced to as simple a system as possible. The decrement curves are derived for a system consisting of a single generator supplying a load at its terminals. The generator referred to in the paragraphs immediately following is assumed to be the equivalent generator resulting from the reduction process.

The curves of Figs. 1 and 2 give the maximum and minimum probable short-circuit currents, respectively, expressed in terms of the ratio of the actual short-circuit current to the equivalent generator full load current, for various per cent reactances to fault. The fault current in amperes is obtained by multiplying this ratio by the normal generator current in amperes. These curves are used in a manner similar to others which have been published from time to time.

The curves of Figs. 3 and 4 are constructed to give, respectively, the maximum and minimum short-circuit currents, the current being plotted in terms of the ratio of the actual short-circuit current to the instantaneous symmetrical short-circuit value. The fault current in amperes is obtained by multiplying this ratio by the instantaneous symmetrical short-circuit current in amperes. Since it is common practice to determine the instantaneous symmetrical short-circuit current as the first step in the solution of a problem, the use of these curves facilitates solution.

In most cases it will be sufficiently accurate to assume the open circuit time constant of the equivalent generator equal to 5 sec, which is the value used

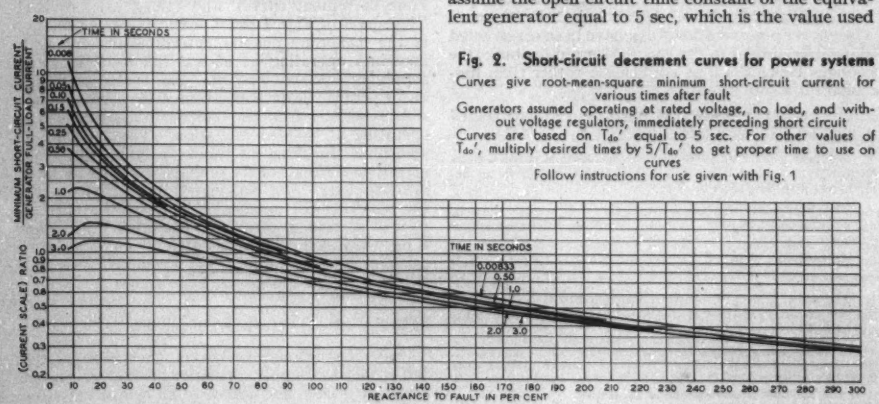


Fig. 2. Short-circuit decrement curves for power systems

Curves give root-mean-square minimum short-circuit current for various times after fault

Generators assumed operating at rated voltage, no load, and without voltage regulators, immediately preceding short circuit

Curves are based on T_{do}' equal to 5 sec. For other values of T_{do}', multiply desired times by $5/T_{do}'$ to get proper time to use on curves

Follow instructions for use given with Fig. 1

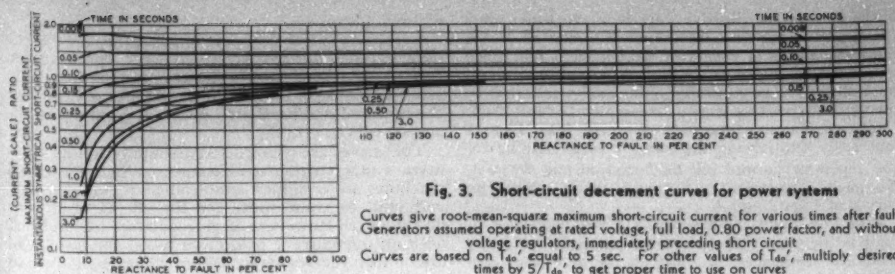


Fig. 3. Short-circuit decrement curves for power systems

Curves give root-mean-square maximum short-circuit current for various times after fault
Generators assumed operating at rated voltage, full load, 0.80 power factor, and without voltage regulators, immediately preceding short circuit
Curves are based on T_{do}' equal to 5 sec. For other values of T_{do}', multiply desired times by $5/T_{do}'$ to get proper time to use on curves

in constructing the curves. If more accurate results are desired, the open circuit time constant can be calculated from the formula given below:[1]

$$T_{deq}' = \frac{1}{x - x'} \sum (T_{deq}(x_{d1} - x_{d1}')u_1^2 \ldots\ldots\ldots) \quad (1)$$

or

$$T_{deq}' = \frac{x^2}{x - x'} \sum (T_{deq} \frac{(x_{d1} - x_{d1}')}{x_{d1/}^2} \ldots\ldots\ldots) \quad (2)$$

where:

T_{deq}' = equivalent open circuit time constant
x = synchronous reactance of system to fault
x' = transient reactance of system to fault
T_{deq} = open circuit time constant of first machine
x_{d1} = synchronous reactance of first machine
x_{d1}' = transient reactance of first machine
$x_{d1/}$ = synchronous reactance of first machine to fault
u_1 = ratio of sustained current in first machine to total sustained current in fault (all reactances must be expressed on the same kilovoltampere base)

In cases where there is no appreciable reactance between the machines and the point where the equivalent generator is assumed, this constant can be determined roughly by simple proportion:

$$T_{deq}' = \sum (T_{deq} \frac{kva_1}{kva_t} \ldots\ldots\ldots) \quad (3)$$

where:

kva_1 = kva capacity of first machine
T_{deq} = open circuit time constant of first machine, etc.
kva_t = total kilovoltampere capacity of system.

The instructions given on the curves are sufficient

Instructions for Use of Figs. 3 and 4:

Reactance to fault must be based on generator (or equivalent generator) kilovoltamperes, and not the particular kilovoltamperes chosen as a base for calculations
To obtain the short-circuit current in amperes, multiply current scale reading by instantaneous symmetrical short-circuit current, for type of fault considered
For various types of faults, proceed as follows:
Three-phase Fault: Reactance to fault equals (x_1)
Line to Line Fault: Reactance to fault equals ($x_1 + x_2$)
Line to Ground Fault: Reactance to fault equals ($x_1 + x_2 + x_0$)

for ordinary use. If the open circuit time constant is other than 5 sec, an approximate correction should be made. The desired time is multiplied by 5 divided by the actual time constant. The result can then be used in determining values from the curves. Curves showing typical open circuit time constants of synchronous machines are given in Figs. 5 and 6, which have been taken from Hahn and Wagner.

The reactance to fault must be referred to the equivalent generator capacity in kilovoltamperes as a percentage, and not to the arbitrary kilovoltampere base used for calculations. The resistance of the actual system must be neglected in this determination, proper account having been taken of the average system in deriving the curves.

Three-Phase Short Circuits. The reactance to fault is the positive sequence reactance (x_1), the value which ordinarily determines the instantaneous symmetrical short-circuit current for this type of fault. The reactance to fault is the generator subtransient reactance plus the external reactance to fault ($x_1 = x_d'' + x_k$). The current scale gives the current as described previously.

Line to Line Short Circuits. The reactance to fault

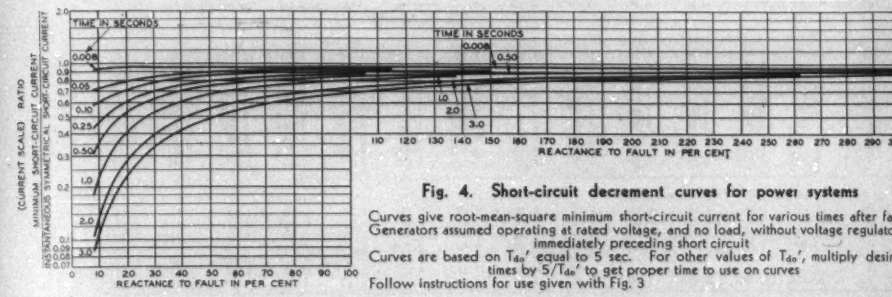


Fig. 4. Short-circuit decrement curves for power systems

Curves give root-mean-square minimum short-circuit current for various times after fault
Generators assumed operating at rated voltage, and no load, without voltage regulators, immediately preceding short circuit
Curves are based on T_{do}' equal to 5 sec. For other values of T_{do}', multiply desired times by $5/T_{do}'$ to get proper time to use on curves
Follow instructions for use given with Fig. 3

is the sum of the positive sequence reactance plus the negative sequence reactance to fault $(x_1 + x_2)$. Since the values of generator subtransient reactance and negative sequence reactances are nearly equal numerically, it is generally sufficiently accurate to use twice the positive sequence reactance to fault $(2x_1)$.

The current in amperes is obtained from Figs. 1 and 2, by multiplying the current scale reading by the generator normal full load current and by $\sqrt{3}$. No such calculation is required when using the curves of Figs. 3 and 4.

Line to Ground Short Circuits. The reactance to fault is the sum of the positive, negative, and zero sequence reactances to fault $(x_1 + x_2 + x_0)$. As before, this reactance may be taken equal to twice the positive plus the zero sequence reactance $(2x_1 + x_0)$. The corrections for open circuit time constant apply as before. The current in amperes is obtained from Figs. 1 and 2, by multiplying the current scale reading by the generator full load current and by 3. No such calculation is required when using the curves[8] of Figs. 3 and 4.

Except as noted, both sets of curves are used in the same manner, and give identical results for any given case. The values used in constructing the curves are given in Tables I to V, inclusive. It is obvious that the required results can be obtained from either the proper curve or table.[6]

The curves are constructed assuming that no automatic voltage regulators are used. Where the actual machines are equipped with voltage regulators, they will tend to compensate for the effects of current decrement. However, if a regulator is furnished with an overcurrent protective relay, the latter will disconnect the regulator before it has had time to operate, and the curves may be used. In case the regulator is not provided with a protective relay, and quick response system is not used, the curves may be used up to the first $^1/_4$ sec after fault, since the regulator requires some time to operate. Regardless of the type of excitation system, the curves may be used to determine the initial currents, and

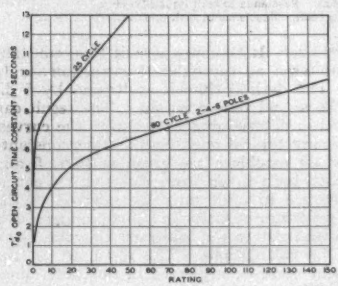


Fig. 5 (left). Open circuit time constants of turbine-generators

Fig. 6 (right). Open circuit time constants of a-c generators and motors

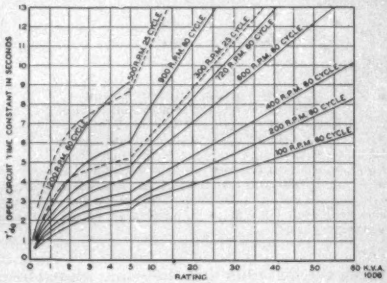


Table I—Decrement Curve Construction

Assumed Generator Constants:

$x_d = 1.15 \quad x_d' = 1.4x_d'' + 0.02 \qquad x_1 = x_d'' + x_b$

$x_q = 1.00 \quad x_q'' = x_1$, for x_1 less than 0.15

$T_{do}' = 5.00 \quad x_d'' = 0.15$, for x_1 greater than 0.15

Assumed System Constants:

$Z_b = x_b \angle 72.0°$ $\qquad Z_f = x_f \angle 36.8°$

$= 0.325x_b + jx_b$ $\qquad = 0.8 + j0.6$

x_1	0.08	0.10	0.12	0.15	0.20	0.30	0.40	0.50	0.75	1.00	1.50	2.00	2.50	3.00
x_d''	0.08	0.10	0.12	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
x_d'	0.132	0.160	0.188	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
I''	12.5	10.0	8.33	6.66	5.00	3.33	2.50	2.00	1.33	1.00	0.67	0.50	0.40	0.33
Maximum Current Curve Construction														
e_{do}''	1.05	1.06	1.08	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
e_d'	1.08	1.10	1.12	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
e_d	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92
e_{go}	2.17	2.19	2.22	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29	2.29
i''	13.1	10.6	8.96	7.32	5.32	3.43	2.52	1.99	1.31	0.975	0.645	0.483	0.388	0.330
i'	8.20	6.91	5.98	5.00	3.98	2.81	2.18	1.76	1.21	0.915	0.619	0.468	0.388	0.330
i	1.89	1.91	1.93	1.99	1.83	1.58	1.39	1.25	0.975	0.802	0.592	0.468	0.388	0.330
R					0.017	0.038	0.091	0.127	0.21	0.28	0.38	0.45	0.506	0.55
X					0.047	0.129	0.194	0.249	0.345	0.407	0.478	0.517	0.541	0.553
T_d'	0.574	0.695	0.818	1.00	1.16	1.41	1.59	1.74	1.99	2.15	2.33	2.44	2.52	2.58
Minimum Current Curve Construction														
e_{do}	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
i''	12.5	10.0	8.33	6.66	5.00	3.30	2.45	1.95	1.29	0.965	0.641	0.479	0.382	0.318
i'	7.58	6.25	5.32	4.34	3.57	2.61	2.06	1.70	1.17	0.90	0.61	0.461	0.372	0.311
i	1.00	1.00	1.00	1.00	0.959	0.885	0.821	0.766	0.654	0.566	0.455	0.376	0.321	0.280
R					0.016	0.049	0.081	0.114	0.195	0.276	0.438	0.602	0.765	0.925
X					0.050	0.15	0.25	0.35	0.60	0.85	1.35	1.85	2.35	2.85
T_d'	0.574	0.695	0.818	1.00	1.17	1.46	1.73	1.95	2.41	2.75	3.22	3.53	3.75	3.91

Table II—System Short-Circuit Current Decrement Factors, Minimum Probable Current

Time in Sec	Rms Total Current Expressed as a Ratio Equal to: Minimum Short-Circuit Current / Generator Full Load Current for Various Reactances to Fault (in Per Cent x_1)													
	8	10	12	15	20	30	40	50	75	100	150	200	250	300
0.008	11.6	9.35	7.83	6.30	4.78	3.19	2.39	1.91	1.27	0.96	0.636	0.476	0.381	0.317
0.05	8.84	7.25	6.17	5.03	3.99	2.81	2.18	1.77	1.21	0.92	0.619	0.466	0.375	0.313
0.10	7.19	6.06	5.26	4.34	3.54	2.59	2.04	1.69	1.17	0.90	0.610	0.460	0.371	0.311
0.15	6.30	5.42	4.72	3.98	3.33	2.47	1.97	1.64	1.15	0.88	0.603	0.457	0.370	0.310
0.25	5.29	4.58	4.20	3.61	3.08	2.33	1.89	1.59	1.12	0.87	0.598	0.455	0.369	0.309
0.50	3.75	3.56	3.34	3.03	2.66	2.11	1.75	1.49	1.08	0.84	0.588	0.450	0.367	0.308
1.00	2.16	2.25	2.27	2.23	2.07	1.75	1.51	1.32	1.00	0.80	0.568	0.440	0.360	0.304
2.00	1.20	1.29	1.37	1.45	1.42	1.33	1.21	1.09	0.88	0.73	0.538	0.424	0.351	0.299
3.00	1.03	1.07	1.11	1.16	1.15	1.11	1.04	0.97	0.803	0.68	0.516	0.412	0.344	0.294

Time in seconds is the time from instant of short circuit

Table III—System Short-Circuit Current Decrement Factors, Minimum Probable Current

Time in Sec	Rms Total Current Expressed as a Ratio Equal to: Minimum Short-Circuit Current / Instantaneous Symmetrical Short-Circuit Current for Various Reactances to Fault (in Per Cent x_1)													
	8	10	12	15	20	30	40	50	75	100	150	200	250	300
0.008	0.932	0.935	0.940	0.945	0.955	0.957	0.955	0.956	0.953	0.960	0.954	0.952	0.953	0.952
0.05	0.706	0.725	0.741	0.755	0.798	0.843	0.871	0.885	0.905	0.920	0.929	0.932	0.936	0.940
0.10	0.575	0.606	0.631	0.655	0.708	0.776	0.815	0.845	0.877	0.900	0.915	0.920	0.927	0.933
0.15	0.504	0.542	0.565	0.597	0.666	0.741	0.788	0.820	0.862	0.880	0.905	0.915	0.925	0.930
0.25	0.424	0.458	0.504	0.542	0.616	0.699	0.756	0.795	0.840	0.870	0.897	0.910	0.923	0.926
0.50	0.300	0.356	0.402	0.455	0.532	0.632	0.700	0.745	0.810	0.840	0.882	0.900	0.915	0.924
1.00	0.173	0.224	0.273	0.334	0.414	0.525	0.604	0.660	0.748	0.800	0.853	0.880	0.900	0.912
2.00	0.097	0.129	0.165	0.217	0.284	0.399	0.484	0.545	0.660	0.730	0.807	0.849	0.878	0.898
3.00	0.083	0.107	0.134	0.174	0.230	0.333	0.416	0.484	0.602	0.680	0.774	0.822	0.860	0.882

Time in seconds is the time from instant of short circuit

Table IV—System Short-Circuit Current Decrement Factors, Maximum Probable Current

Time in Sec	Rms Total Current Expressed as a Ratio Equal to: Maximum Short-Circuit Current / Generator Full Load Current for Various Reactances to Fault (in Per Cent x_1)													
	8	10	12	15	20	30	40	50	75	100	150	200	250	300
0.008	21.5	17.4	14.7	12.0	8.81	5.68	4.18	3.30	2.18	1.62	1.07	0.807	0.650	0.551
0.05	16.1	13.3	11.4	9.35	6.94	4.59	3.42	2.72	1.82	1.36	0.905	0.684	0.553	0.464
0.10	12.3	10.2	8.82	7.31	5.57	3.75	2.85	2.28	1.54	1.16	0.778	0.584	0.479	0.407
0.15	9.75	8.25	7.31	6.03	4.67	3.25	2.49	2.01	1.38	1.04	0.705	0.531	0.436	0.372
0.25	6.95	6.06	5.48	4.76	3.84	2.78	2.17	1.78	1.23	0.940	0.637	0.486	0.402	0.342
0.50	4.66	4.40	4.15	3.84	3.24	2.44	1.96	1.63	1.16	0.891	0.614	0.468	0.388	0.330
1.00	3.00	3.10	3.13	3.10	2.74	2.19	1.81	1.54	1.12	0.873	0.610	0.468	0.388	0.330
2.00	2.08	2.19	2.28	2.40	2.21	1.88	1.62	1.41	1.06	0.846	0.604	0.468	0.388	0.330
3.00	1.92	1.98	2.03	2.14	1.99	1.75	1.51	1.34	1.03	0.830	0.599	0.468	0.388	0.330

Time in seconds is the time from instant of short circuit

Table V—System Short-Circuit Current Decrement Factors, Maximum Probable Current

Time in Sec	Rms Total Current Expressed as a Ratio Equal to: Maximum Short-Circuit Current / Instantaneous Symmetrical Short-Circuit Current for Various Reactances to Fault (in Per Cent x_1)													
	8	10	12	15	20	30	40	50	75	100	150	200	250	300
0.008	1.72	1.74	1.77	1.80	1.76	1.71	1.67	1.65	1.64	1.62	1.61	1.61	1.63	1.65
0.05	1.29	1.33	1.37	1.40	1.39	1.38	1.37	1.36	1.36	1.36	1.36	1.36	1.38	1.39
0.10	0.983	1.02	1.06	1.10	1.12	1.13	1.14	1.14	1.15	1.16	1.17	1.17	1.20	1.22
0.05	0.781	0.825	0.876	0.905	0.936	0.974	0.995	1.01	1.03	1.04	1.06	1.06	1.09	1.12
0.25	0.556	0.606	0.657	0.714	0.768	0.835	0.869	0.885	0.922	0.940	0.955	0.970	1.01	1.02
0.50	0.374	0.440	0.497	0.576	0.648	0.732	0.784	0.815	0.870	0.891	0.920	0.936	0.970	0.991
1.00	0.240	0.310	0.376	0.465	0.548	0.656	0.724	0.770	0.836	0.873	0.915	0.936	0.970	0.991
2.00	0.167	0.219	0.264	0.360	0.441	0.564	0.648	0.705	0.796	0.846	0.905	0.936	0.970	0.991
3.00	0.154	0.198	0.243	0.321	0.398	0.526	0.604	0.670	0.772	0.830	0.900	0.936	0.970	0.991

Time in seconds is the time from instant of short circuit

the sustained currents can be estimated by multiplying the calculated sustained current by the ratio of the maximum exciter current to the nominal exciter current. The nominal exciter current is that value of excitation required to produce rated voltage at the machine terminals before fault. In any case, it should be safe to assume that the maximum current will not exceed either the initial current or the

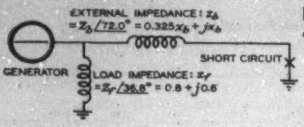


Fig. 7. Diagram of typical system

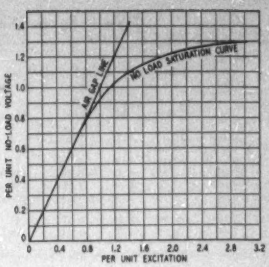


Fig. 8. Typical saturation curve

sustained current. Values of sustained currents i are given in Table I.

Conclusions

It is important to note that the results obtained using decrement curves on an actual system are at best approximate due to the assumptions used, and in cases demanding accurate results, rigorous methods must be used. For instance, the assumption that the arc resistance is zero is rarely met in practice. The assumption that the generated voltages are in phase assumes that the machines slow down together, again a condition rarely observed in practice. The present curves and tables are subject to the limitations discussed by Hahn and Wagner, and the reader is referred to their article for comprehensive treatment. Special attention is called to their discussion regarding salient pole machines without dampers.

A ready means of estimating fault currents on actual systems is of value, and it is believed that the results obtained using these decrement curves and tables will be sufficiently accurate to permit proper selection of oil circuit breakers and relay settings on the ordinary power system.

Appendix I—Derivation of Decrement Curves

In previously published decrement curves it has been assumed that all reactance was in the generator for values of x_1 less than 0.15. For values of x_1 greater than 0.15, this value was assumed in the generator and the remainder external thereto. As this assumption has been generally accepted, it is used in the present curves. The generator transient reactance x_d' is taken equal to $1.4x_d'' + 0.02$, and the Potier reactance x_p to $1.3x_d''$. The generator synchronous reactance in the direct axis x_d is assumed to be 1.15, and the quadrature axis synchronous reactance x_q to be 1.00.

The relation between the direct-axis transient short-circuit time constant T_d', and the direct-axis open-circuit time-constant T_{do}', for machines without saturation, when short-circuited through an external resistance r is:[7,8]

$$T_d' = \frac{T_{do}'}{\left[1 + \frac{x_q(x_d - x_d')}{r^2 + x_d'x_q}\right]}$$

When the machine is short-circuited through an external impedance $(r + jx)$, the formula becomes:

$$T_d' = \frac{T_{do}'}{\left[1 + \frac{(x_q + x)(x_d - x_d')}{r^2 + (x_d' + x)(x_q + x)}\right]} \tag{4}$$

This equation is used to determine the short-circuit time constant, assuming that the effects of saturation are negligible. The open-circuit time constant is taken as 5 sec, which is an average value for modern machines.

The external impedance is assumed to have a ratio of resistance to reactance equal to 1/3.077 (corresponding to an impedance angle of 72 deg.).

The curves giving the maximum current are obtained as follows. The current supplied by the generator equals the internal voltage previous to fault divided by the impedance to fault. The current supplied to the fault is less than the generator current because some of the current is taken by the load (see Fig. 7). The internal voltages are computed using round rotor theory and neglecting saturation except in the calculation of the sustained currents.

The magnitude of the internal voltage behind the subtransient reactance e_d'' immediately before short circuit is:

$$e_d'' = \sqrt{(E_t + Ix_d'' \sin\phi)^2 + (Ix_d'' \cos\phi)^2}$$
$$= \sqrt{(1.00 + 0.6x_d'')^2 + 0.64\, x_d''^2}$$

in which E_t is the generator terminal voltage before fault (E_t = 1.00), I is the load current before fault (I = 1.00), and ϕ is the load power factor angle (ϕ = 36.8 deg). Similarly, the magnitude of the internal voltage behind the transient reactance e_d' immediately before short circuit is:

$$e_d' = \sqrt{(1.00 + 0.6\, x_d')^2 + 0.64x_d'^2}$$

and the magnitude of the internal voltage behind synchronous reactance e_d immediately before short circuit (neglecting saturation) is:

$$e_d = 1.92$$

The correction for saturation is computed corresponding to the actual voltage generated in the machine using the Potier reactance. The correction is obtained by measuring the difference between the air gap saturation line and the typical no-load saturation curve of Fig. 8, for the value of actual generated or virtual voltage e_v. The magnitude of the virtual voltage of the machine immediately before short circuit is:

$$e_v = \sqrt{(1.00 + 0.78x_d'')^2 + 1.08x_d''^2}$$

The actual internal voltage e_{do} equals the arithmetic sum of the internal voltage plus the correction for saturation.

From Fig. 7, it is evident that the magnitude of the initial subtransient current supplied to the fault is:

$$i'' = \frac{e_d''}{x_d'' + \frac{z_b z_f}{z_b + z_f}} \cdot \frac{z_f}{z_b + z_f}$$

$$= \frac{e_d''}{\sqrt{x_b^2(0.325 - 0.606\, x_d'')^2 + (x_b + x_d''[1.00 + 0.86\, x_b])^2}}$$

The magnitude of the initial transient current in the fault equals:

$$i' = \frac{e_d'}{\sqrt{x_b^2(0.325 - 0.606x_d')^2 + (x_b + x_d'[1.00 + 0.86\, x_b])^2}}$$

Similarly, the magnitude of the sustained current in the fault equals:

$$i = \frac{e_{do}}{\sqrt{0.138x_b^2 + (1.99x_b + 1.15)^2}}$$

The direct-axis transient short-circuit time constant equals (from eq 4):

$$T_d' = \frac{5.00}{\left[1 + \frac{(x_q + X)(x_d - x_d')}{R^2 + (x_q + X)(x_d' + X)}\right]}$$

where R and X are the equivalent resistance and reactance respectively, of the parallel circuit consisting of the load and external

impedance. Expressed in terms of the external reactance to fault they are:

$$R = \frac{x_3(0.8\,x_3 + 0.294)}{x_3^2 + 1.56\,x_3 + 0.906} \qquad X = \frac{x_3(0.6\,x_3 + 0.906)}{x_3^2 + 1.56\,x_3 + 0.906}$$

The subtransient component of fault current at any time t equals:

$$i_{st} = (i'' - i')e^{-t/T_d''} = (i'' - i')e^{-t/0.05}$$

The value of T_d'' equal to 0.05 sec is an average value corresponding to $T_{do}' = 5$ sec.

The transient component of fault current at any time t equals:

$$i_t = (i' - i)e^{-t/T_d'}$$

The total symmetrical fault current is:

$$I_{st} = i + i_t + i_{st}$$

The direct component of fault current at any time t equals:

$$I_{dc} = \sqrt{2}\, i''\, e^{-t/T_a} \text{ is } = \sqrt{2}\, i''e^{-t/0.15}$$

where T_a, the short-circuit time constant of the circuit is given an average value of 0.15 sec.

The magnitude of the total short-circuit current in the fault is:

$$I_{sc} = \sqrt{I_{st}^2 + I_{dc}^2}$$

Values of current computed as outlined above are included in Table I, IV, and V, and give the current from the first quarter cycle to 3 sec after fault. The values have been plotted to give the curves of Fig. 1. The curves of Fig. 3 were obtained by plotting the ratio of the short-circuit current to the instantaneous symmetrical short-circuit current ($I'' = 1/(x_d'' + x_3)$).

The curves giving the minimum current are obtained in a similar manner. All internal voltages are unity for this case, since the machine is assumed to be operating at no load previous to fault. The correction for saturation is taken equal to 0.15, and the load is omitted. Since the absolute minimum current is desired, only the symmetrical fault current is calculated. Values of the symmetrical fault current are included in Tables I, II, and III, and give the currents from the first quarter cycle to 3 sec after short circuit. The values have been plotted to give the curves of Fig. 2. The curves of Fig. 4 were obtained in a manner exactly similar to that described for Fig 3 above.

Appendix II—Sample Problems

The following problems will be solved to illustrate the correct use of the decrement curves and tables. The system considered is represented by the one line diagram, Fig. 9, with a dead short circuit occurring at point x. The maximum short circuits are calculated assuming the system loaded and all generators operating. The minimum short-circuit currents are calculated considering generators 1 and 2 only, their excitations corresponding to no load. When no automatic voltage regulators are used, compute:

1. The maximum short-circuit current for a 3-phase fault 0.50 sec after fault.

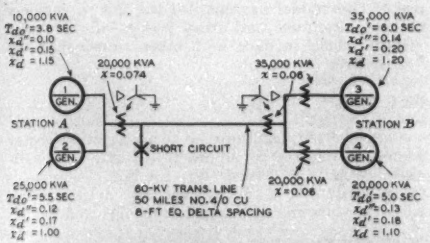


Fig. 9. Typical system used in sample problems

2. The maximum short-circuit current for a line to line fault 0.50 sec after fault.

3. The maximum short-circuit current for a line to ground fault 0.50 sec after fault.

4. The minimum short-circuit current for a 3-phase fault 0.50 sec after fault.

Assuming that generators 1 and 2 are equipped with voltage regulators, the ratio of exciter ceiling voltage to rated voltage when delivering full load being 130 per cent, calculate the sustained short-circuit current for a 3-phase fault. Consider the generators loaded previous to fault.

PROCEDURE

a. Determine the capacity of the equivalent generator.

b. Calculate the reactance to fault, x_f, as a percentage on the equivalent generator kilovoltampere capacity.

c. Estimate or calculate the open circuit time constant T_{doe}' of the equivalent generator.

d. Determine the proper time t to use on the curves, using the equivalent generator open circuit time constant and the desired time in seconds.

e. Obtain the short-circuit current in the fault from the curves or tables, using the reactance to fault and the corrected time from *b* and *d* above.

SOLUTION 1. FIG. 1 OR TABLE IV

a. Equivalent generator capacity is the total system kilovoltamperes and equal 90,000 kva.

b. Reactance to fault $x_f = x_1$

$x_1 = 1/I'' = 1/10.39 = 0.0964$ on 20,000-kva base, from Fig. 10 $= 0.434$ or 43.4 per cent on 90,000-kva base.

c. For a first approximation, assume $T_{doe}' = 5.0$ sec.

d. Correct time to use on curves equals 0.50 sec. (No correction when $T_{doe}' = 5$ sec.)

e. From Fig. 1, or interpolating from Table IV, using $x_f = 43.4$ per cent, $t = 0.50$ sec, $I_{sc} = 1.84 \times 90{,}000/60\sqrt{3} = 1{,}590$ amp, *answer*.

More accurate results are obtained by calculating T_{doe}' from eq 1, using Fig. 10.

$$T_{doe}' = \frac{1}{1/2.96 - 1/8.96}\left[3.8(2.30 - 0.30)\left(\frac{0.386}{2.96}\right)^2 + 5.5(0.80 - 0.136)\left(\frac{1.114}{2.96}\right)^2 + 6.0(0.685 - 0.114)\left(\frac{0.90}{2.96}\right)^2 + 5.0(1.10 - 0.18)\left(\frac{0.56}{2.96}\right)^2\right] = 4.98 \text{ sec}$$

(In this particular case, the correction in time is too small to warrant attention from a practical standpoint.)

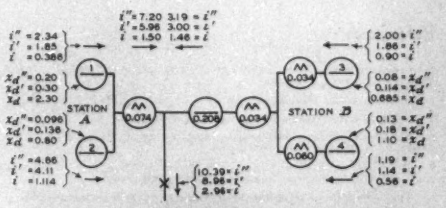
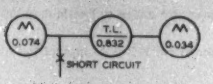


Fig. 10. Diagram of positive and negative sequence network reactance, and positive sequence current distribution

Per unit values on 20,000-kva base
(Assumes generator $x^2 = x_0''$)



Per unit values on a 20,000-kva base
Assumed transmission line $x_0 = 4.0x_1$

Fig. 11. Diagram of zero sequence network reactance

SOLUTION 2. FIG. 1 OR TABLE IV

The solution for a line to line short circuit is similar to that outlined above with the following exceptions:

b. Reactance to fault $x_f = 2x_1 = 2 \times 43.4 = 86.8$ per cent on 90,000-kva base.

e. From Fig. 1 or Table IV, using: $x_f = 86.8$ per cent, $t = 0.50$ sec, $I_{sc} = 1.02 \times \sqrt{3}[90{,}000/60\sqrt{3}] = 1{,}530$ amp, *answer*.

SOLUTION 3. FIG. 1 OR TABLE IV

Again the solution is similar, but with the following exceptions:

b. Reactance to fault $x_f = 2x_1 + x_0$

x_0 = equivalent reactance of 0.074 and (0.832 + 0.034) in parallel
= 0.0682 on 20,000-kva base, from Fig. 11
= 30.7 per cent on 90,000-kva base

$x_f = (2 \times 43.4 + 30.7) = 117.5$ per cent on 90,000-kva base.

e. From Fig. 1 or Table IV, using: $x_f = 117.5$ per cent, $t = 0.50$ sec, $I_{sc} = 0.77 \times 3[90{,}000/60\sqrt{3}] = 2{,}000$ amp, *answer*.

SOLUTION 4. FIG. 4 OR TABLE III

a. Equivalent generator capacity is 35,000 kva.

b. Reactance to fault from station $A(x_f) = (x_1)$.

$x_f = 1/I''_A = 1/7.2 = 0.139$ on 20,000-kva base
= 24.3 per cent on 35,000-kva base. (See Fig. 10.)

c. Since there is no reactance between the generators and the point where they are paralleled, use eq 3.

$$T_{dcs}' = 3.8 \times \frac{10{,}000}{35{,}000} + 5.5 \times \frac{25{,}000}{35{,}000} = 5.02 \text{ sec}$$

d. $t = 0.50 \times 5/5.02 = 0.50$ sec, approximately.

e. $I'' = 7.2[20{,}000/60\sqrt{3}] = 1{,}385$, instantaneous symmetrical short-circuit current in amperes.

From Fig. 4 or Table III, using the above values, $I_{sc}/I'' = 0.585$. $I_{sc} = 1{,}385 \times 0.585 = 810$ amp, *answer*.

For the case of voltage regulators procede as follows.

a. Equivalent generator equals 35,000 kva.

b. Reactance to fault equals 24.3 per cent on 35,000 kva.

The above values are obtained from preceding solutions.

Interpolating from Table I, $i = 1.72$.

$I_{sustained} = 1.72 \times 130/100 = 2.23$
$= 2.23 \times 35{,}000/60\sqrt{3} = 752$ amp, *answer*.

References

1. STANDARD DECREMENT CURVES, W. C. Hahn and C. F. Wagner, A.I.E.E. TRANS., v. 52, 1933, p. 353–62.
2. N.E.L.A. Relay Handbook, 1926.
3. N.E.L.A. Relay Handbook and Supplement, 1931.
4. DECREMENT CURVES FOR SPECIFIC SYSTEMS, W. C. Hahn, ELEC. ENGG. (Abs.), v. 51, 1932, p. 131.
5. CALCULATION OF SHORT CIRCUITS ON POWER SYSTEMS, C. F. Wagner and S. H. Wright, ELEC. ENGG. (Abs.), v. 51, 1932, p. 131.
6. THE APPLICATION OF DECREMENT FACTORS IN SHORT-CIRCUIT STUDIES, W. R. Woodward, *Elec. Jl.*, v. 21, 1924, p. 213–6.
7. REACTANCE OF SYNCHRONOUS MACHINES, R. H. Park and B. L. Robertson. A.I.E.E. TRANS., v. 47, 1928, p. 514–35.
8. THREE-PHASE SHORT CIRCUIT OF SYNCHRONOUS MACHINES V, R. E. Doherty and C. A. Nickle. A.I.E.E. TRANS., v. 49, 1930, p. 700–14.
9. PROPOSED DEFINITIONS OF TERMS USED IN POWER SYSTEM STUDIES, report of subject committee on definitions (Sels). ELEC. ENGG., v. 52, 1932, p. 106–7.

Reactance and Stray Losses of Power Transformers

In this paper are discussed some of the problems of the transformer design engineer in regard to the effect of different winding arrangements, and some of the means employed to predetermine transformer reactance and to keep stray losses at a minimum. A reactance model has been developed to assist the transformer design engineer in checking reactance and stray loss calculations.

By H. L. COLE
MEMBER A.I.E.E.

Westinghouse Elec. and Mfg. Co., Sharon, Pa.

POWER TRANSFORMERS of the present day are required to meet many varied and complicated requirements as a result of which the transformer design engineer is faced with many difficult problems. This paper discusses some of these problems, dealing mainly with the reactance and stray losses of interleaved coil shell type transformers. A discussion is given of the accepted tolerances for transformer reactance and what these tolerances mean to the operator and the designer. Various methods of obtaining uniform reactances on transformer taps are described. The advantages of subdivided conductors in interleaved coil designs are shown. Stray losses in 3-winding transformers under certain load conditions present special problems in all designs.

A reactance model has been developed to analyze reactance formulas experimentally. It consists of power transformer core and coils constructed on a small scale so that various sizes of coils and core openings may be assembled and tested experimentally. It is to the design engineer what the calculating board is to the transmission engineer. The use of this model has enabled the design engineer to keep reactance and stray loss calculations and measurements in pace with other transformer developments.

REACTANCE

The inherent reactance of a power transformer usually is referred to, in practical terms, as "reactance drop." Defined by A.I.E.E. Standards (Rule 13–116) it is the voltage drop in quadrature with the current. The operating engineer is con-

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery. Manuscript submitted Oct. 25, 1933; released for publication Nov. 8, 1933. *Not published in pamphlet form.*

cerned mainly with the effect of transformer reactance on voltage regulation, its influence on the load division of transformers connected in parallel, and its effect in limiting short-circuit currents. The design engineer in working out the problems of meeting a specified reactance is concerned with the effect on the proportions of the design (*e. g.*, the ratio of copper, insulation, and iron) and the mechanical stresses within the windings under short-circuit conditions. Both operating and design engineers are concerned with the cost of obtaining a desired reactance, and its effect on the practicability of the design.

Several years ago a joint committee of National Electric Light Association and National Electric Manufacturers Association representatives formulated a rule for standard tolerances for transformer impedance (Rule TR6-28 N.E.M.A. Standards) a rule which from the standpoint of the power transformer engineer is virtually a reactance tolerance because of the negligible effect of resistance on the difference between reactance and impedance. The rule provides a tolerance of plus or minus 7.5 per cent for 2-winding transformers, and 10 per cent for auto-transformers or transformers with 3 or more windings. These tolerances were arrived at after a comparison of the calculated and tested reactances of practically all designs made for about 3 years preceding the formulation of the rule. They represent what the manufacturer can guarantee without materially increasing his costs (by virtue of having to make changes in design, after tests are made). The determination of reactance in a transformer design is not a precise calculation, because it involves reactance paths and magnetic fields difficult to calculate accurately. Slight variations in manufacture also will cause appreciable differences in reactance, so that it is necessary to have a tolerance factor for this feature of a design. Like most tolerance standards, the N.E.M.A. rule represents a compromise of 2 opposite interests: that of the user of the apparatus who requires adherence to a specified performance in order to plan and operate his system successfully; and that of the manufacturer who should not take undue risks in making guarantees that the development of the art indicates are unsafe or unreasonable.

It is obvious that in order to enhance his position in the industry the manufacturer will do everything within his power to build transformers that have as nearly as possible the specified reactances. The object of this paper is to discuss (1) some of the problems of the design engineer in regard to the effect of winding arrangement (particularly of shell type transformers) required for various types of designs, and (2) some of the means employed to predetermine the reactance and to keep the stray losses to a minimum.

In power transformers of the shell type the windings are interleaved with groups of coils forming what are known as 2 H-L, 4 H-L, or 6 H-L designs indicative of the number of spaces between high and low voltage windings across which leakage flux is set up under load conditions (see Fig. 1). In a simple 2-winding transformer without taps the turns are distributed evenly within the groups as shown in Fig. 1. In such transformers the calculation of reactance and stray losses is fairly simple. Reactance formulas have been developed, by both analytical and empirical methods, which give very satisfactory results. When the transformer has a large portion of winding tapped out, as in designs for tap changing under load, or furnace transformers the problem of reactance becomes more complicated. It is desirable to have the reactance on all taps approximately the same.

In analyzing an interleaved coil design for reactance calculations, the first step is to divide it into groups of ampere turns. A picture of the relative field intensity for the magnetomotive force produc-

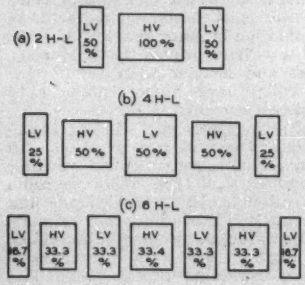


Fig. 1. Horizontal cross sections of interleaved coil shell type transformers without taps, showing simplest arrangements of coil groups

Figures represent per cent of total turns; H. V. and L. V. represent high and low voltage coils, respectively

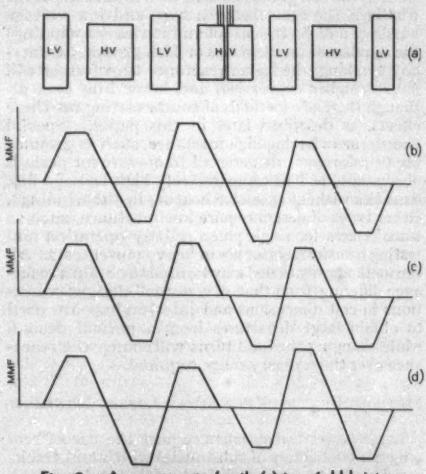


Fig. 2. Arrangement of coils (a) in a 6 H-L interleaved coil shell type transformer with 4 5-per cent taps in the high voltage winding, and magnetomotive force diagrams with (b) all taps in; (c) winding in normal position; (d) all taps out

The reactance is proportional to the sum of the squares of the magnetomotive forces across the H-L spaces; variation from mean reactance is less than 3 per cent of the normal reactance

ing leakage flux at various points along the axis of the windings may be obtained by plotting the total ampere turns against distance, or length of winding (see Fig. 2). Each group is analyzed separately, and the reactance voltage drops of all groups are added arithmetically to obtain the total drop. When a large portion of winding is tapped out in one group the reactance on different taps will vary approximately as the sum of the squares of the ampere turns at each H-L space, as shown in Fig. 2. In order to make the reactance as nearly as possible the same on all taps, it is desirable to place the taps in the center of one of the groups, or at the outside of the 2 end groups, where the leakage flux is at or nearly zero. In this location the idle coils do not contribute to the copper loss as they would if they were in a strong leakage field. Figure 2 shows an arrangement of a transformer with 6 H-L groups with the taps in the middle high voltage group, and Fig. 3 with the taps in the outside of the low voltage grounded end groups. In both these designs the variation in reactance on taps is small. For Fig. 2 the reactances on the extreme taps will not deviate more than 3 per cent (plus or minus) from the mean reactance.

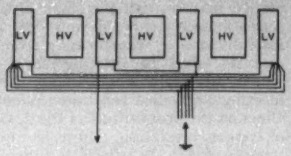


Fig. 3. Interleaved coil design of shell type transformer with taps in the grounded neutral of the low voltage winding

Taps are placed in the end groups to minimize the variation in reactance

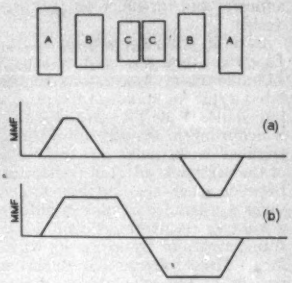


Fig. 4. Horizontal cross section of a 3-winding transformer with magnetomotive diagrams (a) when winding C is idle and (b) when winding B is idle

Under condition (b) the entire winding B is in a strong leakage field, and comparatively high stray losses are produced in it

Methods Used to Vary Reactance

The reactance of a transformer varies directly as the square of the number of turns; it also varies with a factor depending upon the physical dimensions of the coil group, the length of mean turn of the windings, the space between high and low voltage windings and (in the case of an interleaved winding) the number of interleavings or H-L groups. Generally speaking, the higher reactance transformer will have a higher copper loss and lower iron loss, although there are methods of compensating for these effects, as described later in this paper. Special transformers having high reactance, such as grounding transformers, are designed to operate for periods of a minute or 2 at comparatively high leakage flux densities without excessive heating in the windings. Other types of design require low reactance, such as transformers for single-phase railway operation and testing transformers for use in heavy power tests. All the methods mentioned may be used to obtain a reactance differing from that of a normal design; variations in coil dimensions and interleavings are used to obtain large departures from a normal design, while changing the total turns will change the reactance over the ordinary range required.

Methods Used to Keep Stray Losses Minimum

Large power transformers require the use of rectangular conductors of substantial width and thickness in order to obtain sufficient mechanical strength to handle the coil during manufacture and to support the winding against the heavy forces set up during short-circuit conditions. For the past 8 years the practice of subdividing conductors in interleaved shell type windings has been in general use and has contributed largely to the high efficiencies obtained in this type of design. (See "Subdivided Conductors in Shell-Type Transformers," by R. L. Brown, *Electrical Journal*, March 1933.) The stray losses in an interleaved design vary directly with the square of the width of the conductor. With the subdivided conductor it is possible to wind coils with 2 or more narrow conductors ($^1/_8$ to $^1/_4$ in. wide) side by side and obtain a coil that is fully as strong as the older type of coil (with conductors $^1/_4$ to $^1/_2$ in. wide) and even better mechanically from a manufacturing standpoint. Transpositions in the parallel conductors are made either physically near the center of the coil or by electrical connections at the coil ends, in order to place each conductor in a uniform leakage field and obtain full advantage of the subdivision of the winding.

Compared with the older type of single conductor winding, the subdivided winding with 2 half-width conductors side by side will reduce the total stray losses of the transformer 75 per cent. Practically it is more economical to use subdivided conductors of greater than $^1/_2$ the width of the former solid coils. This results in fewer coils, better space factor of winding, and a reduction in stray losses of 25 to 50 per cent. Actual tests have proved that such coils, which are thicker and heavier than the former single-conductor coils, have higher strength to withstand short-circuit currents.

The problem of stray losses in 3-winding transformer design requires careful consideration. In all 3-winding transformers, regardless of whether they are of the core or shell type, there are some conditions of operation in which the leakage flux set up by the operation of 2 windings as a primary and secondary will produce stray losses in the third, or idle winding. Figure 4 shows a simple arrangement of coils in a 3-winding transformer. The

sketch represents either a horizontal cross section of coils through the "window" of a shell type transformer, or a vertical section through the "window" of a core type transformer. When windings A and B, or B and C, are operated together, the third winding has little or no loss in it; but when A and C are operated as primary and secondary, the third winding (B) is entirely in a strong leakage field, and has comparatively high stray losses. This is particularly true if the windings all have the same or nearly the same kilovoltampere capacity. This coil arrangement in shell designs ordinarily is used only when A is a tertiary winding of not more than $^1/_3$ the capacity of the other windings; in this case the magnetomotive force shown in Fig. 4b is only $^1/_3$ as great and the stray losses in the middle winding (B) are not high. The use of subdivided conductors in this connection keeps the stray losses at a minimum.

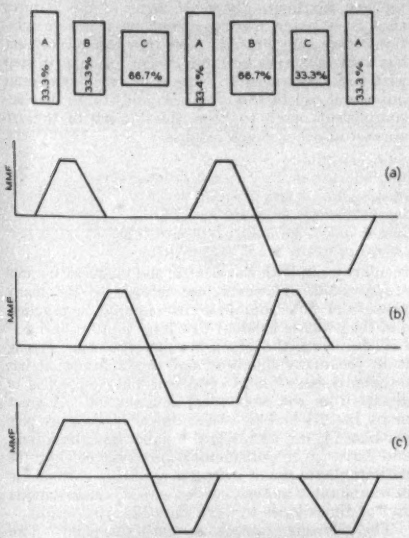


Fig. 5. Three-winding interleaved shell type transformer with equal reactances, and magnetomotive force diagrams for (a) winding C idle; (b) winding A idle; (c) winding B idle

Not more than $^1/_3$ of the idle winding is in a strong leakage field, in any case; hence stray losses are comparatively low

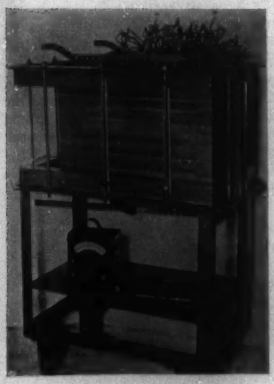


Fig. 6. Model of core and coils of a shell type transformer for predetermining transformer reactances

A method of equalizing stray losses in 3-winding, shell type transformers with windings of equal output is shown in Fig. 5. In this arrangement each pair of windings is located so as to provide a 3 H-L arrangement; and in no condition of operation is more than $^1/_3$ of the idle winding in a strong leakage field. This disposition of windings has been used many times not only to produce low stray losses but also to give substantially equal reactances A to B, A to C, and B to C.

Use of Reactance Model

Several years ago the idea was conceived of using a small scale working model of a transformer core and coils, to predetermine reactance. Figure 6 shows such a model of a shell type transformer. It is built with linear dimensions $^1/_5$ of those of a 20,000-kva transformer. Coils of scale dimensions approximating those of large transformers may be assembled quickly on the core of this model and the impedance and reactance measured. The core is made similar to the regular shell type magnetic circuit, except that at one end joints are butted instead of interleaved. With this arrangement the coils may be assembled without dismantling the core, and the length of the openings or "windows" of the core may be adjusted to any desired length. Steel structural parts are made in proportion to those in commercial designs so that data on stray losses under load conditions may be obtained. Coils of various widths and of various numbers of turns are employed to permit winding combinations having physical dimensions and constants corresponding to nearly all sizes and arrangements of shell type power transformer windings.

As an example of the usefulness of the reactance model, the winding for a 20,000-kva transformer on order was set up on the model core to check the reactance calculations. The transformer was required to operate in parallel with another unit having 7.13 per cent reactance on the normal voltage tap. When built, the new transformer tested 7.12 per cent by actual measurement (calculated to be 7.16 per cent by the use of the model); for the lowest voltage tap the transformer tested 7.63 per cent (calculated to be 7.66 per cent). Such results are within the errors of measurement. It is not expected that such close agreement always can be obtained, but this example is given to illustrate the effectiveness of the model.

The reactance model is to the transformer engineer in a large degree what the calculating board

is to the transmission engineer. Theoretical formulas for reactance and stray losses readily are checked and special reactance investigations quickly are made with the model. A transformer design with windings unsymmetrical with respect to number of turns, or coil dimensions, or both, may be investigated for reactance and stray losses before the transformer is built. Unusual dimensions of coil groups, which might otherwise involve some risk because of lack of test data to confirm theoretical formulas, readily are checked. The division of load currents in 3 or more paralleled windings, in a transformer in which all the windings are not exactly symmetrical, can be determined experimentally with the model in a fraction of the time required to make all the calculations that otherwise would be required. The model is very useful in the investigation of reactance constants and stray losses of 3-winding and autotransformers.

Power transformers of the present day are required to meet many complicated conditions. Surge-proof insulation, voltage, and phase-angle control by tap changing under load, double-secondary and 3-winding designs, autotransformers with tertiary windings—these are some of the features that have made reactance and stray loss calculations more complicated. The transformer engineer has kept reactance and loss design formulas in step with new requirements. The reactance model is an important aid in this progress, and its use has accomplished much to keep this branch of the art abreast of other developments.

Irregular Windings in Wound Rotor Induction Motors

The importance of using regular windings in polyphase wound rotor induction motors is stressed in this paper. Harmful effects upon the efficiency, power factor, breakdown torque, and noise of the motor may result with an irregular winding, due to differential leakage. The Goerges diagram of tooth fluxes is presented for studying this phenomenon. Means of avoiding trouble of this sort also are pointed out. It is further observed that 3-phase motors having a number of poles which is a multiple of 6 are most likely to be troublesome.

By
R. E. HELLMUND, FELLOW A.I.E.E. — Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
C. G. VEINOTT, ASSOCIATE A.I.E.E. — Westinghouse Elec. & Mfg. Co., Springfield, Mass.

It is generally appreciated that the most advantageous number of slots for induction motors is one that is divisible by the product of the number of poles and phases. With this arrangement, the windings can be distributed uniformly and regularly all around the circumference, and all undesirable irregularities in both the electric and magnetic circuits are avoided. However, on account of the many phase and pole combinations required in practice, and the expense incident to a large number of different dies and the stock-keeping problems arising from too many different slot combinations, it has frequently been found expedient and economical to depart from the most ideal combination. A great many motors in which the number of slots per pole per phase is not an integral number have been built and have given satisfactory performance, but the indiscriminate use of irregular windings, particularly in wound rotor motors, carries with it certain dangers and at times leads to very unsatisfactory results.

The following example illustrates this point. Two rotors were built for a one-horsepower 6-pole 3-phase wound-rotor induction motor having 36 stator slots, one rotor having 27 slots and the other having 24. The designs were in general very similar, but on test it was found that the 24-slot rotor gave a very much inferior performance; in fact, much more so than indicated by the regular routine calculations for the slight difference in rotor slots. Such calculations indicated approximately a 10 per cent difference in the breakdown torque, but it was found that the 27-slot rotor in reality developed a breakdown torque 42 per cent higher than that developed by the 24-slot rotor. A more careful analysis of the designs indicated that this great difference must have been due to the very much larger differential leakage in the 24-slot rotor which is caused by the irregularities in the secondary winding and for which allowance is not made in conventional leakage calculations.

Causes of Differential Leakage

As has been developed in several previous publications (see list at end of paper, particularly refer-

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery. Manuscript submitted Oct. 21, 1933; released for publication Dec. 2, 1933. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

ences 1, and 4–8) differential leakage exists whenever the winding distribution of the secondary member does not properly match the winding distribution of the primary member for any, or all, of the rotor positions. Whenever this is the case, it is not possible for the secondary tooth fluxes or magnetomotive forces to balance exactly at all points the primary tooth fluxes or magnetomotive forces even though a short-circuited secondary without resistance or reactance is assumed. In ordinary polyphase induction motors, the matching of the 2 members is obtained only when the stator and rotor have the same number of phases and the same coil throw and also when the rotor is in such a position that its phase belts line up exactly with the phase belts of the stator. As soon as the rotor is moved to any other position, differential leakage is obtained. Also in all cases where the number of phases or the coil throw of the rotor differs from the stator, differential leakage is present. This effect is the conventional "belt leakage" as it was first called by Adams,[1] and various means for allowing for it are given in literature.[5]

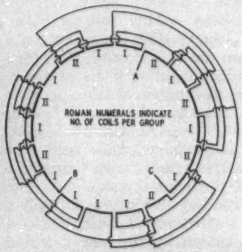
Considering that the fundamental nature of differential leakage is as indicated above, it is at once evident that if one member has a winding with a distribution irregular to a greater or lesser degree, even if the winding distribution of the other member is regular, the matching of the 2 windings will be imperfect to a greater or lesser degree and usually more so than in cases where both members have regular windings. It follows directly, then, that greater amounts of differential leakage effects are to be expected.

Importance of Differential Leakage

The practical importance of such conditions has already been indicated by the reference to the breakdown torque previously given, but some additional experimental data may be of interest. In further consideration of these data, it should be kept in mind that, while both rotor windings are irregular, they are irregular to a very much different degree. The 27-slot winding, with $1^1/_2$ slots per pole per phase, permits a layout giving absolutely balanced secondary voltages with proper 120-deg phase displacement. Such a layout can be obtained by the "least-common-multiple" method of tabulation due to Tingley.[9] On the other hand, the 24-slot winding cannot be made to give perfectly balanced secondary voltages. However, it is possible to lay out a winding to give approximately balanced voltages. Such a winding is shown in Fig. 1, and the voltages induced therein are indicated in Fig. 2. Expressed in terms of symmetrical components, and based upon a positive phase sequence voltage of 100 per cent, the negative phase sequence voltage is only 2.8 per cent and the zero phase sequence voltage is only 4 per cent. In spite of such small dissymmetry, it has been found that windings of this nature (12-pole 48-slot windings are equivalent and have been used extensively) when used in smaller squirrel-cage motors, have given generally satisfactory results. While a slight unbalance in the stator currents and certain damping currents in the rotor cause some additional losses, the efficiency is only slightly affected thereby. The damping currents of the rotor, on the other hand, largely eliminate irregularities in the fluxes, and consequently differential leakages, and their harmful effect on power factor and breakdown torque are largely avoided. This, however, is not the case when such an irregular winding is used in either the primary or the secondary in combination with another phase-wound member, even if that member has a regular winding, and as a result, unsatisfactory performance is obtained. Further comparative test data on the locked reactances obtained with the 2 rotors are given in Table I.

Table I—Test Data on Locked Reactances

Method of Measurement	27-Slot Rotor	24-Slot Rotor
1. A locked reading at 220 volts (normal voltage), 60 cycles, using total watts input and average amperes	5.95 ohms	7.4–7.7 ohms
2. A locked reading at 40 volts, measuring watts per phase and voltage to neutral		7.48–9.65 ohms
3. Calculated from observed breakdown torque (see reference 10) at 220 volts, 60 cycles	6.6 ohms	9.85 ohms
4. Locked readings at 200 volts, 300 cycles, measuring watts per phase and voltage to neutral	40–41 ohms	54.0–72.7 ohms



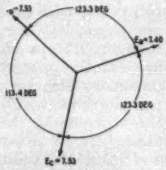


Fig. 1 (left). A 3-phase 6-pole 24-slot winding

Fig. 2 (right). Voltages induced in the 3-phase 6-pole 24-slot winding, shown in Fig. 1

Of the locked reactances, probably the most reliable are those calculated from the breakdown torque and these show the average reactance with the 24-slot rotor is 49 per cent higher than that with the 27-slot rotor. But even more enlightening are the curves shown in Fig. 3, which give the reactances of the individual stator phases for various rotor positions with both rotor windings. Briefly, these curves were taken as follows: The secondary was short-circuited and a balanced 3-phase 300-cycle electromotive force of 200 volts was impressed on the stator. Meters were inserted in the stator phases to measure phase volts, watts, and amperes. Readings were then taken every 10 mechanical degrees throughout a complete revolution of the rotor. This interval, which corresponds to a stator slot pitch,

was sufficiently small because it was found that on account of the rotors being skewed, the variation in zig-zag leakage through a slot pitch was negligible. The reactances thus obtained were proportioned down to equivalent 60-cycle reactances based upon the assumption that 6.6 ohms at 60 cycles is proportional to 40.5 ohms at 300 cycles. The following experimental facts shown by the curves in Fig. 3 should be carefully noted:

1. When the 24-slot rotor is used, the short-circuit reactance of each stator phase varies cyclically as the rotor is turned through a pole pitch. Moreover, this reactance is always larger than that with the 27-slot rotor, ranging, in fact, from 133 to 179 per cent of the average reactance obtained with the latter.

2. At no position of the rotor are the leakage reactances of all 3 phases equal to each other, but the reactance of each phase, as the rotor is revolved, goes through its own cycle which is displaced 60 electrical degrees from the reactance cycles of the other 2 phases.

3. Qualitatively, statement 2 holds for the 27-slot rotor as well as for the 24-slot rotor, but the variation is so small as to be of little practical significance and probably would not ordinarily be detected.

Two important differences between the belt leakage obtained with regular windings and the differential leakage evident in Fig. 3 are that, in the former cases, the leakage reactances of the stator phases are balanced at all times and the reactances of all the phases simultaneously vary cyclically throughout a phase belt. Neither of these conditions holds in our case.

From these figures it can be seen readily that the irregularity of the 24-slot winding introduces such a large amount of differential leakage as to seriously affect motor performance. In Fig. 4, comparative brake tests with the 2 different rotors are given. With the 27-slot rotor, the brake test was taken at 220 volts; with the 24-slot rotor, the brake test was taken at 253 volts, which was the voltage found necessary in order for the 24-slot rotor to develop the same breakdown torque as the 27-slot rotor. A slight advantage in efficiency, particularly at light loads, and a conspicuous advantage in power-factor at all loads, is noted for the 27-slot rotor.

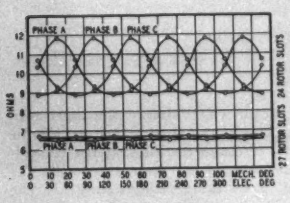


Fig. 3. Leakage reactance comparisons with the 27-slot and 24-slot windings, in various rotor positions

Moreover, noise measurements showed the 27-slot rotor to be 6 decibels quieter than the 24-slot rotor.

Methods of Analyzing Irregular Windings

In view of the great practical importance which differential leakage may assume in certain cases of irregular windings, the designer is, of course, interested in having at his disposal means for analyzing irregular windings so as to avoid those leading to unsatisfactory performance. Unfortunately, the correct quantitative analysis for this purpose would be very complicated. Certain diagrams developed by Goerges and a method given by Hellmund showing their application to the study of differential leakage offer useful tools in connection with a study such as the one given in this paper. (See references, particularly 4 and 5.)

Briefly stated, the Goerges diagrams are vector diagrams indicating the magnetomotive forces set up in the various teeth. In Fig. 5c is a Goerges diagram constructed for the stator winding and which may be used to illustrate the quickest method of constructing such a diagram. The stator winding was chorded one slot and therefore the currents and magnetomotive forces in the top and bottom coil sides in the various stator slots are as given in 5a. The magnetomotive force acting across the slot due to any coil side can be represented by one of the 3 unit vectors in 5b. Starting from any arbitrary point such as P in Fig. 5c, a vector is laid off to represent the total magnetomotive force acting across the slot. In the chosen case, for slot 1, this vector is twice the unit vector A in Fig. 5b. From the end of this vector, the magnetomotive force acting across the next slot, and so on, is laid off until the diagram closes upon itself. It can be readily shown that the vectors from the center of the figure to various points of the circumference represent the magnetomotive forces acting upon individual teeth.[2,7]

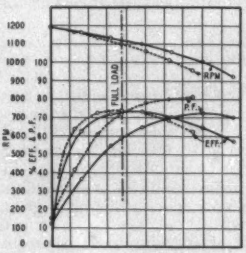


Fig. 4. Comparative brake tests with 27-slot and 24-slot rotors

Solid lines—24-slot rotor performance
Dotted lines—27-slot rotor performance

If the primary had been wound full pitch, instead of chorded, the Goerges diagram would have been the regular hexagon shown in heavy, solid lines in Fig. 6. If the secondary winding is also 3 phase, full pitch, with an integral number of slots per pole per phase, its Goerges diagram is likewise a regular hexagon. If, in addition, the secondary phase belts are exactly opposite the primary phase belts, the secondary diagram coincides exactly with that of the primary and there is no differential leakage. If, on the other hand, the secondary is shifted one-half a phase belt, its hexagon is shifted by a similar amount and takes the position shown by the heavy dotted lines in Fig. 6. The magnetomotive forces (radius vectors) for the individual points of the circumference are no longer alike in all cases, and as a consequence, differential leakage is obtained. The shaded areas

in Fig. 6 are an indication of the amount of differential leakage to be expected. It can be readily seen that the differential leakage for all relative positions of the primary and secondary would be avoided if both the primary and secondary diagrams were found to be a circle, a condition which, of course, can be obtained only with an infinite number of phases and slots in both members.

Goerges Diagrams Should Approach a Circle

While the actual amount of differential leakage is governed by the relation of the diagrams of the primary and secondary member to each other, as indicated by the shaded areas in Fig. 6, it is possible to obtain a fairly good idea of the merits of each of the individual windings with reference to differential leakage by comparing its diagram with a circle of about equivalent area. In general, it can be said

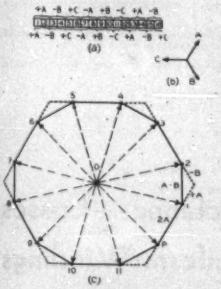


Fig. 5 (left). Diagrams for the stator winding, 36 slots, 6 poles, 3 phase, coil throw 1–6

a. Arrangement of coils in slots b. Unit vectors c. Goerges diagram

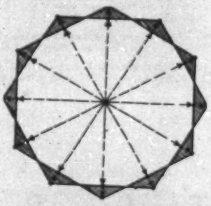
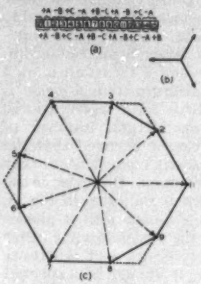


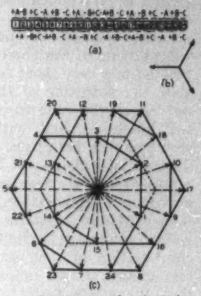
Fig. 6. Differential leakage fluxes with 2 full pitch 3-phase windings

that the more nearly the Goerges diagrams of the stator and rotor approach a circle, the less differential leakage there will be. Constructing the Goerges diagrams for the 27-slot and 24-slot rotors after the fashion of Fig. 5, we obtain the diagrams (full lines) given in Figs. 7 and 8. From these figures, it is at once evident that the results in the 2 cases should be very different. The diagram of Fig. 7, applying to the 27-slot combination, does not depart from the circle appreciably more than does the hexagon applying to a full-pitch 3-phase winding indicated by the dotted lines.

The extreme irregularity of the diagram in Fig. 8 applying to the 24-slot arrangement, however, indicates plainly why large differential fluxes are obtained. The reason why the leakage varies cyclically throughout a pole pitch is indicated also on Fig. 8. The diagram does not close after a single pair of poles has been traversed, but closes only after the entire 6 poles of the winding have been traversed. Consider any one position of the rotor and take note of all the rotor tooth fluxes with reference to some arbitrarily chosen tooth of the stator. Now let the rotor revolve slowly until a condition is obtained where the tooth fluxes of the rotor occupy exactly the same position with respect to the previously selected stator tooth. The failure of the Goerges diagram to close until the entire rotor winding is



a. Arrangement of coils in slots
b. Unit vectors
c. Goerges diagram



a. Arrangement of coils in slots
b. Unit vectors
c. Goerges diagram

Fig. 7 (left). Diagrams for the 27-slot rotor winding, 6 poles, 3 phase, coil throw 1–5

Fig. 8 (right). Diagrams for the 24-slot rotor winding, 6 poles, 3 phase, coil throw 1–5

traversed indicates that this condition will not be obtained until the rotor has turned through one complete revolution. As far as only the rotor winding itself is concerned, we might, therefore, expect the differential leakage to vary cyclically throughout a revolution; but when we consider that each pole of the stator winding is identical with every other pole, we see that, after the rotor has turned through one pole pitch, the rotor tooth fluxes occupy a position with respect to the stator tooth fluxes similar to the starting position and, therefore, the differential leakage should vary cyclically throughout a pole pitch as observed. If, however, the stator winding also had 24 slots and a diagram as given in Fig. 8, we would expect the differential leakage to vary cyclically throughout a revolution. A somewhat similar line of reasoning could be applied to the 27-slot rotor to show why its differential leakage also varies cyclically throughout a pole pitch; except that, in this case, no matter how irregular a winding distribution were used on the stator, the differential leakage cycle could not take more than a pair of pole pitches to complete itself because the Goerges diagram for the rotor closes after a pair of poles. It is also evident why the reactance cycles of the stator phases are displaced by one phase belt; suppose the rotor to be in a position to give maximum differential leakage in one of the rotor phases, the maximum differential leakage will not be obtained in the adjacent phase until the rotor has moved one phase belt. Thus the Goerges diagrams serve well

to explain the 3 experimental facts to which particular attention was drawn previously.

Goerges Diagrams Can Be Plotted Quickly

As previously mentioned, the actual computation of the differential leakage in the winding just discussed is very difficult and would consume far more time than the design engineer could profitably afford to spend for the purpose. On the other hand, the plotting of the Goerges diagram can be accomplished in a very short time, and if the result is such that the departure of the diagram from a circle is not much different from that for a conventional full pitch winding with an integral number of slots per pole per phase, it can be assumed that the differential leakage will be about equivalent to that obtained with the regular winding. However, if the departure is appreciable, such as indicated in Fig. 8, it is generally advisable in a motor with a phase-wound secondary to change the design to some other combination of slots and windings, and wherever this change is not possible, it should be expected that the motor performance may depart very appreciably from that indicated by ordinary methods of calculation.

Goerges Diagrams of Other Windings

A few words as to the type of Goerges diagram to be expected in other windings may be of interest. Windings irregular in distribution but balanced according to the "least-common-multiple" system of tabulation give a more regular diagram and less differential leakage than other irregular distributions in substantially the same number of slots. Previous mention was made as to the significance of the number of poles required to be traversed before closure of the diagram was obtained. It is desirable that the diagram close after a pair of poles and this condition will be obtained if the number of possible parallels of the winding is equal to the number of pairs of poles. In any "least-common-multiple winding," the number of pairs of poles required for closure of the Goerges diagram is given by the quotient

$$\frac{\text{pairs of poles}}{\text{highest common factor of (No. of slots) and (No. of pairs of poles)}}$$

It should be pointed out that particular heed should be given to those 3-phase windings for which the number of poles is a multiple of 6, as the number of slots into which a balanced winding can be used is very limited. For example, for a balanced 3-phase winding of 6, 12, 24, or 30 poles, the number of slots must be a multiple of 9 and for a balanced 3-phase winding of 18 or 36 poles, the number of slots must be a multiple of 27.

Conclusions

The principal point brought out in this paper is that certain windings with slight phase unbalance which have been used satisfactorily for years on polyphase squirrel-cage motors, may prove entirely unsatisfactory for wound rotor motors due to the unbalanced magnetomotive forces and consequent large amounts of differential leakage. The vector diagrams shown afford a simple means for studying the adequacy of a given winding.

References

1. The Leakage Reactance of Induction Motors, C. A. Adams. *Trans.* of The International Electrical Congress at St. Louis, v. 1, 1904, p. 706–24.

2. Die Berechnung der EMK von Mehrphasen- und Einphasen-Wicklungen auf Grund eines Vektordiagrammes der Feldstärke, Von H. Görges. *E. T. Z.*, 1907, p. 1–6.

3. Graphical Treatment of the Rotating Field, R. E. Hellmund. A.I.E.E. Jl., 1908, p. 927–48.

4. Belt-Leakage in Induction Motors, R. E. Hellmund. *Elec. Rev. and Western Electrician*, 1909, p. 32–5.

5. Die Differentialfelder in Drehfelde, R. E. Hellmund. *E. T. Z.*, 1909, p. 841.

6. Role des Champs Differentiels dans les Moteurs d'Induction; Influence du Pas d'Enroulement Racourci, R. E. Hellmund. *La Lumière Electrique*, October 1909, p. 21–4.

7. La Dispersion Differentielle dans les Machines d'Induction, M. Krondl. *Revue Generale de l'Electricite*, v. 23, 1928, p. 433–50 and 479–96.

8. Transformer Ratio and Differential Leakage of Distributed Windings, R. E. Hellmund and C. G. Veinott. A.I.E.E. Trans., v. 49, 1930, p. 1043–54.

9. Two-Phase and Three-Phase Lap Windings in Unequal Groups, E. M. Tingley. *Elec. Rev. and Western Electrician*, 1915, p. 166–8.

10. Performance Calculations on Induction Motors C. G. Veinott. A.I.E.E. Trans., v. 51, 1932, p. 743–54.

Transformer Reactance and Losses With Nonuniform Windings

A simplified method of calculating the reactance and eddy current losses of transformers with nonuniformly distributed windings is presented in this paper. The method has been in use for several years and has yielded highly satisfactory results.

By
H. O. STEPHENS
MEMBER A.I.E.E.

General Elec. Co., Pittsfield, Mass.

When the ampere turns of the 2 windings of a concentric transformer are distributed uniformly, the leakage flux due to the load current is virtually parallel to the axis (axial) and the reactance and eddy current losses may be calculated accurately by the conventional formulas for concentric windings. When there are large irregularities in the windings of concentric transformers occasioned by

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery. Manuscript submitted Aug. 30, 1933; released for publication Oct. 18, 1933. *Not published in pamphlet form.*

taps, extra end turn insulation, etc., the conventional formulas for concentric windings do not yield accurate results because the leakage flux is no longer parallel to the axis, but has substantial components of cross flux perpendicular to the axis (radial) depending upon the amount of the irregularities.

In this paper, the reactance and eddy current calculations have been resolved into 2 components, one depending upon the axial flux and one depending upon the radial flux; conventional formulas for concentric windings are used for the former, and conventional formulas for interleaved windings for the latter. This method has been in use for several years and has yielded very accurate results; it has greatly simplified and reduced the labor of calculating the reactance and eddy current losses of

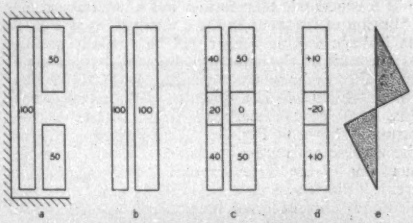


Fig. 1. Diagrams illustrating the calculation of reactance of a simple concentric transformer with taps out of the center of the outside winding

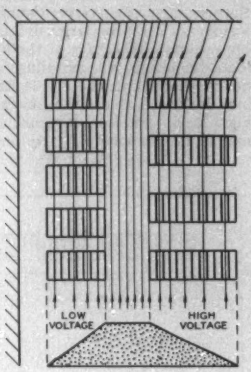
transformers with concentric windings with large irregularities in the windings.

Tap Connections Must Be Designed Properly

For many years it was the practice to specify transformer reactance and losses only on the full winding connections. If the transformer was provided with taps, the reactances on the tap connections seldom were calculated; and if the taps were for full capacity, the losses were considered only to the extent necessary to assure the designer that the transformer would meet its heating guarantee. If transformers are to operate in multiple, it is essential that the reactance on all tap connections involved in multiple operation be within the limits for satisfactory multiple operation; and even though the transformer meets its heating guarantee, it is important that the losses not be increased unduly on the tap connections.

Practical formulas have been available for many years for determining the reactance of transformers with concentric windings when the turns were distributed uniformly axially and also for balanced interleaved windings. If a large part of the windings of a concentric transformer be tapped out at the center, the turns will not be distributed uniformly axially along the 2 windings and the usual concentric reactance formula gives only a rough approximation of the reactance which is always too small a value. It is theoretically possible to calculate the reactance by dividing the windings into several co-axial cylinders and calculating each pair separately. At best this is a time consuming and tedious process. About 8 years ago the author suggested a method of eliminating this extra labor by resolving the reactance

Fig. 2. Section through a portion of windings of a conventional concentric coil transformer; diagram at bottom shows relative leakage flux densities



calculation of such unbalanced windings into operations involving only the simple concentric and interleaved reactance formulas familiar to all transformer designers.

The following simple case illustrates the method to be pursued. Figure 1a represents a section through a part of a simple concentric transformer with taps cut out of the center of the outside winding so that the idle space in the center of the outside winding is 20 per cent of its total length. The numbers in the rectangles represent the percentage of the total active winding in each section. The operations necessary for calculating the reactance are as follows:

1. Assume a uniform distribution of turns in the 2 windings as in Fig. 1b. If the over-all lengths of the coils are not the same, use the greater. Calculate the reactance on the basis of this uniform distribution by the conventional formula for concentric winding reactance.

2. Divide each winding into sections and indicate the actual percentage of active turns in each section as in Fig. 1c.

3. Opposite each section set down the difference in percentage turns between the 2 windings, marking this difference positive when the outside winding turns are greater and negative when the inside winding turns are greater, as in Fig. 1d.

4. Call the positive ampere turns primaries and the negative ampere turns secondaries, and calculate an interleaved reactance component from this set-up using the dimensions of the winding with unequally distributed turns and the conventional formula for the reactance of interleaved windings.

5. Multiply this interleaved reactance component by the ratio $\frac{\text{interleaved effective turns}}{\text{total effective turns}}$ in order to convert it into percentage of line voltage. Add this final value to the concentric reactance to obtain the total effective reactance of the transformer.

The same method can be used for much more complicated irregularities such as windings of unequal lengths, taps in more than one place, thinning out of

turns due to extra insulation at the line ends, and inequalities in both stacks. A very useful application of this method is in calculating the reactance between either of 2 interleaved windings and a third concentric winding.

In Fig. 2 is shown a section through a portion of the windings of a conventional concentric coil transformer as used for large units. The lines show the approximate direction of the leakage flux due to the load current in the windings and the flux diagram below shows the relative leakage flux densities. It may be noted that the leakage flux cuts these windings in a direction approximately parallel to the major, dimensions of the conductors. Since the eddy current losses in a conductor vary as the square of its dimension perpendicular to the cutting flux, it may be seen that the concentric transformer possesses an important inherent advantage when wound with strands having their greater dimensions axially. Where currents are large, the conductor must consist of several strands in multiple, in which case it is essential that the conductors be so transposed that each will have the proper reactance to carry its share of the load.

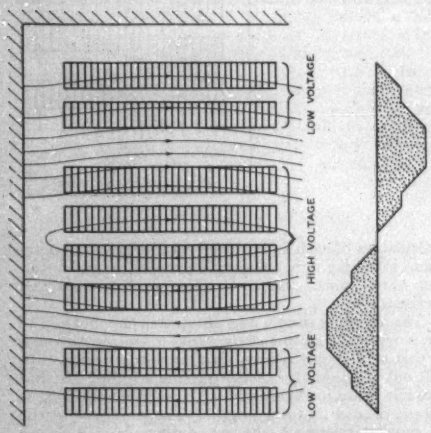


Fig. 3. Section through a portion of windings of a conventional interleaved coil transformer; diagram at right shows relative leakage flux densities

Figure 3 shows a section through a portion of the windings of an interleaved transformer; the lines shows the approximate direction of the leakage flux due to the load current, and the flux diagram shows the relative leakage flux densities. It may be noted that the leakage flux cuts the conductor in a direction perpendicular to the major dimensions of the conductor. This inherent disadvantage is an important handicap in designing very large interleaved transformers because the eddy current losses in those conductors adjacent to the main leakage gap between the 2 windings where the flux density is highest will be very high unless the conductors are made very narrow or laminated and transposed—a distinct disadvantage from a mechanical standpoint.

If a concentric transformer has a nonuniform distribution of its turns in the 2 windings as in Fig. 1a its leakage flux no longer will be virtually parallel to the axis of the windings, but will have a small cross flux component depending upon the irregularity. Figure 1e is a diagram of the relative cross flux densities as determined from the unbalanced turns as shown in Fig. 1d. This cross flux will cut the conductors perpendicular to the maximum dimensions of the strands; and if the unbalance is great, it may cause in addition to increased reactance high eddy current losses, particularly near the tapped out portion where the cross flux densities are greatest. The method used in calculating the reactance due to unbalanced turns is also very useful in calculating cross flux eddy current losses. Exactly the same method of calculation is used as in interleaved transformers familiar to transformer designers, but using the cross flux diagrams as in Fig. 1e.

A study of the diagrams resulting from irregularities in the windings of a transformer will show how it is possible to reduce the cross flux reactance and eddy current losses due to taps. Figure 4a represents a transformer with 20 per cent of the outside winding tapped out, and is a repetition of the diagram in

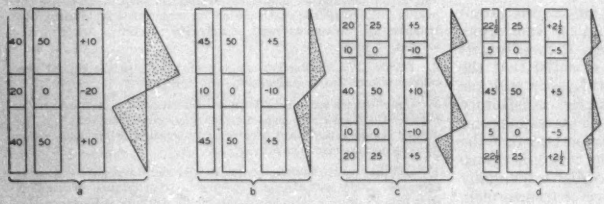


Fig. 4. Diagrams showing how the cross flux reactance and eddy current losses resulting from taps can be reduced by thinning out the turns opposite the tap irregularities

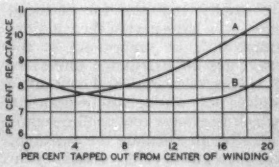


Fig. 5. Reactance of a transformer with 4 5-per cent taps cut from the center of one of the windings (A) compared with (B) that of the same transformer with proper thinning of turns

Fig. 1. If the turns of the inside winding are thinned out to half the density in that portion of the winding opposite the tap break, and if the turns so thinned out are crowded into the remainder of the winding, the diagrams in Fig. 4b show the result. This device results in about $^1/_4$ the maximum cross flux reactance and eddy current losses.

If instead of taking all of the taps from the center of the winding they are distributed at two points along the winding as in Fig. 4c, again the cross flux reactance and eddy current losses will be reduced to about $^1/_4$ of that resulting from the turn distribution in Fig. 4a. Now if the turns in that part of the winding opposite the 2 tapped out portions be thinned out, the cross flux reactance and eddy current losses will be reduced still further as shown by the diagrams in Fig. 4d.

The curves in Fig. 5 show the reactance of a transformer with 4 5-per cent taps cut from the center of one of the windings, compared with the same transformer with proper thinning of the turns of the winding opposite the tap irregularities.

This method has been in use for several years and has greatly simplified and improved the accuracy of the reactance and eddy current loss calculation of concentric winding transformers with irregularities in the windings. It also has been very helpful in indicating to the designer conditions of design that might result in high localized losses, and in enabling him to avoid such conditions.

Modern Transportation's Most Recent Contribution to Speed and Safety

THIS new transport plane, reported to be the fastest multimotor passenger carrier ever built, is made possible by modern engineering developments, among the most important of these being many of the recent developments in the electrical field. Electrical devices contribute much to the safety and comfort of flying. A fleet of 41 of these Douglas airliners are being placed in service on the lines of Transcontinental and Western Air, Inc.; these planes have a speed of 210 miles per hour at 8,000 ft altitude, and a landing speed of less than 60 miles per hour. Tests have proved that with only one of the 2 motors in operation the plane can take off, fly to an altitude of 9,000 ft and maintain a speed of almost 120 miles an hour. These planes incorporate, in addition to the many features noted on the diagram, Sperry hydraulic-pneumatic pilots for automatic flying. The automatic pilots keep the plane on a level and straight course in any kind of weather and leave the pilot free for other operations. Guests of the Institute's recent winter convention were afforded the opportunity of riding in 12-passenger planes of this same line, almost as modern as the one illustrated here.

News
Of Institute and Related Activities

Winter Convention Marked by Good Attendance

THE official registration of the Institute's 1934 winter convention recently held in New York, N. Y., Jan. 23–26, totaled 1,227 persons. This attendance was particularly gratifying to all who had worked to make the convention a success, as it is an appreciable increase over last year's registration. Also, there was a notable increase in out-of-town attendance. This, and other information, is revealed by a study of Tables I and II. The nominal registration fee charged all nonmembers except enrolled students and wives and children of members, and applied this year for the first time in recent winter conventions, apparently did not act to hold down the registration. Several innovations were introduced into this year's convention, as may be noted in the following paragraphs.

Table I—Registration at Recent Winter Conventions

1934	1,227	1928	1,475
1933	1,099	1927	1,317
1932	1,429	1926	1,423
1931	1,589	1925	1,445
1930	1,607	1924	1,738
1929	1,375	1923	1,200

Table II—Registration for 1933 and 1934 Winter Conventions

District	1933	1934
New York City and Foreign (3)	791	812
North Eastern (1)	130	179
Middle Eastern (2)	132	161
Great Lakes (5)	23	40
Canada (10)	14	16
South West (7)	2	11
Southern (4)	4	5
North Central (6)	2	2
Pacific (8)	0	1
North Western (9)	1	0
Total	1,099	1,227

Opening Session Included Presentation of Sprague Bust

The convention was opened on Tuesday, January 23, at 10 a.m., C. R. Jones, chairman of the winter convention committee presiding. Immediately following Mr. Jones's opening, J. B. Whitehead, president of the Institute, presented his message in which he stated that he considered the Institute's annual winter convention to be one of the most pleasurable of the Institute's activities. Continuing, he made an appeal for loyalty to the Institute by its members. President Whitehead then introduced Frank Hedley, president of the Interborough Rapid Transit Company, New York, N. Y., who delivered the presentation speech in connection with the gift to the Institute of a bust of Frank J. Sprague which was included as part of the convention's opening session.

Mr. Hedley, after commenting upon the three-quarter relief portrait bust of Doctor Sprague, whom he termed "The Father of Rapid Transit," introduced the sculptress, Florence M. Darnault, and congratulated her upon her artistic achievement in executing the Sprague portrait bust. Mr. Hedley then continued with a tribute to Doctor Sprague which was followed by the acceptance of the bust by President Whitehead. Appropriate remarks then were made by Doctor Sprague, which, together with Mr. Hedley's tribute, are reported in greater detail on succeeding pages of this issue. (A biographical sketch of Doctor Sprague is given in ELECTRICAL ENGINEERING for February 1932, p. 139–40, in connection with the award to him of honorary membership in the Institute.)

As the concluding event of the opening session, R. N. Conwell, chairman of the technical program committee announced the procedure for the technical sessions which were to follow.

Technical Sessions

The 10 technical sessions which were held during the winter convention are not included in this news report, as all of the technical papers which were discussed have already appeared in full in the issues of ELECTRICAL ENGINEERING for August, November, and December 1933, and January 1934. Discussions of these papers presented at the winter convention are scheduled for inclusion in future issues of ELECTRICAL ENGINEERING.

Judging from comments overheard during the convention the newly adopted practice of publishing all papers in ELECTRICAL ENGINEERING in advance of the meeting, thereby making unnecessary the distribution of pamphlet copies, met with widespread favor and added considerably to the value of the discussions of these papers during the convention sessions.

Education Session Held

In addition to the technical sessions of the convention, a session on education was held on Wednesday morning, as an open meeting of the committee on education and the committee on Student Branches. Both of these committees are under the chairmanship of L. A. Doggett, who presided at this session. Mr. Doggett presented a brief abstract of the current activities of these 2 committees. Following this a paper on "The University of Pittsburgh-Westinghouse Graduate Program" was presented by H. E. Dyche and R. E. Hellmund, following which J. W. Barker reviewed the activities of the Engineers' Council for Professional Development. Among the various points brought out in the discussion which followed was the suggestion that the committee work out some means whereby information of particular interest to students be brought to their attention regularly.

Women's Entertainment

The luncheon and bridge at the Engineering Women's Club, which has become a feature of the entertainment for women attending recent winter conventions was held this year on Wednesday, January 24, with about 40 present. In addition to the regular convention activities, including the dinner-dance at the Waldorf-Astoria, which are of particular interest to women, a trip exclusively for them was arranged to the Radio City broadcasting studios on Friday, January 26, where Walter Damrosch was broadcasting. About 60 women attended this trip. Mrs. H. R. Woodrow was chairman of the women's committee being assisted by Mrs. T. F. Barton, Mrs. C. R. Beardsley, Mrs. C. O. Bickelhaupt, Mrs. R. N. Conwell, Mrs. A. F. Dixon, Mrs. C. R. Jones, Mrs. E. B. Meyer, and Mrs. D. M. Simmons.

Buffet Dinner and Smoker

About 550 persons attended the annual smoker held on Tuesday, January 23. This attendance taxed to the limit the facilities for serving the excellent buffet dinner which the committee had arranged. Moving pictures were available in the auditorium during the latter part of the dinner period. Following the moving pictures a show was presented in the auditorium which brought forth many comments on the entertainment value and the mysteries of the performances.

R. A. McClenahen was the chairman of the smoker committee, assisted by E. S. Banghart, G. D. Edwards, W. H Farlinger, J. E. Goodale, H. C. Schlaijker, F. H. Stoppelman, E. E. Thrall, H. G. Wood, and J. E. McCormack.

Dinner-Dance and Buffet Supper Arranged

The combined dinner-dance and buffet supper was arranged for Thursday night, this combined event being held at the Waldorf-Astoria Hotel. Approximately 167 persons attended the dinner and dance, while approximately 168 took advantage of the opportunity of coming only for the dancing and the buffet supper served at midnight. About 129 attended both the dinner-dance and the buffet supper-dance, bringing the total attendance to 464. Preceding the dinner, a reception in honor of President Whitehead was held in the Basildon Room of the Waldorf-Astoria.

The flexibility of the plan arranged for this year proved attractive to many who otherwise would not have attended. The committee responsible for this successful affair consisted of George Sutherland, chairman, assisted by P. L. Alger, John Bassett, C. A. Butcher, C. M. Gilt, H. L. Huber, J. F. Kelly, R. F. Penman, C. S. Purnell, S. S. Reynolds, H. R. Searing, T. E. Shea, and D. M. Simmons.

Inspection Trips Concentrated on Friday

Another plan which differed from that of preceding winter conventions was the arranging of all regular inspection trips for the same day. Friday, January 26, was reserved for inspection trips at this convention, no technical sessions being held on that date. The visit to the studios of the National Broadcasting Company in the R.C.A. Building, attended by 107 persons, proved to be the most attractive. The trip which included the Hudson Avenue generating station, Brooklyn Edison Company's cafeteria, city subway rectifier substation, and Kings Brewery, attended by 56 persons, was next in order. Tied for third place were the trips to the Newark airport including a flight, and the trip to Electrical Research Products, Inc., where educational pictures were shown. Each of these 2 trips drew 37 registrants, while the motor bus trip through northern New Jersey where 3 radio stations were inspected was next in order with 34 registrants. The Roseland switching station of the Public Service Electric and Gas Company of New Jersey attracted 18 visitors, while smaller groups went to each of the other 6 prearranged trips. All together, 363 persons were registered for trips.

The inspection trips committee consisted of H. C. Otten, chairman, assisted by G. F. Fowler, Henry Kurz, S. A. Smith, Jr., H. B. Stoddard, E. R. Thomas, R. H. Twiss, and R. L. Webb.

Directors and Committees Meet

The meeting of the Institute's board of directors held on Monday, January 22, is reported elsewhere in the news section of this issue. Many committee meetings also were held during the convention; these were meetings of the committees on standards, power generation, communication, research, electrochemistry and electrometallurgy, transportation, power transmission and distribution, general power applications, technical program, automatic stations, protective devices, production and application of light, electrical machinery, and Sections. There also was a meeting of the sectional committee on electrical definitions, and an open meeting of the committees on education and student branches.

In charge of arrangements for the 1934 winter convention were the general committee and the convention executive committee. The general convention committee consisted of C. R. Jones, chairman, assisted by T. F. Barton, C. R. Beardsley, C. O. Bickelhaupt, R. N. Conwell, A. F. Dixon, E. B. Meyer, H. S. Osborne, and D. M. Simmons. The convention executive committee consisted of C. R. Beardsley, chairman, assisted by R. A. McClenahen, H. C. Otten, George Sutherland, and Mrs. H. R. Woodrow.

Principal Addresses Given in Connection With Frank J. Sprague Presentation

A BRONZE portrait bust of Frank J. Sprague (A'87, F'12, HM'32, and past-president) was presented to the A.I.E.E. as the outstanding feature of the opening session on January 23, of the Institute's recent winter convention held in New York, N. Y. The presentation was made by Frank Hedley, president of the Interborough Rapid Transit Company, on behalf of the Frank J. Sprague anniversary committee. The portrait bust was executed by Miss Florence Darnault.

The procedure followed at this presentation ceremony is outlined elsewhere in this issue as part of the general news report on the winter convention. Following is that part of the presentation speech made by Frank Hedley, president of the Interborough Rapid Transit Company, which applied to Mr. Sprague; following this Mr. Sprague's remarks are given.

Mr. Hedley's Tribute to Doctor Sprague

"Frank Julian Sprague, scientist, inventor, and engineer, and rightfully termed "father of electric traction," was born in Milford, Conn., on July 25, 1857. He attended the United States Naval Academy from 1874 to 1878. He represented the United States Navy at the Crystal Palace Exhibition in London in 1882. He resigned as ensign of the United States Navy in 1883. He became assistant to Thomas Edison with whom he was associated for one year. He then formed the Sprague Electric Railway and Motor Company. This was in 1884. That company received the contract for the Richmond, Va., Railways in 1887, followed by 110 other railways before merging with the Edison General Electric in 1890.

"In 1892 the Sprague Electric Elevator Company was formed for the development and promotion of electric elevators. The first battery was installed in the Postal Telegraph building in 1893. In 1895 he invented the "multiple-unit" system and placed his first installation on the South Side Elevated Railway in Chicago in 1897. In 1897 the Sprague Electric Company was formed and in 1902 this Company was absorbed by the General Electric Company.

"Mr. Sprague was a member of the commission for the electrification of Grand Central Terminal which lasted from 1903 to 1908. During that time, namely in 1906, he developed the automatic train control and organized the Sprague Safety Control and Signal Corporation. In 1927 he developed the dual elevator system and in 1929 new forms of electric signs.

Mr. Sprague has been awarded: The Gold Medal, Paris Electrical Exhibition, 1889; Elliot Cresson Medal, Franklin Institute, 1904; Grand Prize, St. Louis Exhibition, 1905; Edison Medal, A.I.E.E., 1910; and the Franklin Medal, Franklin Institute, 1921. He has received the honorary degrees of: doctor of engineering from Stevens Institute of Technology; doctor of science from Columbia University; and doctor of laws from the University of Pennsylvania. He is also an honorary member of: The A.I.E.E., 1932; Franklin Institute; and the Engineers' Club. He is past-president of: The A.I.E.E.; New York Electrical Society; American Institute of Consulting Engineers; and the Inventors Guild. During the late war he was a member of the United States Naval Consulting Board.

"As to his accomplishments, we who are engaged in transportation, properly take a particular pride in Mr. Sprague because of the major contributions which he has made to transportation. He, more than any other man, must be regarded as having brought electric transportation into practical being. He installed in Richmond, Virginia, in 1887 the first electric railway system of any size in the world. This is the parent of all modern trolley lines.

"The invention of the multiple-unit system of train operation a few years later marked the opening of another new epoch in transportation and an important one in that it permitted the make-up of a train of any length with all the characteristics of a single car. This system of combining a group of individual cars, each complete in all respects, and providing for operating all controllers simultaneously through a train line from a master switch on any car, offers the only possible method by which the exacting conditions, particularly of rapid transit in congested territory, may be met. Therefore, I say that in addition to being called the "father of the trolley line," Frank Sprague should be called also the "father of rapid transit."

"If I were called upon to name the most powerful influence contributed by Frank Sprague to the railway industry, I think I should say it was his pioneering vision, supplemented by his fighting spirit. His vision

has been translated into accomplishment to such an extent that transportation, while considered by us a dynamic industry, has become very commonplace in the public mind. The passenger is seldom conscious of the almost miraculous devices employed in carrying him back and forth through the city and country, under rivers and over mountains, with a remarkable degree of safety and comfort. It is only on occasions such as this that an opportunity is afforded to remind people of what is going on around them that is so necessary to their daily lives and to which they naturally give no thought.

"The traveling public using our rapid transit lines here in New York City, with which most of you are familiar, owe, and always will owe, a tremendous debt to Frank Sprague for his remarkable inventive genius, which has given them a type of service which never could have been rendered without the use of his ingenious devices; and, of course, this is equally true with respect to rapid transit travelers wherever such facilities exist throughout the world.

"In closing, I give you the following quotation written by the editor of one of our leading technical magazines: 'Inventors there have been whose talents lay so wholly in invention and so little in life, that they lacked either the driving force to get their ideas before the public, or the ability to make friends or at least believers who would attend to such details for them. But once in a while there appears a man whose grasp on business affairs is equal to his superlative inventive ability—an inventor, a fighter, a pusher—one who is not content to produce what is new and better, but who will fight to the last gasp and the last penny to force an uninterested and reluctant world to adopt what he has to give. Such a man is Frank J. Sprague, who more than any other one man must be recognized as having brought electric transportation into being.' "

Remarks of Doctor Sprague

Following acceptance of the bronze portrait bust of Doctor Sprague by President Whitehead, Doctor Sprague remarked as follows:

"It is a curious coincidence that this year of 1934 marks not only the end of a half century since the holding of the first Electrical Exhibition at Philadelphia and the founding of the American Institute of Electrical Engineers, but it is also the Jubilee of my independent entrance into the electric power field, although while a cadet midshipman I had for some years been concerned with electrical matters.

"A kindly Providence has, in spite of the steady march of the calendar, permitted me the privilege of witnessing, and also contributing something to, the development of the modern electric age, which, while largely based upon the experiments and discoveries of Faraday and Henry, received its major impulse, both in this country and abroad, on the installation of the first general electrical supply station in 1882 under the courageous leadership and responsibility of Mr. Edison.

"Although briefly associated with him as a mathematical and technical assistant in central station work, I continued strongly imbued with the conviction that the use of electricity for industrial power and traction would play a major part in its function as a universal servant. An early resignation has been followed during many more or less controversial years in fostering that belief by practical work, and a year and a half ago, when I finished my three-quarter century stretch, many colleagues, and friends were good enough to note that event here in a unique birthday party, attended by many evidences of highly prized character.

"Now, under the auspices of the same committee, and with the coöperation of Miss Darnault, the sculptor, whose talent and patience in handling a somewhat difficult subject I deeply appreciate, a portrait bust has been tendered the Institute as a token of recognition of work in specific fields. In accepting this, Dr. Whitehead, you and the great society over which you now preside, and which it has been my privilege to serve, have done me signal honor in giving it a home among its immortals.

"I find difficulty in expressing my appreciation in being thus transposed from the record of the printed page and the photograph into a metallic replica exposed to present and future critics, but I would not be human if I, and those who are my kin did not feel a deep inward satisfaction.

"May I also record a debt of indirect association with a great university? Under the leadership of Henry Rowland, John Hopkins established preëminence in the scientific world. Incidentally, he made the first report on my embrionic railway developments. His successors, Doctor Duncan and Doctor Hutchinson, became my associates and cooperated in building the first large electric locomotive. Now you, Doctor Whitehead, who as dean of the engineering councils, have for many years happily carried the burden of maintaining the Rowland standard, have again placed me under a happy obligation.

"As I look back over an active past I often ask myself what has been the guiding impulse, and what is the heritage I most wish to leave. As to the first, there has been an impelling urge for creation, in which I have tried to be guided by the rigid tenets of a naval training and the high ethical standards of our beloved profession; and second, that as it is better to give than to receive, to help rather than hinder, and to do rather than hesitate, it is one's highest privilege and most lasting satisfaction to contribute in some effective fashion to the general good of humanity. May I venture the hope that, as evidenced by the generous remarks of Doctor Whitehead and Mr. Hedley, such will remain the verdict of electrical history.

"It has never been my good fortune to devote myself to the joys of pure research, of the kind that crowns the work of many brilliant and devoted scientists, but rather to combine invention and work for current needs. But whatever the sources of endeavor the marriage of ideal conception and discovery with practical application is essential to insure progress in our work-a-day civilization.

"As to the future, I will not venture into prophecies additional to those I have often made. On the one hand the astronomer and mathematician, with the aid of the physicist, seeks solution of the beginning, extent and future of an incredibly vast celestial universe, and on the other, the masters of science, largely with the aid of electrical equipment, strive to break through the infinitesimal but mighty barriers which protect the structure of the atom, and even to seek the source of life itself. Whatever, and however interesting, the results, I question the optimistic predictions of unlimited and economic sources of power from the breakdown of the atom's structure.

"What to me is of present transcendent

Portrait bust of Frank J. Sprague presented to the Institute on behalf of the Frank J. Sprague anniversary committee by Frank Hedley (right) during the opening session of the recent winter convention. Dr. Sprague (left) in his remarks following the presentation expressed his great appreciation of this tribute

importance is to make the fullest use of what we have at hand. Naturally, I look to a greatly enlarged use of electricity in the railroad field, partly with the help of the Government funds, as some time ago I urged as a fully warranted activity in the current public works program.

"Time does not permit me to discuss the many new projects, here and abroad, but I would refer to the recent reports of the British Commission, the provision for extension of the electrification of the Pennsylvania Railroad, and the ambitious proposal by Mr. McDonald detailed at the last meeting of our sister-society, that of the Civil Engineers.

"While I again express my heartfelt thanks to the Institute, to Miss Darnault and to the committee, may I register the universal feeling of relief on the recovering from a serious illness, of our former president, Dr. Gano Dunn, and also express the great grief with which old friends and associates have learned of the recent sudden death of Mr. William B. Potter, a gifted and active pioneer and upbuilder in the electric railway field."

Future AIEE Meetings

North Eastern District meeting,
Worcester, Mass., May 16–18, 1934

Summer convention,
Hot Springs, Va., June 25–29, 1934

Pacific Coast convention,
Salt Lake City, Utah, Sept., 1934

Edison Medal for 1933 Presented to Doctor Kennelly

WITH ceremony simple but fitting to the occasion, the Edison Medal, highest award of the A.I.E.E., for 1933 was presented to Dr. Arthur Edwin Kennelly for "meritorious achievements in electrical science, electrical engineering, and the electrical arts as exemplified by his contributions to the theory of electrical transmission and to the development of international electrical standards." Doctor Kennelly is professor emeritus of electrical engineering, Harvard University and Massachusetts Institute of Technology; he is an honorary member and past-president of the A.I.E.E. Doctor J. B. Whitehead, president of the A.I.E.E., presented the medal, together with a certificate bearing the foregoing citation, at a special session of the Institute's recent winter convention, held during the evening of January 24, 1934. After brief introductory remarks, President Whitehead called upon Mr. C. E. Stephens, chairman of the Edison Medal committee, to outline briefly the history of the medal; Mr. Stephens' remarks follow.

History of Edison Medal Outlined by C. E. Stephens

"The Edison Medal was founded 20 years ago (February 11, 1904) by an organization of associates and friends of Thomas A. Edison who desired to commemorate the achievements of a quarter of a century in the art of electric lighting with which Edison had been so prominently identified.

"It was decided that the most effective means of accomplishing this object was by the establishment of a gold medal which could serve 'as an honorable incentive to scientists, engineers, and artisans to maintain by their works the high standard of accomplishment' which had been set by Edison. The American Institute of Electrical Engineers was invited to undertake the responsibility of making the awards. The Institute accepted, and organized the Edison Medal committee, or board of award, composed of 24 members.

"Three of these members are appointed each year by the president of the Institute to serve for a term of 5 years each; 3 are elected each year by the Board of Directors from its own membership to serve for a term of 2 years each; the other 3 members are *ex-officio*—the president, the national treasurer, and the national secretary of the Institute.

"The by-laws of the committee provide for making one award each year, and the deed of gift specifies that the award shall be made to some one resident in the United States or Canada, for meritorious achievement in electrical science, electrical engineering, or the electrical arts.

"The medal was designed by James Earle Fraser, and carries on the obverse the portrait of Thomas A. Edison and on the reverse an allegorical conception of the genius of electricity crowned by fame.

"Previous awards have been made as follows:

1909 ELIHU THOMSON. For meritorious achievement in electrical science, engineering and arts, as exemplified in his contributions thereto during the past 30 years.

1910 FRANK J. SPRAGUE. For meritorious achievement in electrical science, engineering and arts, as exemplified in his contributions thereto.

1911 GEORGE WESTINGHOUSE. For meritorious achievement in connection with the development of the alternating-current system for light and power.

1912 WILLIAM STANLEY. For meritorious achievement in invention and development of alternating-current systems and apparatus.

1913 CHARLES F. BRUSH. For meritorious achievement in the invention and development of the series arc lighting system.

1914 ALEXANDER GRAHAM BELL. For meritorious achievement in the invention of the telephone.

1916 NIKOLA TESLA. For meritorious achievement in his early original work in polyphase and high-frequency electrical currents.

1917 JOHN J. CARTY. For his work in the science and art of telephone engineering.

1918 BENJAMIN G. LAMME. For invention and development of electrical machinery.

1919 W. L. R. EMMET. For inventions and developments of electrical apparatus and prime movers.

1920 MICHAEL I. PUPIN. For his work in mathematical physics and its application to the electrical transmission of intelligence.

1921 CUMMINGS C. CHESNEY. For early developments in alternating-current transmission.

1922 ROBERT ANDREWS MILLIKAN. For his experimental work in electrical science.

1923 JOHN W. LIEB. For the development and operation of electric central stations for illumination and power.

1924 JOHN W. HOWELL. For his contributions toward the development of the incandescent lamp.

1925 HARRIS J. RYAN. For his contributions to the science and the art of high-tension transmission of power.

1927 WILLIAM D. COOLIDGE. For his contributions to the incandescent electric lighting and the X ray arts.

1928 FRANK B. JEWETT. For his contributions to the art of electrical communication.

1929 CHARLES F. SCOTT. For his contributions to the science and art of polyphase transmission of electrical energy.

1930 FRANK CONRAD. For his contributions to radio broadcasting and short wave radio transmission.

1931 E. W. RICE, JR. For his contributions to the development of electrical systems and apparatus and his encouragement of scientific research in industry.

1932 BANCROFT GHERARDI. For his contributions to the art of telephone engineering and the development of electrical communication.

"I read these names with reverence; the achievements of the recipients are as varied as the personalities of the men themselves. Their names stand for progress in generation of electric power, in its transmission, in its utilization and in its use for transmission of intelligence—in fact, these names have figured prominently in every development of the use of electricity which has made our lives more livable. And tonight we are gathered here to add to that great honor roll the name of Dr. Arthur E. Kennelly."

Kennelly Career Outlined by Dr. Clayton H. Sharp

Following Mr. Stephens' brief history of the Edison Medal Dr. Sharp, longtime member of the Institute (A'02, F'12) outlined Dr. Kennelly's career:

"The body of science and technology on which electrical engineering is based is the work of many men of diverse talents. There have been experimental physicists, theoretical physicists, mathematicians, inventors, and finally engineers who, taking the mass of experimental facts, of substantiated theory and of successful inventions, have leavened it with their own practical knowledge, experience, and resourcefulness and have produced the huge and useful structure which is the electrical industry of today. Most of the workers in this science have been capable of classification in one or more of these groups. However certain ones, by the versatility of their genius, defy classification. They take a high place in the hierarchy of pure scientists. As mathematicians they are not plodders, they are originators. Withall, they are, in the highest sense of the term, practical men; inventors and engineers. The chief of this group was Lord Kelvin. It is to this group

that Doctor Arthur Edwin Kennelly belongs.

"Like another illustrious member of the group, Professor Elihu Thomson, Doctor Kennelly is of British parentage. He was born in India and educated in England, Scotland, France, and Belgium. His first position was that of assistant secretary of the Society of Telegraph Engineers of London, now the Institution of Electrical Engineers. In 1876 he joined the Eastern Telegraph Company, thus entering into the most highly developed electrical field of that time. He was promoted steadily until in 1886 he became senior ship electrician on submarine cables, a position which made severe demands on the technical knowledge and resourcefulness of the occupant. It is reasonable to infer that his familiarity so gained with the theory and practice of the transmission of signals over long lines having distributed capacity formed the basis for his future work in the field of telephony and in the mathematical treatment of the phenomena of transmission lines.

Became Associated With Edison in 1887

"He came to America in 1887 and became the principal electrical assistant to Mr. Thomas A. Edison, which position he held until 1894. These years in a hard and intensely practical school could not have been other than instructive and stimulating to a young engineer. In 1893 he was, in addition, consulting electrician to the Edison General Electric Company now the General Electric Company, which is good enough evidence of the success of his work with Mr. Edison.

"In 1902 he was appointed professor of electrical engineering at Harvard University and occupied that chair until his retirement as professor emeritus in 1930. During the years from 1913 to 1924 he also was professor of electrical engineering at Massachusetts Institute of Technology and now is professor emeritus of that institution also. During some years of his active service at M.I.T. he was director of electrical engineering research and chairman of the faculty.

"With all these duties and responsibilities Doctor Kennelly nevertheless has found time and energy to engage in many outside activities. He has served 2 terms as President of the A.I.E.E. (1898–1900). He was president of the Illuminating Engineering Society during the early days of that organization when his guidance was particularly valuable. He has been president of the Institute of Radio Engineers, of the Metric Association, and of the Union Radio Scientifique Internationale. He is honorary secretary of the United States National Committee of the International Electrotechnical Commission.

International Efforts

"In the international field his services have been of unusual distinction. He was a United States delegate to The Electrical Congresses of 1900, of 1904 where he carried out the onerous duties of general secretary, and of 1932; also to international radio conferences in Paris in 1921 and in Washington in 1927 where international allocations of radio transmission frequencies were made. He is a member of the International Committee on Weights and Measures, the last meeting of which at Sevres in 1933 Doctor Kennelly attended. During the year 1921–22 he represented 7 coöperating American universities as first exchange professor in engineering and applied science at several French universities. He has published many books and is the author of more than 350 papers many of which were presented before scientific organizations at home and abroad. Without stint he has given of his time in committee work in accomplishments for which he has neither desired not received personal credit. At the present time he is chairman of the Committee on Electrical Definitions which already has accomplished an important work.

"Doctor Kennelly joined the A.I.E.E. as an Associate in 1888. In 1894 he had already became a manager, having among his colleagues in that office Pupin, Steinmetz, Ryan, and Carty. He was also chairman of the only technical standing committee of the Institute, namely, the committee on units and standards. The committee was wrestling with the question of the names of the magnetic units. Forty years later we find Doctor Kennelly chairman of the advisory committee of the International Electrotechnical Commission which is laboring on the same subject. Doctor Kennelly has been at the forefront of all the discussions of all the intervening years. At the Paris Congress of 1901 it was Kennelly who delivered the vote of the United States. We expect that he will succeed in his task of getting complete international accord, for in power of reasoning and persuasion he is unexcelled. This is only one instance. For 45 years the Transactions of the Institute have been enriched by his contributions of papers and discussions.

Classic A.I.E.E. Contribution in 1893

"One of these contributions, which is now a classic, demands further consideration even in as brief a review as can be made in the time allotted for this discussion. In April 1893 (Trans., v. 10, p. 175) Doctor Kennelly presented a paper under the title 'Impedance' in which he gave the first application ever to be made of complex quantities to technology, and to the extension of Ohm's law to alternating circuits. In the paper he first showed that in a circuit containing resistance and inductance, the impedance is given by the hypothenuse of a right triangle, the other sides of which are the resistance and a quantity which he called the inductance-speed, namely the inductance multiplied by 2π times the frequency. He said: 'The impedance is therefore the geometrical or vector sum of the resistance and inductance-speed, when these are plotted on two rectangular axes. Calling this impedance i, Ohm's law gives

$$c = \frac{e}{i} \qquad e = ic \qquad i = \frac{e}{c}$$

corresponding to the usual formulas for continuous currents.'

"The paper went on to show how the impedance of reactors in series is given by the vector sum of their individual impedances; how the impedance triangle of a resistance in series with a condenser is drawn, taking the reciprocal of the capacity-speed of the condenser as the vertical side of the triangle and turning it downward; how problems of resistance and reactances in multiple may be solved by vector methods.

"Finally Doctor Kennelly enunciated the following general law. Any combination of resistances, non-ferric inductances, and capacities, carrying harmonically alternating currents, may be treated by the rules of unvarying currents, if the inductances are considered as resistances of the form $pi\sqrt{-1}$, and the capacities as resistances of the form $-\frac{1}{kp}\sqrt{-1}$, the algebraic operations being then performed according to the laws controlling complex quantities.

Times Wide World Photo

Dr. J. B. Whitehead (left) president of the A.I.E.E. presenting the 1933 Edison Medal to Dr. Arthur E. Kennelly at the special ceremony on January 24, 1934, held during the Institute's recent winter convention in New York

"How completely novel the method and the ideas set forth in the paper were is indicated by the fact that the members called upon to discuss it (and they included some who were already famous in the profession, at least one of whom later became an Edison medallist) expressed their appreciation of it, but declined to make further comment on the ground that they had not 'had time to digest it.' Yet, today, how simple and commonplace it all seems!

Supported by Steinmetz

"However, Doctor Steinmetz, who had not been present at the meeting, sent in after adjournment a written discussion from which it is seen that his keen mind had instantly grasped the full significance of Doctor Kennelly's disclosure. He wrote, after quoting the (Kennelly) rule and emphasizing its significance:

"'It is well known that the points of a plane can be represented by complex quantities in their rectangular representation $a + bj$, or their polar representation r (cos $\phi + j$ sin ϕ), and use has been made hereof repeatedly in the mathematical treatment of vector quantities. It is, however, the first instance here, so far as I know, that attention is drawn by Mr. Kennelly to the correspondence between the electrical term impedance and the complex numbers.'

"The importance hereof lies in the following: The analysis of the complex plane is very well worked out, hence by reducing the electrical problems to the analysis of complex quantities they are brought within the scope of a known and well understood science.'

"Doctor Steinmetz's subsequent development and use of the method in his many published works have been largely responsible for the familiarity which we have with it today; so much so that the credit for the original idea is sometimes given to him. It is interesting on this occasion to note that this whole matter was one of the results of the work which Doctor Kennelly did while associated with Mr. Edison.

"In April 1895 Doctor Kennelly, in collaboration with Professor Houston, presented the first of his many papers employing complex angles in dealing with transmission line problems.

Kennelly–Heaviside Layer

"The thing for which Doctor Kennelly is best known is undoubtedly his explanation of the mechanism of the transmission of radio waves. In the beginnings of radio telegraphy it was supposed, most reasonably, that radio transmission to any great distance was practically hopeless, both on account of the curvature of the earth's surface and because with the field strength varying inversely as the square of the distance, the energy would be attenuated very rapidly. Marconi's audacity in putting this idea to the test in his famous Cornwall to Newfoundland experiment, proved that this was not so. Evidently some unknown factor intervened to change the conditions. To explain this it might be supposed that there exists high up in the earth's atmosphere, a conducting region or layer by which the radio waves are deflected and turned back toward the earth, so that the curvature is overcome and the energy spread restricted to two dimensions. Thus the attenuation of signals would vary with the first power of the distance instead of the square. Doctor Kennelly not only did this but he went much further.

"His publication of the matter in the number of the *Electrical World and Engineer* for March 15, 1902, had the significant title On the Elevation of the Electrically-Conducting Strata of the Earth's Atmosphere. In this article he did not assume the existence of purely speculative conducting strata but, basing his calculations on data of J. J. Thomson's, he showed that electrically conducting strata must exist because of the rarefaction of the atmosphere, at a height of the order of 50 miles, with a conductivity several times as great as that of sea water. The presence of such strata being thus assured from independent consideration, the explanation of long-distance radio transmission followed at once and was given with precision and clearness and for the first time.

"Doctor Kennelly is noted for his accuracy of statement. If he cites a numerical value which is not exact even unto the third and fourth generation of decimals, he calls it an approximate value. He never leaves the reader in doubt as to what units he is employing. He has introduced a simple system of prefixes: 'ab' for the absolute magnetic system and 'stat' for the absolute electrostatic system.

Efforts Toward Practical System of Units

"He has been endeavoring for years, chiefly through the International Electrotechnical Commission, to get an agreement on an absolute practical system of units which should include the mechanical as well as the electrical units. The prospects for success have become much brighter during the past year.

"In conferences and in committee work his urge is always to get something tangible done, something agreed to. An imperfect agreement is better than no agreement, for at least it records progress made and can later be amended. He never attempts to force his own views on his colleagues. Stubbornness and pride of opinion or of parentage are foreign to his nature. He sees his adversary's point of view as well as his own, and is always fair, judicial, and tolerant. The combination of these characteristics with a complete mastery of his subject accounts for the large measure of success which his work in these directions has achieved.

World-Wide Recognition

"We, who have been his associates for many years, have known the modesty of his deportment, the geniality of his personality, the transparent honesty of his nature and the loyalty of his friendship. We have, perhaps, been too close to him to realize readily what his stature is among his contemporaries. The many scientists and engineers in foreign lands who know him personally and through his writings have, at their distance, been in a more favorable position. Thus, while he is an Honorary Member of this Institute, he is an Honorary Member of the Institution of Electrical Engineers of London, of the Societe Francaise des Electricians, of the Elektrotechnischer Verein and of the Institute of Electrical Engineers of Japan. He is a Corresponding Member of the British Association for the Advancement of Science and a Fellow of the Royal Astronomical Society.

"His affiliations at home are not confined to engineering organizations. He is a Member of the National Academy of Sciences, of the American Philosophical Society, of the American Mathematical Society, of the American Physical Society, and of the American Association for the Advancement of Science. He is a Fellow of the American Academy of Arts and Sciences.

Early Recognition

"This is not the first occasion on which Doctor Kennelly has received an award. As a young man, in 1887, he received the Institution Premium from the Institution of Electrical Engineers, and in 1889 he received the Fahie Premium from the same body. The Franklin Institute of Philadelphia granted him the Longstreth silver medal in 1916 and the Howard Potts gold medal in 1917. He was the recipient of the Volta medal in 1927 and the gold medal of the Institute of Radio Engineers in 1932. The French Government has conferred on him the Cross of the Legion of Honor.

"In the list of distinguished engineers on whom the American Institute of Electrical Engineers has conferred the Edison Medal, the highest honor which it can bestow, none has been more worthy than Doctor Arthur Edwin Kennelly."

Dr. Kennelly Extols Edison in Response to Presentation

Immediately following Dr. Sharp's biographical discourse President Whitehead read the citation and presented medal and certificate to Dr. Kennelly who, in responding stated to Dr. Whitehead that ". . It seemed to me that behind your welcoming hand I could imagine the hand of Mr. Edison," Dr. Kennelly then spoke at length upon the life and works of his onetime associate, Thomas A. Edison, in whose honor the medal is named:

"I think it is fitting that upon this occasion when the twenty-third Edison Medal is awarded, and 2 years after the death of our great chief, Edison, himself, that we should pause and take stock . . . .; we should see what they have meant to us and what he has meant to us. Mr. Edison was a pioneer electrical generation and distribution engineer, a pioneer illuminating engineer, and a pioneer acoustical engineer. I have taken the liberty of presenting to you here, through the kindness of the Edison Works and Mr. Denning, an early model of the Edison Phonograph, about the vintage of 1878, the tin foil phonograph from which he made this great discovery. He was the first acoustical engineer to record and reproduce sound, music, and speech . . . . (Dr. Kennelly then spoke into the relic which subsequently reproduced his statements loudly enough for most of the 800 persons present to hear; motive power furnished by Mr. Denning.)

Mr. Edison not only discovered the phonograph but he also produced the carbon button transmitter . . . . which made the Bell Telephone . . . . practical for service in everyday life.

"He also was the first to produce a loud speaker . . . . (exhibits device) . . . . a so-called chalk telephone receiver or electric motorgraph, in which a little moistened chalk cylinder is mounted in such a way that an electric contact connected mechanically with the vibrating diaphragm can be allowed to press softly upon the cylinder of chalk. When a very feeble alternating speech or voice current is passed through the contact the electrolytic effect of the current alters the friction between the stationary vibratory points and the slowly moving cylinder. The vigor and power of the sound that that instrument produces is astonishing. Of course, it had to be rotated either by motor or by hand and Mr. Edison had contemplated in the later part of his life to make this instrument practical for loud speaking, but I think he never carried his development . . . . very far. I merely wanted to show how much we owe Mr. Edison as an acoustical engineer.

"Then we all know how much we owe to Mr. Edison in regard to electric lighting and illuminating engineering. . . . The fact that we enjoy all these products of his hard work and development is lost upon us by familiarity. . . . . It was not merely his genius as an inventor, but his wonderful tenacity of purpose, his wonderful capability of holding on to a problem, his faith in the success of a problem which made the electric age possible to us.

"The wonderful improvements that have taken place since Mr. Edison's time are shown in many ways, but a striking way is the fact that in the days when I first came to work for him, electric motors of the ordinary constant-potential type had to be watched; you couldn't let them work long out of your sight. If the load on the motor varied considerably, they sparked at the brushes. Today we know that engineers take electric motors and seal them up inside refrigerators and don't allow you to look at them or touch them for a year or more. . . . So I hope . . . . that this medal may be a reminder to us all of how much we owe to the great man in whose honor this medal was founded.

"The future of electricity is beyond our perception, beyond our estimate. It is advancing with great rapidity. The electric switch is the great device by which all our daily tasks are made so much easier than they used to be. In the days of Ancient Greece and Rome the work . . . . was rendered lighter through the agency of slaves, captured in war, from whom you could get perhaps (the equivalent of) 20 watts each as a regular performance. Of course, they were not expected to be highly enthusiastic over his work, but you could count them about 20 watts apiece. But the average power that is available for every man, woman, and child in the United States is, as you know, about 60 watts per head, day and night . . the equivalent of . . 3 electric slaves potentially at work at the bidding of each individual. Formerly, in the days of Greece and Rome, you had to know how to handle your slaves in order to make them carry on with any degree of reasonable achievement. If you were too severe, if you cut their heads off, the rest remained rather sour and you couldn't do very much with them. Sullen slaves always indicated a hard taskmaster, but a man who could make his slaves fairly enthusiastic and stir them up to achievement was a man who was successful in that period in carrying on his work. We don't have to consider our electrical slaves, our motors and our lamps, and so forth. All we have to do is to turn the switch when we are finished with them. All this achievement, all this prospect and possibility, lying before us and before our successors, is largely due to the man in whose honor this medal has been founded."

A.I.E.E. Directors Meet During Winter Convention

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute Headquarters, New York, N. Y., on January 22, 1934.

There were present: *President*—John B. Whitehead, Baltimore, Md. *Past-president*—H. P. Charlesworth, New York, N. Y.; *Vice-presidents*—R. B. Bonney, Colo.; A. H. Hull, Toronto, Ont.; J. Allen Johnson, Buffalo, N. Y.; E. B. Meyer, Newark, N. J.; R. W. Sorensen, Pasadena, Calif.; and A. M. Wilson, Cincinnati, Ohio. *Directors*—L. W. Chubb, East Pittsburgh, Pa.; A. B. Cooper, Toronto, Ont.; A. E. Knowlton, New York, N. Y.; G. A. Kositzky, Cleveland, Ohio; Everett S. Lee, Schenectady, N. Y.; A. H. Lovell, Ann Arbor, Mich.; L. W. W. Morrow, New York, N. Y.; A. C. Stevens, Schenectady, N. Y.; R. H Tapscott, New York, N. Y.; and H. R. Woodrow, Brooklyn, N. Y. *National treasurer*—W. I. Slichter, New York, N. Y. *National secretary*—H. H. Henline, New York, N. Y.

Minutes were approved of the board of directors' meeting held October 20, 1933, and of the executive committee's meeting of December 8, 1933.

The board approved the finance committee's report of monthly disbursements amounting to $13,873.96 in December and $19,625.36 in January.

Authorization was given for a joint student activities conference of Districts Nos. 8 and 9 during the Pacific Coast convention, Salt Lake City, in September 1934.

Reports were approved of meetings of the board of examiners held December 20, 1933, and January 17, 1934. Upon the recommendation of the board of examiners, the following actions were taken upon pending applications: 5 applicants were transferred to the grade of Fellow; 36 applicants were transferred to the grade of Member; 11 applicants were elected to the grade of Member and 89 were elected to the grade of Associate as of February 1, 1934; 192 Students were enrolled.

A resolution was adopted to the effect that the 1934 annual meeting of the Institute will be held at Hot Springs, Va., on Monday, June 25.

Amendments to the by-laws were adopted, containing the new prices for Institute technical publications made necessary by the recent changes in publication policy. These prices have been announced in ELECTRICAL ENGINEERING.

The committee on Iwadare Foundation reported that it had arranged for Dr. C. E. Skinner to give a series of lectures in Japan next spring, under the Iwadare Foundation.

C. A. Adams and C. E. Skinner were reappointed as the Institute's representatives upon the council of the American Association for the Advancement of Science for the year 1934.

Upon recommendation of the standards committee, the board approved the reorganization of the Sectional Committee on Scientific and Engineering Symbols and Abbreviations, as follows:

1. The continuation of the present Sectional Committee Z10, but that the committee have charge only of "standardization of symbols and signs for equations and formulas," under the joint sponsorship of the same 5 organizations now sponsors.
2. The organization of a new Sectional Committee under the joint sponsorship of A.I.E.E., A.S.M.E., and A.S.C.E., to have charge of "the standardization of graphical symbols and of abbreviations."
3. Inclusion of the work now covered by Sectional Committee C10, electrical equipment of buildings, in the scope of the new Sectional Committee.
4. The inclusion of the work of subcommittee 6 of Sectional Committee Z14 on drawings and drafting room practice in the scope of the new Sectional Committee.

The annual report of the president of the U.S. national committee of the International Commission on Illumination was received, and the question of its publication in ELECTRICAL ENGINEERING was referred to the publication committee.

The board voted that in future information regarding the Institute budget shall be published in ELECTRICAL ENGINEERING.

Upon recommendation of the committee on research, in view of the retrenchment policy of the Federal Government, the board adopted a resolution calling attention to the importance of adequately maintaining the technical standardizing and research activities of the Bureau of Standards in the electrical field. (This resolution is published elsewhere in this issue.)

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

Student Convention at M.I.T. Successful

The first New England student convention including all the A.I.E.E. Student Branches in New England was held at Cambridge, Mass., on December 9, 1933, under the sponsorship of the Massachusetts Institute of Technology. The afternoon session opened the program, an address of welcome being given by Dr. Karl T. Compton (F'31) president of M.I.T., followed by the student papers. These were "Cable Testing" by Mr. Smith of Harvard, "Electrical Prospecting" by Mr. Fink of M.I.T., and "The Electrical Brain" by Mr. Krim. A talk on "Electrostatic Generation of High Voltages for Atomic Disintegration" was given by Dr. van de Graaff. Approximately 200 students and faculty members attended this meeting, which was followed by an inspection of the electrical laboratory.

The convention included a dinner meeting in the evening, at which there were 100 present to hear Dr. D. C. Jackson (A'87, F'12) compliment the students on the success of their convention, and to hear Prof. W. H. Timbie (A'10, F'24) tell of the interest and belief of the national organization in the students. Following these talks a lecture and demonstration on the sodium

vapor light were given by C. A. B. Halvorson (M'22) of the General Electric Company, Lynn, Mass.

Chairmen's Meeting Held

Following the afternoon session of the convention, a meeting of the Branch chairmen were held. Present were:

R. F. Wilson	Yale University
Ralph Dixon	Brown University
Amos E. Kent	Rhode Island State College
Stephen Smith	Harvard University
R. M. Dougherty	University of Maine
Henry Backenstoss	Massachusetts Institute of Technology

At this meeting it was agreed that the session just concluded had been very successful and was worthy of continuation. Means of promoting the next New England student convention were discussed, and suggestions were made for organizing and conducting future meetings. It was felt that the time of the year at which the meeting was held was suitable. Regarding the general lack of student papers, all agreed that this would be remedied in future years, when the students would be aware of the meeting far in advance. It was suggested that the meeting place be shifted among the various schools; Harvard spoke for the 1934 meeting, and Brown for the 1935 meeting.

Counselor's Conference

A meeting of the Student counselors also was held following the main afternoon session. Present were:

William Anderson	Rhode Island State College
W. B. Hall	Yale University
F. N. Tompkins	Brown University
R. G. Porter	Northeastern University
W. H. Timbie	Massachusetts Institute of Technology

The counselors were enthusiastic concerning the large attendance of students to the convention and the high standard of the papers, as well as the excellent manner in which they were delivered. The problem of membership of Student Branches was discussed, the opinion being expressed that the local membership was undesirable, but necessary at the present time. Methods of encouraging the students to join the national organization rather than the local organization were presented, and it was hoped that some progress on the solution of the problem of student membership could be made during the coming year.

Demonstration of Music in Auditory Perspective

A fine demonstration of transmission and reproduction of speech and music in auditory perspective was given during the Institute's recent winter convention on the evening of Wednesday, January 24, immediately following the Edison Medal presentation ceremony. Dr. Harvey Fletcher of the Bell Telephone Laboratories, Inc., conducted this demonstration and interposed appropriate remarks so as to give to the audience, many members of which were not technically minded, some appreciation of what was taking place, and what the future possibilites were of these new developments in the transmission and reproduction of sound. As the technical features of the equipment had been discussed in considerable detail during the technical session on communication held during Wednesday afternoon, and as these papers were published in full in the January 1934 issue of Electrical Engineering, no discussion of the technical features is included in this news report.

Doctor Fletcher explained that in addition to several features necessary for the satisfactory reproduction of music and which previously have been available, a new feature is now added which makes possible the control of the apparent "direction" of the sound reproduced. Previous progress in reproduction has been concerned with improving the quality, in the sense of reproducing with greater fidelity all the tones and overtones present in the original and reproducing them in their correct proportion, and with increasing the range of volume, or intensity. The new feature demonstrated by Doctor Fletcher enables the addition to the previously available qualities, of the illusion of localization of sounds from different sources.

This method of reproduction, termed "auditory perspective," makes it possible for the first time to transmit and reproduce electrically the music of a symphony orchestra so that the audience is unable to detect except by sight that the orchestra is not present. The feeling is produced in the audience of being able to detect, or localize, the different stage positions from which the various sounds come.

In demonstrating the equipment, Doctor Fletcher not only showed the audience the æsthetic effects which were available only by the reproduction of music by this method, but also performed many "tricks" which mystified the audience. Sounds of different kinds were made to move about the stage in a weird and often amusing fashion. Other demonstrations included the varying of the sound gradually from the lowest frequency audible to the human ear to the highest, and the control of the intensity of sound over a great range. Particularly at the lower frequencies, parts of the auditorium, such as windows, were caused to vibrate and produce considerable noise themselves. As the frequency was varied, these points of vibration traveled to different parts of the auditorium, producing a very ghostlike effect and forcefully demonstrating the large amount of sound energy available in the reproducing equipment.

To those interested in the reproduction of satisfactory music, perhaps the most interesting features of the demonstration were the feeling of depth of sound produced by the directional effect, and the independent control of sounds of different frequencies and origins which were shown to be available.

A.I.E.E. Board Urges That Activities of U.S. Bureau of Standards Be Maintained

The following resolution was adopted by the Institute's board of directors on January 22, 1934, at its meeting held during the Institute's recent winter convention in New York, N. Y.

Whereas the American Institute of Electrical Engineers is a professional society of 16,000 members engaged in promoting the electrical art and

Whereas a necessary and fundamental part of the art is the determination and maintenance of fundamental standards and tests and

Whereas this essential work has been done by the Bureau of Standards under this authority of congress for many years as part of an expanding national and international program to

(a) determine and maintain the value of the ampere, the volt, and the ohm

(b) improve the physical standards of resistance

(c) maintain and improve standard cells

(d) maintain, devise, and improve measuring methods and devices for current, voltage, light, magnetism, insulation, frequency and other fundamental elements in the electrical field; and

Whereas this work conforms to the original purpose for which the Bureau was established and has been done so well as to gain it national and international favor and reputation and

Whereas the American Institute of Electrical Engineers believes this work to be of great scientific value and necessary to practical advances in electrical engineering and improvements in the electrical industry and

Whereas, as a consequence of the retrenchment policy of the Federal Government, those activities of the Bureau of Standards have been curtailed drastically, which has resulted in serious detriment to the art and the industry

Be It Resolved, therefore, that the attention of proper committees and members of Congress be called to this critical situation with the request that in making appropriations for the coming fiscal year, provision be made for the necessary and adequate technical standardization and research activities of the Bureau of Standards in the electrical field so that it may continue its valuable contributions to the art and industry and

Be It Further Resolved that copies of this resolution be sent to other technical societies similarly concerned with the scientific work of the Bureau of Standards and to the American Engineering Council with the suggestion that they also survey this critical situation with the view of taking similar action.

Plans Progressing for Institute's Fiftieth Anniversary Celebration in May

ORGANIZED May 13, 1884, the American Institute of Electrical Engineers will, on May 13, 1934, complete a half century of constructive professional and public service. As reported on p. 931 of ELECTRICAL ENGINEERING for December 1933, suitable commemoration of this anniversary date has been under consideration by Institute officers and committeemen for some time, and has been segregated definitely into 3 general classifications:

1. An enlargement of the May 1934 issue of ELECTRICAL ENGINEERING and the conversion of that issue into a special anniversary number containing a wide variety of material of historical significance and importance to the Institute and to the profession.

2. Special meetings that are being planned by many Sections and Branches to commemorate not only the Institute's 50th anniversary but also the anniversary of the organization of the Section or Branch.

3. A special program to be presented in connection with the annual summer convention at Hot Springs, Va., June 25–29, 1934.

A meeting of the anniversary committee was held in New York, on Wednesday, November 22, and since that time the plans have been developing rapidly. Principal contributors to the anniversary issue will be the 25 living past-presidents of the Institute, 2 of whom are among the 6 living charter members of the Institute. From the wealth of experience accumulated by these professional leaders will come a group of powerful articles, some dealing with important matters in electrical history, some with colorful personal reminiscences, some with special technical phases of the art and their significance, some with the Institute's organization and development, and some with the experiences and expectancies of electrical engineers in the realm of education, government, and human relations.

With respect to the annual convention in June, it is contemplated that an inspiring program in celebration of the anniversary will be developed and built around the living charter members of the Institute and all of its past-presidents, many of whom it is hoped will be present there.

Space available in this issue precludes the possibility of going further into detail at this time. However, further and more complete information is scheduled for publication in later issues of ELECTRICAL ENGINEERING.

An Appeal for Papers on Industrial Power Applications

RECOGNIZING the difficulty of securing suitable articles and papers for publication on the subject of industrial power applications, the Institute's technical committee on general power applications under the chairmanship of M. R. Woodward is making a well organized attempt to secure papers describing particular cases of industrial power applications which should be of interest to members in this field. The stimulation of such papers has been assigned to an editorial and review subcommittee under the chairmanship of A. E. Knowlton. Following the acceptance of the chairmanship of this subcommittee by Mr. Knowlton, one of his first acts was the circulating under date of December 5, 1933, of a letter to all members of the committee on general power applications, urging their coöperation in the securing of papers of industrial power applications.

Since there are many members of the Institute not members of this committee, but fully qualified to assist in its work, this matter was considered worthy of being brought to the attention of the entire membership through the columns of ELECTRICAL ENGINEERING. The following excerpts are from this letter to the members of the committee:

"In your practicing or consulting contacts with industrial users of electrical power and equipment have you not learned of at least one worth-while accomplishment in the realm of the industrial engineer? Especially desirable would be a paper from the engineer himself in contrast to one from the electrical manufacturer who made the installation. There have been many of that type and more are to be available. If each committee member will turn in one live lead of this nature it would assuredly put the committee in a position to discharge its manifest duty along these lines.

"Fourteen and one-half per cent of the A.I.E.E. members are classified occupationally as industrial (other than electrical manufacturing, which represent 20 per cent). It is presumed that these members have a desire and a right to hear and see presented papers that pertain to their field of activity in electrical engineering. Of the 21 papers on hand at A.I.E.E. headquarters ready for publication, 2 were listed as having appeal to industrial electrical engineers but neither of them was from a practicing industrial electrical engineer. Of the papers promised or proposed only 1.4 per cent could be classed as having occupational appeal to industrial electrical engineers.

"It is evident that the $^1/_2$ of the membership represented by this group is not receiving in return by way of specific literary contributions anywhere near its due. . . . . I believe it is incumbent on the committee on general power applications to make a determined effort to correct this situation in the interests of the Institute and of the professional status of its members in industrial electrical pursuits.

"In the last analysis there can be only 3 obstacles to the production of an adequate number of power application papers:

1. Industrial electrical engineers make no creative contribution to the electrical art.

2. Even if they do so, they do not have the aptitude for recording their accomplishments in print.

3. Even if they did have the aptitude, they would not be allowed by their superiors to exercise it.

"In my belief the third is the dominant obstacle, and therefore the one to be attacked. Until this is overcome to the extent that chemical, mechanical, metallurgical and other engineers have overcome it, the electrical engineer in the industrial plant will lag in relative professional status.

"In asking you therefore to volunteer information as to prospective sources of papers I ask you to have this broad objective in mind as well as the immediate objective of balancing the paper program of the Institute."

Suggestions which may be made by members of the Institute in accordance with this request should be addressed to A. E. Knowlton, chairman, editorial and review subcommittee, care of *Electrical World*, 330 West 42nd Street, New York, N. Y.

Columbia University Offers E.E. Scholarships

The governing bodies of Columbia University have placed at the disposal of the A.I.E.E. each year, a scholarship in electrical engineering in the school of engineering of Columbia University for each class. The scholarship pays $350 toward the annual tuition fees which vary from $340 to $360, according to the details of the course selected. Reappointment of the student to the scholarship for the completion of his course is conditioned upon the maintenance of a good standing in his work.

To be eligible for the scholarship, the candidate recommended will have to meet the regular admission requirements, in regard to which full information will be sent without charge upon application to the secretary of the University or to the National secretary of the Institute, 33 West 39th St., New York, N. Y.

In a letter addressed to the national secretary of the Institute, an applicant for this scholarship should set forth his qualifications (age, place of birth, education, reference to any other activities, such as athletics or working way through college, references and photograph). A committee composed of W. I. Slichter, *chairman*, Francis Blossom, and H. C. Carpenter will consider the applications and will notify the authorities of Columbia University of their selection of a candidate. The last day for filing of applications for the year 1934–35 will be June 1, 1934.

The course at the Columbia school of engineering is a graduate course which may be either elective leading to the degree of master of science or prescribed leading to the degree of electrical engineer. For the former, requirement for admission is the completion of a 4-year course in electrical engineering as evidenced by a bachelor's degree from an approved institution. For

the professional degree, the requirements are more specific as to course content and include a considerable proficiency in mathematics, physics and chemistry, and some knowledge of the humanities, as well as the usual undergraduate technical courses. The candidate is admitted on the basis of his previous collegiate record without undergoing special examinations. Other qualifications being equal, members of the Student Branches of the A.I.E.E. will be given preference.

The purpose of this advanced course is to produce a high type of engineer, trained in the humanities as well as in the fundamentals of his profession. It is hoped that enrolled students and others qualified will show a keen interest in this scholarship.

Boulder Dam Visited by San Francisco Engineers

AN interesting inspection trip through Boulder Dam was made early in December by 52 engineers under the auspices of the San Francisco (Calif.) Engineering Council. Leaving San Francisco on special cars Friday morning, December 8, Saturday and Sunday were devoted to inspection, the return being completed Monday evening. The following excerpts from a report prepared by H. W. Crozier (A'03, M'12) should be of interest to all engineers, reflecting as they do some of the most important features at Boulder Dam:

The deep canyon of the Colorado was a hive of industry. Concrete is being placed night and day so steadily that the dam has now risen 150 ft from the rocky bottom of the river and is just a little above the level of the water in the river. Great cableways spanning the canyon are used to lift the big buckets of concrete for the dam, and one of them, the largest ever made, will be used to place the machinery and be retained permanently.

The gravel pit, aggregate washing and classification plant, high-mix and low-mix concrete plants were visited. The Nevada spillway, cableways, diversion and power tunnels were inspected and an opportunity was given every one to see all details of the placing of concrete in the dam, the refrigerating system of pipes for heat extraction, and intake tower and powerhouse foundation work in progress.

The Colorado River, which filled the 4 50-ft by-pass tunnels within a few feet of their tops during the high water in June, had shrunk so low in December that one tunnel only was needed to carry the water. The engineers went through the other tunnels and inspected the work of preparing to lower the great steel stop gates and place the concrete plugs to stop the water forever. The tunnels for the pipes which will deliver the water to the great turbines and the preparation of the powerhouse foundations were also scenes of activity.

As the dam rises the removal of the heat resulting from the setting of the cement becomes an important problem because of the enormous mass of the dam, and one which has heretofore never been encountered on such a large scale. This problem has been successfully solved by a system of pipes, placed in the dam before pouring the concrete, in which ice cold cooling water, produced in a special refrigeration plant, is circulated. This system for removing the chemical heat released during the setting of the concrete, is used for the first time at Boulder Dam and is one of the most interesting and successful features of the great project.

Also interesting was the large pipe welding plant of the Babcock and Wilcox Company where steel plates 3 in. thick are being rolled into pipes and the seams electrically welded. Machines welding pipes 9 ft up to 30 ft in diameter were in operation, and miles of seams must be welded in the next 2 years before all the pipes are made and placed in position. (Editor's Note: See ELECTRICAL ENGINEERING, September 1933, p. 644, for a further description of the field fabricating plant.)

Every foot of welded seam is inspected by an X ray machine, the most powerful ever devised, and a picture made through the steel on a photographic film 4 in. wide and 14 in. long. The photographs are so clear that a perfect job is assured, because no defect can escape the all-seeing eye of the X ray. (Editor's Note: See ELECTRICAL ENGINEERING, May 1933, p. 349, for a further description of these X ray units.)

One of the most delightful features of the trip was the way the inherent faculty of the engineers for management and planning manifested itself when they organized their excursion for their own convenience and comfort, as one of those smoothly running machines that apparently run themselves. Dividing the tasks of looking after the sustenance, housing, and direction of the sightseeing among themselves by a scheme of committees, nearly all members of the party accepted responsibility for some part of the job of running things, and were ably assisted by the efficient coöperation of the Santa Fe organization, with the result every one had ample leisure to devote to the important job of sightseeing.

The *Las Vegas Age*, in commenting on the concluding dinner of the trip, says, in part:

"W. B. Young was introduced as the second speaker and gave a most interesting discussion of the project. He entered upon some of the phases of the work and the results to be expected. Speaking of the silt problem, he stated the probability that it would require 300 years for the deposit of silt to fill the reservoir, provided there were no dams constructed in the upper river. In 50 years amortization period of the project, the reservoir would contain only 300,000 acre feet of silt, only $^1/_{10}$ of its capacity. He said that the reservoir, when completed, will become a national asset because of its peculiar scenic attractions.

"Describing the power plant, he stated

Two interesting views of the Boulder Dam project taken during the recent visit of 52 San Francisco engineers to Boulder Dam for an inspection of the many unusual features involved

that the generators to be installed in the powerhouses would generated 1,835,000 hp, and that there will be 663,000 hp of firm or primary power.

"The time for the completion of the project was originally set for April 1938. Through the energy of the Six Companies, Inc., who have advanced the work until it is 15 months ahead of schedule, the dam proper will be completed in May or June 1935 and it will be possible to generate some power September 1935. Because of the massiveness of the generators, 40 ft in outside diameter, the power installation will not be completed until after this date. There will be 17 power units installed, 15 of which will be of 115,000-hp capacity. Four of these larger generators and one smaller one have been contracted for and are under construction."

Annual Meeting of U.S. Committee on Illumination

The 1933 annual meeting of the United States national committee of the International Commission on Illumination was held in New York, N. Y., November 8, 1933. Officers were elected, committee appointments were made, and the annual report of the president was presented.

An extended review of technical committees and other activities indicated substantial progress in the United States in preparation for the plenary session, scheduled for Germany in 1935.

L. B. Marks (A'90, F'12 member for life) wa selected honorary president, U.S. National Committe. E. C. Crittenden (A'19, M'22) and G. H. Stickney (A'04, F'24) were reëlected respectively as president and secretary-treasurer. They were also reëlected as United States members of the I.C.I. executive committee, of which committee C. H. Sharp (A'02, F'12, member for life), vice-president of the I.C.I. is also a member. J. W. Barker (M'26, F'30) P. S. Millar (A'03, M'13) and L. A. S. Wood (M'24) were appointed to serve with the officers on the (United States) executive subcommittee.

The 3 U.S. secretariat committees were reappointed. As U.S. representatives on technical committees, P. S. Millar was appointed for No. 4 glare (streeting lighting); L. A. S. Wood for No. 23(*a*), street lighting; W. F. Little for No. 23(*b*) automobile lighting. All other technical committee representatives were reappointed.

E. C. Crittenden was appointed representative on the division of foreign relations, National Research Council and L. A. S. Wood was appointed auditor of the national committee.

Annual Report Presented

At the annual meeting, on November 8, Eugene C. Crittenden (A'19, M'22), president of the committee, presented his annual report. A brief summary of this report follows:

Developments during the past year have emphasized the difficulty involved in carrying on international activities like those of the International Commission on Illumination, but have at the same time shown the importance of maintaining American participation in them. It has been found expedient to postpone for a year the session of the commission, originally scheduled to be held in Berlin in 1934, and the illumination congress which is to be coupled with it. Nevertheless, some of the technical work of the commission has made notable progress, and the results obtained are of material importance to the lighting industry in America as well as abroad.

The activities in which most definite progress has been made are the fundamental problems of measurement, in which international standardization is highly desirable. Work initiated by the commission now gives promise of bringing about world-wide uniformity in units and standards of light and in the method of specifying colors. Discussions are also under way on physical photometers and on the evaluation of ultraviolet as an adjunct to lighting.

The International Committee on Weights and Measures is the legal agency established by treaty among 32 nations to direct all metrological work which the governments concerned desire to have carried on jointly. By a recent amendment to the treaty, electrical units and standards were placed under the jurisdiction of this committee, and this extension of authority has been construed to include photometry. However, the committee operates under the authority of a general conference on weights and measures, which, in authorizing the establishment of an official international advisory committee on photometry in October 1933, stipulated that in the choice of its members special consideration shall be given to the personnel of the special committee on units and standards of light established by the International Commission on Illumination in 1931.

Continuation of the work of various committees of the I.C.I. previously reported has been carried on throughout the past year, and considerable progress has been made toward the next session of the commission and the illumination congress. Increased interest in this work, however, was urged.

Distribution of the 2-volume Proceedings of the 1931 Congress continues in a satisfactory manner.

The financial status of the national committee is satisfactory for the present, but the dissolution of the National Electric Light Association combined with changes in the rate of foreign exchange, will make the annual expenses greater than the income. Business or industrial interests concerned with the development of lighting are considered as the most likely sources of additional support.

Novel Use of Electrical Illumination

An unusual use was made of electrical illumination this past Christmas season when 22,000 watts of electricity were used to light the Gothic ice chapel building on the campus of Lawrence College, Appleton, Wis. The entire chapel, which is 23 ft long, 14 ft 7 in. wide without the side buttresses and 18 ft high to the ridge pole, is constructed entirely of ice with the exception of the roof which is overlain with evergreen branches. The chapel was built following a modified Gothic design, and was so constructed that the lights which were used in the night illumination had varying effects according to the thickness of the walls. All of the reflectors and lighting effects were designed and built under the supervision of W. E. Schubert, chief engineer for the Wisconsin-Michigan Power Co. The large unit reflectors gave off their illumination through a straight reflector system for the larger lights and a flasher system for the smaller lighting. The great amount of heat generated by this battery of lights made it necessary to cover the roof with evergreen branches so that ample ventilation could be provided for. The ice chapel is intended as a permanent event for each Christmas season.

Bureau of Standards Reports Electrical Work

In the annual report of the Secretary of Commerce of the United States the principal projects undertaken by the Bureau of Standards in 1933 are summarized. Items appearing under the heading "Electricity" are reprinted in the following paragraphs because of their interest to various members of the Institute:

1. New basis for electrical units. Determinations of values for the ampere and the ohm by absolute measurements were continued. In the case of the ampere, the average value from results to date is 1 B. S. International ampere = 0.999941 absolute ampere. Values for the ohm are derived from calculated inductances of carefully constructed coils, several of which have been built at the Bureau in recent years. The value (subject to slight corrections) of 1 B. S. international ohm as determined by various coils is:

From the procelain coil: 1.000463 absolute ohms.
From the quartz coil: 1.000442 absolute ohms.
From the pyrex glass coil: 1.000455 absolute ohms.

2. Standards of electrical resistance. Eighteen one-ohm resistance standards of the type recently developed at the Bureau were constructed, and appear to be of exceptional quality. They will probably be used in future, international comparisons, as well as in the maintenance of the unit in the United States.

3. Standards of electromotive force. Improvements in the constancy of the Weston normal cell as a standard of electromotive force have been made possible by the use of materials for the containers which are more inert chemically than those previously employed. A new high precision potentiometer for the comparison of standard cells was constructed and placed in service. Comparisons were made of the Bureau's standards of electromotive force with those of England, France, and Germany.

4. Large absolute electrometer and equipment for testing of current transformers. A number of mechanical improvements have been incorporated in the Bureau's absolute electrometer, and results are now attainable with a precision of a few hundredths of one per cent. The equipment for testing current transformers has been put into commission and has been found satisfactory for tests up to 12,000 amp.

5. Magnetic testing and research. An apparatus for magnetic testing at high magnetizing forces was developed and has been added to the list of approved methods of the American Society for Testing Materials. A magnetic balance was developed for the inspection of austenitic steel. Apparatus was constructed for the application of the "magnaflux" method to the inspection of hollow steel airplane propellers and proved very effective in the location of hidden defects.

6. International standards of candlepower for commercial types of electric lamps. The national laboratories of France, Germany, Great Britain, and the United States have now agreed to bring their standards of light for the commercial types of lamps into accord through the use of visibility factors established by measurements at the Bureau and accepted by the International Commission on Illumination. Values of the colored filters to serve this purpose have been adopted and each participating laboratory has received one of the filters.

7. Primary radio-frequency standard. The Bureau's primary standard of radio frequency was improved and is now automatically protected against power failures.

8. Secondary standards of radio frequency. A semiportable piezoelectric standard was developed to maintain a frequency constant within 1 part in 10,000,000 for several hours without adjustment. A new type of toroidal quartz plate was developed with marked advantages in respect to temperature coefficient and constancy.

9. Dissemination of standard radio frequency. The accuracy of the 5,000-kc radio transmissions was increased to 1 part in 10,000,000. Greater reliability was brought about by a change from 1 to 30 kw in the power of the transmitter and by the development of highly accurate automatic monitoring procedure. The standard frequency signals were made available to the public over wire line connections.

10. Measurements of radio wave variations. Equipment for the automatic recording of received wave intensities was installed and applied to a study of the relative values of different frequencies for broadcasting. The data aided directly the work of 2 international radio conferences (Madrid, 1932, and Mexico City, 1933). Radio transmissions at the lower and the higher frequencies were correlated with solar data and terrestrial magnetic changes. Equipment was developed for a fundamental study of direction and polarization phenomena.

11. Height of ionized layers. Automatic recorders were developed and used for determining the varying heights and ionization of the layers in the upper atmosphere which make possible long distance radio transmission. Part of this work was in connection with the world-wide polar year program of scientific measurements.

12. Storage batteries. It was found that gradual corrosion of the positive grids of storage batteries under ordinary conditions may liberate enough antimony to increase materially the rate of sulphation of the negative plates. Determinations have been made of viscosity and resistivity of sulphuric acid solutions at low temperatures, which will aid in predicting the operating characteristics of storage batteries under severe climatic conditions. Mechanical, electrical, and chemical properties of storage battery separators have been measured for the Navy Department, to determine the suitability of different kinds of wood, both treated and untreated, and the variation of these properties in commercial practice.

13. Insulating properties of rubber. A complete study of the dielectric constant, power factor, and resistivity of rubber-sulphur compounds at temperatures from −75 deg to +150 deg C, and under various pressures, has been completed.

14. Telephone engineering service. Three Government departments and other establishments were advised as to the most economical and efficient methods for supplying telephone and related services in their buildings.

15. Electrical and other safety codes. Bureau representatives have assisted in revision of the National Electrical Code. Handbook no. 17, containing a revision of the code for protection against lightning, was issued, and a model ordinance for electrical inspection was prepared. Two documents on construction of power lines were prepared for the International Electrotechnical Commission. Members of the staff participated in the Annual Safety Congress and in the work of the safety code correlating committee, and assisted State officials and various committees formulating and revising safety codes.

16. Prevention of underground corrosion. The successful use of bituminous coatings on pipe lines requires the setting up of recognized methods for identifying the materials used, and for determining their properties and performance. Two methods for determining the condition of bituminous coatings after service have been developed in coöperation with the American Gas Association and American Petroleum Institute. A laboratory method for determining the resistance of coatings to soil stress, the principal cause of coating failures, is being developed.

Officers of the Institute of Radio Engineers. The list of officers and members of the board of directors of the Institute of Radio Engineers to serve for the year 1934 has now been announced. C. M. Jansky, Jr. (A'20, M'32) Washington, D. C., was elected president and Balth van der Pol, Eindhoven, Holland, was elected vice-president. The following were elected as members of the board of directors: A. N. Goldsmith (M'16, F'20) New York, N. Y., Arthur Batcheller, New York, N. Y., and William Wilson (M'23) New York, N. Y. In addition to these elected directors, the following were appointed to serve as members of the board of directors: Melville Eastham (A'19, M'26) Cambridge, Mass., H. P. Westman, New York, N. Y., J. V. L. Hogan (A'11, M'20) New York, N. Y., L. C. F. Horle (A'20, M'22) Newark, N. J., E. R. Shute (M'17) New York, N. Y., A. F. Van Dyke, New York, N. Y., and H. A. Wheeler, Bayside, L. I., N. Y., W. G. Cady (M'19) Middletown, Conn., and L. M. Hull (M'27) Boonton, N. J., both junior past-presidents of the I.R.E., serve as *ex-officio* members of the board. Other members of the board, holding over from previous terms are: O. H. Caldwell (A'13, M'22) New York, N. Y., R. A. Heising (A'15) New York, N. Y., C. W. Horn, New York, N. Y., F. A. Kolster (M'19) New York, N. Y., E. L. Nelson (A'20, M'26) New York, N. Y., and H. M. Turner (M'20) New Haven, Conn.

Historical Information on Engineering Drawing Requested. The Society for the Promotion of Engineering Education through its division of engineering drawing and descriptive geometry is sponsoring the following projects: (1) A collection of material showing the evolution and variety of instruments used in engineering drawing; (2) a collection of old drawings intended to show the development of engineering drafting room practice and of various means of reproduction on engineering drawings; (3) a collection of the work of writers, old and modern, on the subject of drawing and descriptive geometry; and (4) the preparation of a series of bulletin board posters, carrying a portrait and biography of persons prominent in the history of engineering, and excerpts from their writings emphasizing the value to engineers of training in engineering drawing. The bulletin board posters are intended for general distribution through the drawing departments of all the engineering colleges. They are to be posted week by week, and it is hoped that they will add an inspirational touch to the teaching program. Any persons in a position to lend or contribute to any particular collection write at once to H. M. McCully, Carnegie Institute of Technology, Pittsburgh, Pa., stating the nature of their offering.

International Congress for Applied Mechanics to Be Held. The fourth International Congress for Applied Mechanics will be held in Cambridge, England, July 3–9, 1934. The subjects to be discussed will be groups under the 4 general headings: rational mechanics, including vibrations of structures and machines; mechanics of fluids, including turbulence, the boundary layer, heat transfer, and compressible fluids; materials, including elasticity, plasticity, fatigue, and crystal structure; and water waves, including resistance and stability of shops and seaplanes. The applied mechanics division of The American Society of Mechanical Engineers is coöperating with the committee with the idea of coördinating the participation of other American groups in this congress. Inquiries regarding the congress and promises of manuscripts should be addressed to the applied mechanics division of the A.S.M.E., 29 West 39th Street, New York, N. Y. Those intending to participate are invited to intimate as soon as possible the general nature of their manuscripts. Summaries about 300 words, in English, German, French, or Italian, will be required about April 1, 1934. Although

plans are not definitely formulated, it is proposed to publish only the summaries, together with an abstract of the discussions. Authors are therefore to include in their summaries a list of appropriate references. A free of 15 shillings will be payable by all those taking part in the scientific or social activities of the congress. All those who intimate their intention of attending the congress will receive, early in 1934, a further notice giving details of the arrangements.

A Steam Boiler of New Design

A steam boiler of revolutionary design now being manufactured in England at the works of Messrs. Richardsons, Westgarth & Co., of West Hartlepool, is attracting the attention of marine engineers according to the October 1933 issue of *Industrial Britain*. The boiler is described as being the result of years of research and experiment by Messrs. Brown, Boveri & Co., the Swiss engineering firm now in working agreement with Messrs. Richardsons Westgarth.

Known as the "velox," this steam boiler occupies only about one-eighth the space and is only a quarter the weight of ordinary water-tube boiler plant evaporating an equal amount of steam. Starting from cold, it can attain full steam pressure in about 6 min and full output in 8 min.

The principle is the burning of liquid or gaseous fuel under high pressure in order to obtain high flue-gas velocities and the creation of this high pressure by a compressor driven by a gas turbine using the exhaust gases.

The fuel burns at a pressure of 20 lb per sq in. higher than that of the atmosphere. The small combustion chamber is lined with water tubes, inside of which are 3 or more flue-gas tubes through which the gases pass at about 600 miles an hour. Nearly all the energy employed to drive the compressor is recovered in the form of furnace heat and pressure.

A.S.T.M. to Meet in Washington. The 1934 regional meeting of the American Society for Testing Materials will be held in Washington, D. C., March 7, 1934, with headquarters at the Wardman Park Hotel. The technical feature of this regional meeting will be a symposium on outdoor weathering materials and metallic coatings sponsored jointly by the A.S.T.M. committees *A*-5 on corrosion of iron and steel, and *B*-3 on corrosion of nonferrous metals and alloys. The 1934 group meetings of A.S.T.M. committees also will be held at the Wardman Park Hotel, Washington, March 5–9, 1934.

Mining Engineers to Meet. The 143d meeting of the American Institute of Mining and Metallurgical Engineers will be held in the Engineering Societies Building, 29 West 39th Street, New York, N. Y., February 19–22, 1934. A program including a large number of papers on a variety of subjects in the field of mining and metallurgy will be discussed. Perhaps the most interesting of these from the point of view of electrical engineers will be the sessions on geophysical prospecting and nonmetallic minerals, and the meetings of the iron and steel division and the Institute of Metals Division.

Exchange of Professors Being Arranged. Announcement is made that beginning with the next academic year, 1934–35, the Massachusetts Institute of Technology, Cambridge, will inaugurate a general plan for the exchange of professors with other educational institutions in this country as well as abroad. The purpose of this plan is to broaden the experience, acquaintance, and educational outlook of members of the faculty, and to disseminate quickly and widely the best educational methods as they are developed in the various institutions. In announcing the plan, Dr. Karl T. Compton (F'31) president of M.I.T., states that this plan will tend to overcome any tendency of institutions to become ingrown or isolated. The plan provides for an exchange arrangement each year for one member of the staff of each of the departments of study, embracing the fields of science, engineering, architecture, and humanities.

Report of National Screw Thread Commission Available

Progress in commercial screw thread practice, which is based very extensively upon the standards established by the National Screw Thread Commission, has been such as to require several revisions and some additions to the standards promulgated in the commission's 1928 report. The 4th edition of the report of the National Screw Thread Commission, as approved April 10, 1933, is now available, and is now for sale by the superintendent of documents, Washington, D. C., at a price of 15 cents. This report is miscellaneous publication No. 141.

The initial accomplishment in the standardization of screw threads in the United States was the report under date of December 15, 1864, of a special committee appointed by the Franklin Institute, which recommended a definite thread system. This thread system, adopted as a standard for most lines of work in this country, fulfilled a great need. Later developments, however, required other sizes of screws, and the difficulties encountered in obtaining enormous quantities of war material by the United States government during the World War motivated further standardization of threads. The National Screw Thread Commission was authorized by Congress in 1918, and work started immediately.

In its work of establishing standards for screw threads, the commission has made particular effort to secure actual facts concerning the need of standardization and the economic conditions to be provided for in the production and use of screw threads. Hearings to obtain information were conducted in various industrial centers throughout the country, and extensive use of technical magazines was made in distributing and requesting information. A large number of experiments and tests also were made by the Bureau of Standards, and members of the commission individually conducted experiments and research work at their own expense. The advances made by the commission up-to-date will have tremendous benefit.

In the present report, specifications for threaded products and gauges are included, with sufficient information to permit the writing of definite and complete specifications for the purchase of products. Much supplementary information also is included. The specifications have been arranged, as far as possible, by products, and each section is arranged in the following order: (1) form of thread, (2) thread theory, (3) classification and tolerances, (4) table of dimensions, and (5) gauges.

Psychrometric Charts. Two sets of charts have been developed by the U.S. Bureau of Standards for use in the determination of the pressure of water vapor from psychrometric observations. These charts are based upon the psychrometric formula, one set based upon Fahrenheit temperatures and pressure in inches of mercury, the other upon Centigrade temperatures and pressure in millimeters of mercury; both will give relative humidity in per cent. It is reported that the bureau found in their development that the addition of 2 scales permitted the accurate evaluation of relative humidity as well. In comparison with the customary double interpolation tables it has been found that the use of these charts increased the precision and halved the time required. This 4-page leaflet, Bureau of Standards Miscellaneous Publication No. 143, is for sale by the Superintendent of Documents, Washington, D. C., at 5c per copy.

Domestic Short Wave Radio Communication. In speaking before the Advertising Club of New York, January 16, David Sarnoff, president of the Radio Corporation of America, announced that his company is about to develop a domestic short wave radio communication system through the establishment of stations at Boston, New York, New Orleans, San Francisco, and Chicago, together with such necessary relay stations as may be required to provide an effective communications network. It was announced that the proposed system will "constitute the beginning of the end of the dot-and-dash system of commercial communication." It is expected that transmission speeds of 180 words per minute will be provided by multiplexing the channels, and that facsimile transmission of written or photographic copy will become the order of the day.

American Physical Society to Meet in New York. The 190th regular meeting of the American Physical Society will be held in New York, N. Y., on Friday and Saturday, February 23 and 24, 1934, as a joint meeting with the Optical Society of America. All sessions will be held at Columbia University in the physics laboratories.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers: publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Potential Available for Gaseous Discharge in Insulation Voids

To the Editor:

It is an all too common misconception that the field in a gaseous bubble or void in an insulating material of specific inductive capacity ϵ may be obtained simply by multiplying by ϵ the field that is known to exist at that point in the absence of the void. This is true only if the void has the shape of a flat slab of infinite extent, and only approximately true in that case. In general the larger is ϵ and the smaller the relative dimensions of the void in directions perpendicular to the field the more pronounced is the error in using this abstraction. The error is considerable if the voids are spheres, for example.

I present here the appropriate solutions for general ellipsoids of semiaxes a, b, and c, where a is in the direction of the field, and of several special cases, such as spheres ($a = b = c$), infinite elliptical cylinders perpendicular to the field ($c = \infty$) and flat slabs ($b = c = \infty$). These cases cover, at least approximately, all of the common shapes encountered in voids in oil and paper insulated cable, for example. A butt space void may be closely approximated by an infinite elliptical cylinder, wherein the paper thickness is $2a$ and the butt spacing $2b$.

These solutions are obtained by the method outlined in Mason and Weaver's book "The Electromagnetic Field" (University of Chicago Press, 1929), and may be given in general terms by virtue of the fact that the field is everywhere constant inside voids of these shapes. Indeed, this fact is the essence of the method used to obtain the solutions. In the case of a rectangular parallopiped, for example, the field is not constant throughout the void, the solution is difficult to obtain, and may not be expressed in general terms. The solutions are:

$$E_1 = \frac{\epsilon_2 E_0}{\epsilon_1} \quad \text{infinite plane slab}$$

$$E = E_0 \frac{3\epsilon_2}{\epsilon_1 + 2\epsilon_2} \quad \text{sphere}$$

$$E_3 = \frac{E_0}{1 + \dfrac{b(\epsilon_1 - \epsilon_2)}{\epsilon_2(a + b)}} \quad \text{infinite elliptical cylinder}$$

$$E_4 = \frac{E_0}{1 + \left\{\dfrac{\epsilon_1}{\epsilon_2} - \epsilon_1\right\}\dfrac{abc}{2}\displaystyle\int_0^\infty \frac{dn}{(a^2 + n)\sqrt{(a^2 + n)(b^2 + n)(c^2 + n)}}} \quad \text{general ellipsoid}$$

where E_1, E_2, E_3, and E_4 are the fields in voids of the shapes indicated, E_0 is the field that would exist at the center of the void in the absence of the void, ϵ_2 is the specific inductive capacity of the insulating medium and ϵ_1 is the specific inductive capacity of the material in the void, unity if this is a gas.

It is assumed, in obtaining these solutions, that the field remains undisturbed far from the void. In the case of the sphere it can be shown by the method of images, that the solution is affected to a negligible extent until the sphere is within its own diameter from an electrode. When this occurs the available field is less, lying between E_0 and E_2. These values E_1, E_2, E_3, and E_4 are therefore all maximum values and E_0 is the lower limit, if $\epsilon_2 > \epsilon_1$.

In the case of an infinite slab between parallel electrodes, the electrode effect may be easily derived. If we divide the space between electrodes into 3 slabs of thickness t_1, t_2, and t_3 with specific inductive capacities of ϵ_1, ϵ_2, ϵ_3, respectively, and with the field $E_0 = -\dfrac{V}{d}$ (V is the potential between plates and $d = t_1 + t_2 + t_3$), the correct expression for E'_2, the field in the void, is

$$E'_2 = \frac{E_0 d}{\epsilon_2} \frac{1}{\dfrac{t_1}{\epsilon_1} + \dfrac{t_2}{\epsilon_2} + \dfrac{t_3}{\epsilon_3}}$$

This degenerates into the form of E_1 of the discussion above only if $t_3 = 0$. If $t_2 = t_3 = 0$, then $E'_2 = E_0$, the limiting case when the void fills the entire space between electrodes.

Thus the shape of the void may be a very important factor in a discussion of the possibility of a discharge occurring in it. These considerations must be taken into account in any theory of liquid breakdown that supposes discharges in gas bubbles, in the form of spheres or perhaps long needles in the direction of the field (in which case the field would not differ sensibly from E_0).

To gain an idea of the magnitude of this correction, suppose $\epsilon_1 = 1$, $\epsilon_2 = 3$ in the case of a sphere. Then $E_2 = 1.3E_0$ as compared with $E_1 = 3E_0$ for a thin flat slab.

The above was presented before a meeting of the insulation committee of the National Research Council, Philadelphia, Pa., November 15, 1933.

Very truly yours,

EDWARD B. BAKER
(Office of C. F. Hirshfeld [A'05], The Detroit Edison Co., Detroit, Mich.)

Jogging the Rotor of an Alternator Electrically

To the Editor:

It sometimes happens that it is necessary to uncouple a generator from its turbine to make tests, check up on shaft alignment, or for some other reason. After the generator has been motored, the rotor seems, invariably, to come to rest about 180 deg from its correct position. This, of course, is the worst condition but the probability of bringing the rotor to rest in approximately its right position is very remote, hence it is usually necessary to jack the rotor into position by some mechanical means. With some machines this is not much of a problem but with large alternators it is a big chore. Where there is a spare exciter set, exciter, or excitation bus available in the power house it is possible to use the direct current to turn the rotor into its correct position by one or other of the following methods with very little work.

When the generator has its neutral brought out the arrangement shown in Fig. 1 is probably the easiest and simplest. One of the field leads is connected to the neutral, the other to the source of excitation through the field contactor. The terminals T_1, T_2, T_3, are brought to disconnecting switches, the other poles of which

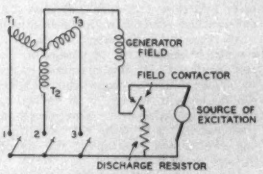


Fig. 1. Method 1

are connected together and to the other side of the source of excitation. If the inductance of the stator winding is not too great it is usually possible to move the rotor around to its required position, 60 electrical degrees at a time, by operating the disconnecting switches alone without at any time opening the field circuit. Starting with phase 1 closed, close the field contactor, then close phase 2, open phase 1, close phase 3, open phase 2, close phase 1, open phase 3 and continue until the rotor comes around to its proper location where the circuit is completely deenergized by means of the field contactor. By following this procedure the field circuit is not opened and it is usually possible to operate the disconnecting switches without particularly bad sparking if it is done slowly. If the sparking is such as to be detrimental to these switches the operation can be performed by the help of field contactor connecting the phases consecutively 1, 2, and 3, closing and opening the circuit by the field contactor, thus bringing the rotor around 120 electrical degrees at a time. In the majority of cases this method of jacking around the rotor does not involve any special switches as it is usually possible to open the line breaker and make use of the

disconnecting switches between the breaker and the generator.

In cases where the generator neutral is not available or where the ampere turns in one leg of the stator winding is not sufficiently great to pull the rotor around, method 2, Fig. 2, can be used. This method, while not requiring a neutral, has the disadvantage of requiring double throw disconnecting switches which are not always as readily available as the single throw disconnecting switches. With this connection

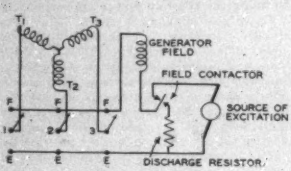


Fig. 2. Method 2

it is possible to bring the rotor around 30 electrical degrees at a time by operating the switches alone without opening the field circuit. Starting with 1-*F* and 2-*E* closed, close the field contactor, then close 3-*E*, open 2-*E*, close 2-*F*, open 1-*F*, close 1-*E*, open 3-*E*, close 3-*F*, open 2-*F*, close 2-*E*, open 1-*E*, close 1-*F*, open 3-*F*, close 3-*E* and continue until the rotor comes around to its required location where the circuit is completely deenergized by means of the field contactor. If this operation causes too much sparking on the switches the rotor can be brought around, as in method 1, by throwing the switches consecutively in positions 1-*E*, 2-*F*; 2-*E*, 3-*F*; 3-*E*, 1-*F*; and closing and interrupting the circuit through the field contactor.

The results of practical experience with these methods in moving around the 300-ton rotors of some 50,000-hp generators showed that with this method it was possible to accomplish in an hour's time with 2 men that which would have required a crew of 6 men 12 hr to do by mechanical means. It was found to be possible, due to the fact that the static friction of the bearings is much greater than the running friction, to advance the rotor several pole pitches at a time by changing the connections for a 120-deg phase advance and closing and quickly opening the field contactor. If the field is left applied the rotor will usually oscillate in its new position several times before coming to rest, but sometimes with a 120-deg phase advance it will jump 2 pole pitches before coming to rest. Thus, if the field is interrupted just as the rotor starts to move, it is possible to make use of the stored energy in the rotor to move it several pole pitches instead of it being used up in oscillation.

By using the first method it is possible to bring the rotor to rest within plus or minus 30 electrical degrees of its required position; with method 2 it is possible to come within plus or minus 15 electrical degrees. As the last few mils in either case has to be obtained by means of a hydraulic jack, method 1 is usually close enough, but if a little closer alignment is required a movement of 30 electrical degrees on either side of the final position may be obtained by shifting the field cable from the neutral to one or other of the phases which is not closed through the disconnecting switch; thus if phase 3 is closed, shifting the neutral cable to phase 1 or 2 will advance or retreat the rotor 30 electrical degrees, leaving the rotor within plus or minus 15 electrical degrees of its required position.

The movements in this article have been described in electrical degrees. To bring any movement in electrical degrees to mechanical degrees multiply by 2 divided by the number of poles. Thus in a 40-pole generator 30 electrical degrees is $\frac{30 \times 2}{40} = 1.5$ mechanical degrees, in a 96-pole generator it would be $\frac{30 \times 2}{96} = 0.625$ degree mechanical, which would be $^1/_8$ of an inch on a 56-in. diameter coupling. Hence, it is within $^1/_8$ of an inch ahead or back of its desired position.

When making these connections with either method 1 or 2, care has to be observed to make sure that the discharge resistor is still across the windings, otherwise punctured field insulation may result.

While this procedure was evolved originally for realigning couplings it may be that it can be used efficaciously with any synchronous machine connected to its prime mover or load for jogging the rotor around for inspection, examination of clearances, timing of valves, injection pumps, etc., of reciprocating engines, replacement of pistons, piston rings, etc.

Very truly yours,

H. R. Sills (A'24, M'31)
(A-C Engineering Dept., Canadian General Electric Co., Ltd., Peterboro, Canada)

Engineering Schools and the Changed Conditions

To the Editor:

In his letter "Engineering Schools and the Changed Conditions" appearing in Electrical Engineering for December 1933, p. 936–7, Professor Brainerd of the Moore School of Electrical Engineering, University of Pennsylvania, strongly advocates the rigid curriculum in preference to the elective or liberalized curriculum which has been adopted by the engineering school at Harvard University and which was described briefly by me in an earlier letter to Electrical Engineering (September 1933, p. 647). I believe that it would be regrettable if engineering education should become standardized. A rigid curriculum possibly may produce the better educational results in some schools, whereas other engineering schools may find that the liberalized curriculum is best adapted to their needs. In education, which cannot be reduced to any formula and which should always be adapting itself to changing conditions, it is only by continual experimenting based upon experience that the best methods are ultimately determined.

Professor Brainerd draws from my letter the conclusion that with the liberalized curriculum, fundamentals are sacrified. I did not intend to convey this impression because it is just contrary to our actual experience and intent. In the first place, it is my belief that in engineering education, "fundamentals" is a very much overworked word and too many times it covers a multitude of educational sins. However, if it be assumed that the teaching of fundamentals means the establishment of engineering phenomena by means of the few basic laws of science, even advanced professional courses cannot be taught, except perhaps in a very superficial manner, without continual reference to "fundamentals." For example, it is not possible to give properly a course in a-c machinery, power transmission, or vacuum tubes without continual reference to such basic laws as Coulomb's law, the law governing the attraction and repulsion of magnetic poles, the Biot-Savart law, Ohm's law, the basic law of electromagnetic induction, electron mobility, etc. In an advanced graduate course in high voltage engineering, which I give, even the more complicated capacitive relationships in high voltage circuits are derived directly from Coulomb's law; throughout the course reference is made to this and to other simple laws in the derivations of the more involved electrostatic laws. To my mind, no professional course in electrical engineering is properly given if reference to the so-called fundamentals is not frequent and continuous.

Moreover, it is our experience that students do not actually learn their "fundamentals" in the so-called fundamental courses, but they merely become very slightly acquainted with them. It is only by continual application in the more advanced professional courses that students even begin to make such laws of their own. It is significant that many students inform us of the excellent training in mathematics which they receive from courses in electrical engineering. The reason is that by frequent application to concrete problems, the student finally understands and gets the ability to use the mathematical principles with which he could become only slightly acquainted in the short time allowed for the mathematics course itself. The teaching of so-called fundamentals does not depend upon the content of the curriculum, but on the engineering teacher himself.

Professor Brainerd undoubtedly infers that in the liberalized curriculum the student will fail to elect the basic courses in mathematics and the sciences, but will complete his curriculum with perhaps more general subjects. We find that just the opposite occurs. As a rule, the engineering student, in his attempt to crowd an engineering education into the standard 4-year period, elects the science courses at the expense of the cultural and more general courses, since he feels that his professional success depends almost entirely upon an adequate training in the applications of mathematics and science to engineering problems. To be specific, I find that a number of our students now elect voluntarily a course, "Introduction to Atomic Physics," in their second year, a course formerly not required in the fixed curriculum. This tendency to specialization may be criticized in that it tends to make the engineering student a narrow technician rather than a more broadly trained engineer. However, as most of us are aware, it is

difficult if not impossible to produce simultaneously the well-trained technician and the more broadly educated man within the standard 4-year period. (In our program students must of necessity elect a certain number of cultural or general subjects, particularly in the first 2 years, since their preparation is sufficient only for a limited number of the technical courses.)

However, in the well-chosen liberalized program, the student cannot omit the basic courses. For example, as a freshman he may decide that he is interested in the 2 professional subjects, power transmission and a-c machinery. He must plan his course of study so that he will be prepared to take these subjects, probably in his fourth or fifth year. Accordingly, he would elect the following sequence of prerequisites:

Mathematics through the introduction to the calculus
Physics
Mathematics through the calculus
Electricity and magnetism or electrodynamics
A-c theory
(Power transmission; A-c machinery)

The foregoing prerequisites may be and are supplemented by other courses such as atomic theory; electron tubes; advanced differential and integral calculus; etc.

Thus, in our liberalized curriculum, it is not possible for the student to omit any of the basic or fundamental subjects.

It is encouraging to learn that at the University of Pennsylvania there now exists a strong feeling that the standard 4-years' course has become inadequate for the proper training of engineers, and that a longer period is necessary. This, of course, has been our own feeling for some time past.

Professor Brainerd believes that there is a need for unity of action and that little can be expected from the engineering societies. Although, at present, the engineering societies may not give aggressive or formal support to the lengthening of the time of the engineering program, they naturally will encourage any educational development which will produce better trained engineers. As Professor Brainerd implies, the initiative must come from some of the leading engineering schools. If the plan proves successful and the graduates of such schools show themselves to be distinctly superior in the broad as well as in the technical sense, other schools in self defense will feel obliged to follow.

Professor Brainerd's statements concerning education in the 2 older professions, law and medicine, are very pertinent to this subject, and I believe that they may even be prophetic. In the earlier days, the educational methods of training for the profession of the law and of medicine would be considered scandalous according to our present-day educational standards. However, both The Johns Hopkins University under President Gilman and Harvard University under President Eliot assumed leadership in the establishment of graduate schools in these professions. At first, in Harvard at least, there occurred immediately a diminution in the number of students, and this diminution continued for some time. It was some years before it became certain that the plan would succeed. However, the higher standards of these graduate schools began to attract the better students in increasing numbers and this type of education in law and in medicine is now practically universal among the leading universities. Undoubtedly, engineering education will go through a similar development and if the Moore School of Electrical Engineering, with a few others, will have the courage to assume leadership and adopt the graduate plan and demonstrate its effectiveness, the better engineering schools are certain to follow the example.

Incidentally, it has been very interesting to note the reaction which is occurring among our own students. I have always felt that students were unusually keen to appraise general conditions both at their own University and in the outside world. They already realize the importance of a more extended period of engineering training and a very large majority, many with very limited financial resources, are choosing of their own volition the 5-year period leading to the master's degree, in preference to the shorter period in which they are able to obtain their bachelor's degree in engineering in 4 years' time.

I can assure Professor Brainerd that Harvard University is one of the schools that is attempting to "lead them on" and it appears that the University of Pennsylvania is in sympathy with the movement.

May I add that I individually am not responsible for these more recent educational policies at the Harvard Engineering School, which were developed by the engineering faculty as a whole under the leadership of Dean Clifford.

Very truly yours,

C. L. Dawes (M'15)
(Associate Professor of Electrical Engineering, Harvard University, Cambridge, Mass.)

Slide Rule Calculation of Unbalanced 3-Phase Currents

To the Editor:

Consider the 3-phase circuit, Fig. 1, in which the values I_{ab}, I_{bc}, and I_{ac} are unequal and are known by reason of their being single-phase loads which are to be connected to the 3-phase circuit. It is required to find the line currents I_a, I_b, and I_c so as to determine the cable sizes necessary for the installation.

The condition, Fig. 1, may be represented graphically by the vector diagram, Fig. 2, in which

$$\dot{I}_a = \dot{I}_{ac} - \dot{I}_{ab} \quad (1)$$

$$\dot{I}_b = \dot{I}_{ab} - \dot{I}_{bc} \quad (2)$$

$$\dot{I}_c = \dot{I}_{bc} - \dot{I}_{ac} \quad (3)$$

For any values of the currents I_{ac}, I_{ab}, and I_{bc} the angular displacement between them will be such that the point O falls at the center of area of the triangle formed by the currents, I_a, I_b, and I_c. Then from geometry it is known that

$$ON = {}^1/_3\, I_{bc}$$

Therefore

$$\dot{I}_{ac} + \dot{I}_{ab} = ON + NM$$

or

$$\dot{I}_{ac} + \dot{I}_{ab} = -\dot{I}_{bc} \quad (4)$$

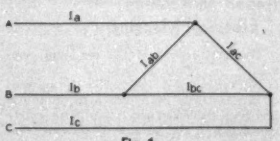


Fig. 1

A mechanical contrivance, as in Fig. 3, can be constructed which will fulfill the condition of eq 4. Four scales, OV, OS, MT, and MW of equal length, and one scale, MX, of double this length are used. Scales MW, MT, and MX are pivoted at M. Scales OV and OS are pivoted at O. Scale MX slides through O. Scales MT and OS are provided with a slide so that point Q can be set anywhere on their length and when once set at this point each of the scales is free to rotate about Q. Point P on MW and OV is similarly adjustable and when set likewise acts as a pivot.

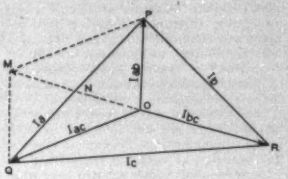


Fig. 2

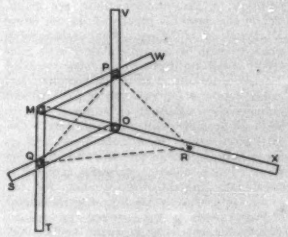


Fig. 3

To arrive at a solution for a certain set of given load currents, I_{ab}, I_{bc}, and I_{ac}, make MP and OQ equal to I_{ac}. Make MQ and OP equal to I_{ab}. Adjust MO until it is equal to I_{bc}. Set length OR equal to MO.

Then from eqs 1, 2, and 3:

$$PQ = I_a$$
$$PR = I_b$$
$$QR = I_c$$

In the solution of problems where the current values as set on the scales would be too small it will be necessary to multiply I_{ab}, I_{bc}, and I_{ac} by the constant K and then to divide the resultants, I_a, I_b, and I_c by K.

Very truly yours,

E. F. Seaman
(Assistant Electrical Engineer, Bureau of Engineering, Navy Dept., Washington, D. C.)

Standards

Graphical Symbols Used for Electric Power and Wiring

A new standards pamphlet, No. *17g2*, has just been issued by the Institute covering the accepted American standards for "Graphical Symbols Used for Electric Power and Wiring." This standard, which was developed by the sectional committee on scientific and engineering symbols and abbreviations working under the procedure of the American Standards Association, contains graphical symbols used for one line and complete diagrams of electric power apparatus, instruments, and relays, and maps and connection diagrams. The symbols are limited to apparatus usually encountered in electric power engineering such as major electrical equipment in power houses, substations, transmission and distribution systems and to system wiring diagrams. They are not intended to cover radio, communication, railway or other allied branches of electrical engineering.

Basic symbols which seem to have widespread use and application and only such symbols, with few exceptions, are given. While the symbols presented do not cover all types of equipment, the variations in practice can be accommodated with relatively small additions to the basic symbols. This is especially true of the complete diagram symbols for rotating apparatus and transformers where it is impracticable to show all possible connections of parts. The final approval of this standard was held up for a long period in an effort to eliminate some of the conflicts between symbols it contained and different symbols for the same apparatus as used in the radio and railway fields. This proved impossible. The final standard contains the conflicts but they have been plainly indicated and the symbols involved have not received approval as standards. This standard, No. *17g2* in the A.I.E.E. series, can be obtained by writing H. E. Farrer, A.I.E.E. Headquarters, 33 West 39th St., New York, N. Y. Cost is 20 cents per copy. Usual 50 per cent discount to A.I.E.E. members on single copies.

Graphical Symbols Used in Radio

This new American standard, No. *17g3*, is now available. It also was developed by the sectional committee on scientific and engineering symbols and abbreviations working in close collaboration with the committee on standardization of the Institute of Radio Engineers. It likewise has been held up for the reasons described for *17g2* above and the problem has been solved in the same way. For copies of this standard, No. *17g3*, write H. E. Farrer, A.I.E.E. Headquarters, 33 West 39th St., New York, N. Y. Cost is 20 cents per copy. Usual 50 per cent discount to A.I.E.E. members on single copies.

Graphical Symbols Used for Electric Traction

This new American standard, No. *17g5*, the third in the new graphical symbol series recently approved was developed by the sectional committee on scientific and engineering symbols and abbreviations. It comprises the graphical symbols used for diagrams for electric traction including railway signaling. The symbols are limited to apparatus used in the electrical equipment of power houses, substations, transmission and distribution systems, electrically operated cars and locomotives, and the electrical and associated equipment in railway signaling. The final approval of this standard has been long held up for the reasons outlined in the 2 preceding cases as outlined above. It has been finally approved with the same reservations indicated. Copies of the standard, No. *17g5*, can be obtained by writing H. E. Farrer, A.I.E.E. Headquarters, 33 West 39th St., New York, N. Y. Cost is 40 cents per copy. Usual 50 per cent discount to A.I.E.E. members on single copies.

Two Welding Standards

Two new American standards, Nos. 38 and 39 in the A.I.E.E. series on "Electric Arc Welding Apparatus" and "Electric Resistance Welding Apparatus," respectively are now available. These standards are revisions of the A.I.E.E. standards on the same apparatus. The revisions were developed by the sectional committee on electric welding apparatus working under the sponsorship of the A.I.E.E. and N.E.-M.A. Copies of both pamphlets may be obtained by writing H. E. Farrer, A.I.E.E. Headquarters, 33 West 39th St., New York, N. Y. Cost is, No. 38, 40 cents; No. 39, 30 cents. Usual 50 per cent discount to A.I.E.E. members on single copies.

Constant Current Transformers

A new American standard on "Constant Current Transformers," No. 12 in the A.I.E.E. series, is now available. This is a revision of the A.I.E.E. standard No. 12, which has been available since May 1930. The revision was developed by the electrical machinery committee of the Institute. Copies may be obtained by writing H. E. Farrer, A.I.E.E. Headquarters, 33 West 39th St., New York, N. Y. Cost is 30 cents per copy. Usual discount of 50 per cent to A.I.E.E. members on single copies.

Report on Rotating Electrical Machinery

The first report of the sectional committee on rotating electrical machinery (C50), organized in 1930 under the auspices of the American Standards Association has just been published and is now being widely circulated for the purpose of securing comments and suggestions. The report includes standards for d-c rotating machines; synchronous generators, synchronous motors and synchronous machines in general; synchronous converters; induction motors and induction machines in general; and a-c and d-c fractional horsepower motors.

The report is largely based upon the 5 standards of the A.I.E.E. on these same subjects, Nos. 5, 7, 8, 9, and 10. Since the proposed new standards are in the nature of a revision, they will, when approved, supersede these 5 standards. The scope of the standards has been broadened, however, to include, in addition to the material covered in the A.I.E.E. standards, a large number of widely used standard rules developed by the National Electrical Manufacturers Association.

Up to the present time these A.I.E.E. and N.E.M.A. standards have served as the principal bases of specifications for electrical machines. It is expected that the combination of these 2 important sets of standards in a single publication, to be approved finally by the A.S.A., will be of maximum usefulness to the buyer, seller, and manufacturer of rotating electrical machinery.

In the proposed standards emphasis has been placed upon the terms and conditions which characterize the rating and behavior of electrical machinery, with special reference to the conditions upon which acceptance tests are based.

The sectional committee on rotating electrical machinery which is under the sponsorship of the Electrical Standards Committee, is composed of 32 representatives of 15 organizations and is broadly representative of the electrical industry. L. F. Adams, General Electric Co., Schenectady, N. Y., is chairman of the committee.

Comments and suggestions are solicited from all interested in order to assist the committee in satisfactorily rounding the standards into final form. All comments should be addressed to E. B. Paxton, General Electric Co., Schenectady, N. Y.

At the end of a 6 months' period, after criticisms and comments have been received and considered, the standards will be submitted through the sponsor, the Electrical Standards Committee, to the American Standards Association for approval as American standards.

Copies of the report may be purchased from the office of the American Standards Association, 29 West 39th St., New York, N. Y., at 25 cents each.

Standard Methods for Electrical Measurements

The long expected recommended practice on "Electrical Measurements" developed by the A.S.M.E. power test codes committee on instruments and apparatus will become available in March 1934. Throughout the progress of the work on this publication the A.S.M.E. committee had the complete coöperation of the A.I.E.E. standards committee.

Electrical and mechanical apparatus are often closely associated in the generation and use of power. In 1918 when the committee on power test codes of The American Society of Mechanical Engineers outlines the scope of its work, it was natural for it to arrange for the development of supplemen-

tary material on electrical measurements and such a section of "Instruments and Apparatus" was subsequently developed by the P.T.C. Committee No. 19 of which Dr. C. F. Hirshfeld is chairman. Other members of the committee most closely associated with this development are F. Malcolm Farmer and Everett S. Lee.

"Electrical Measurements" contains sections on voltage, current, power, energy, resistance, frequency, and power-factor measurements; instrument transformers, load rheostats, and input of motors and output of generators. The last named section is the one to which the greatest amount of attention was given by the reviewers and the committee feels confident that it now records a definite step in advance. The prepublication price to A.I.E.E. members has been set at $1. Orders with remittance should be sent to publication sales dept., The American Society of Mechanical Engineers, 29 West 39th St., New York, N. Y.

American Engineering Council

Officers Elected at Annual Meeting

J. F. Coleman, consulting engineer of New Orleans, La., past-president of the American Society of Civil Engineers, was elected president and F. M. Feiker, formerly director of the bureau of Foreign and Domestic Commerce of the U.S. Bureau of Commerce, was appointed executive secretary of the American Engineering Council at the annual meeting of American Engineering Council held in Washington, D. C., January 11–13, 1934. Other officers representing the several national and local engineering societies were elected as follows: For vice-presidents of the Council, C. O. Bickelhaupt (M'22, F'26, and past vice-president), vice-president of the American Telephone and Telegraph Company, New York, N. Y., representing the A.I.E.E., Paul Doty (A'04, M'12), consulting engineer, St. Paul, Minn., representing The American Society of Mechanical Engineers, A. J. Hammond, consulting engineer of Chicago, Ill., representing The American Society of Civil Engineers, W. H. Woodbury, Duluth, Minn., representing the local engineering societies. C. E. Stephens (M'22) of the A.I.E.E. was elected treasurer, and William McClellan (A'04, M'09, F'12, and past-president), president of the Potomac Electric Power Company of Washington, was elected chairman of the finance committee.

Retiring president of Council, W. S. Lee (A'04, M'04, F'13) of Charlotte, N. C., in his opening address called attention to the 13 years of development of the American Engineering Council pointing out that to its deeper purpose of serving the public, there had been brought together scores of professional men, leaders in the industrial, engineering, and public utility fields as well as those representing municipal, state, and federal activities. Among those who had been active in Council were 46 presidents of the 4 national societies of civil, electrical, mechanical, and mining engineers, 25 presidents of other national engineering societies, and 69 presidents of state and local professional engineering organizations. Mr. Lee pointed out that nearly $^3/_4$ of a million dollars had been spent to prosecute the public good, through the work of the Council, including some $90,000 for direct research into the engineering values of public and private engineering enterprises.

F. M. Feiker Appointed Executive Secretary

Frederick M. Feiker has been appointed executive secretary of American Engineering Council, Washington, D. C., a position for 13 years held by L. W. Wallace, who has resigned to become vice-president of the W. S. Lee Engineering Corporation. Mr. Feiker brings to his new position a unique experience in both private and public business. Since his graduation as an electrical engineer from Worcester Polytechnic Institute in 1904, he has spent the first half of his business life in editorial and publishing work, having been consecutively editor and chairman of the editorial board of the A. W. Shaw Company of Chicago, Ill., and editor and vice-president in charge of editorial policy for the McGraw-Hill Publishing Company, New York, N. Y.

Beginning in 1920, Mr. Feiker undertook a broader field of public service and was successively assistant to the Secretary of Commerce, operating vice-president of the Society for Electrical Development, managing director of the Associated Business Papers, Inc., director of the Bureau of Foreign and Domestic Commerce of the Department of Commerce. During the past 6 months Mr. Feiker has been in charge of an inquiry into the needs and methods of developing trained men for the textile industry, in coöperation with the textile engineering departments of our northern and southern educational institutions, under an educational grant from the Textile Foundation. Mr. Feiker assumed his new duties early in January.

L. W. Wallace Leaves American Engineering Council

Announcement has been made of the resignation of L. W. Wallace as executive secretary of American Engineering Council, Washington, D. C. Mr. Wallace has been appointed to the position of vice-president of the W. S. Lee Engineering Corporation in charge of the Washington office.

Mr. Wallace has been active in guiding the policies of American Engineering Council since its organization 13 years ago. On February 14, 1921, he was elected executive secretary and held this position continuously up to his recent resignation. Mr. Wallace graduated from Texas Agricultural and Mechanical College with the degree of B.S. in M.E. in 1903, later receiving the degree of M.E. from Purdue University in 1912. From 1903 to 1906 he was special apprentice to the Santa Fe Railway, and between 1906 and 1917 rose from the position of instructor to that of professor at Purdue University. Here he was in charge of the department of railway and industrial management. From 1917 to 1919 he was assistant general manager of the Diamond Chain and Manufacturing Company, Indianapolis, Ind., and from 1919 to 1921 was director of the Red Cross Institute for the Blind, Baltimore, Md. This was followed by his long service with American Engineering Council.

Mr. Wallace is a member of many societies including The American Society of Mechanical Engineers, Washington (D. C.), Society of Engineers, Engineers' Club of Philadelphia, Society of Industrial Engineers (past-president), Indiana Engineering Society (past-president), American Academy of Political and Social Science, Washington Academy of Science, and the American Association for the Advancement of Science. He is an honorary member of the Masaryk Academy of Works, Prague, and the Institute of Scientific Management of Poland. He has been decorated with the Cross of Knight of Order of White Lion (Czechoslovakia).

Engineering Foundation

Valuable Books in Engineering Societies Library

The schedule of books in the Engineering Societies Library located at 33 West 39th Street, New York, N. Y., and upon which the annual appraisal for fire insurance is based for 1934, contains so much of interest about the treasures of this library possessed by the 4 national societies of civil, mechanical, mining, and electrical engineers that a brief note is published herewith.

The appraisal of the books of different classifications is as follows:

General books:	137,250 at $2.50	$343,125
Bibliographies:	1,000 at $1.00	1,000
Catalogs, furniture, etc.		75,090
Rare books and manuscripts:		
Books published between 1501 and 1600, maximum value $100		8,400
Books published between 1601 and 1700, maximum value $75		11,000
Books published between 1701 and 1800, maximum value $50		13,475
Other rare books and manuscripts		28,800
Total		$480,800

Perhaps the most interesting item in this table is "other books and manuscripts," and it is to be regretted that space limitations do not permit further amplification here. Many rare and valuable books and manuscripts are included in this classification. Many of them are old, dating back to 1473 and are of considerable value, the most valuable single item being listed at $3,500. Others, such as an Edison manuscript valued at $1,000, are of comparatively recent origin.

Personal Items

C. W. Kellogg (A'19, M'23) formerly president of the Engineers Public Service Company, New York, N. Y., a subsidiary of Stone and Webster, Inc., has been made chairman of the board of this organization. His connection with the Stone and Webster interests dates back to 1903, following graduation from the Massachusetts Institute of Technology. Since 1925 he has been president of the Engineers Public Service Company.

C. O. Bickelhaupt (M'22, F'28, and past vice-president) vice-president of the American Telephone and Telegraph Company, New York, N. Y., and a representative of the A.I.E.E. on the administrative board of American Engineering Council Assembly, was elected a vice-president of the Council for the 2-year term 1934–35, at its annual meeting held in Washington January 11–13, 1934.

C. E. Stephens (M'22) vice-president of the Westinghouse Electric and Manufacturing Company, New York, N. Y., and a representative of the A.I.E.E. on the administrative board of American Engineering Council Assembly, was elected treasurer of American Engineering Council for the term of 1 year at the meeting held in Washington, D. C., January 11–13, 1934.

William McClellan (A'04, M'09, F'12, and past-president) president of the Potomac Electric Company, Washington, D. C., and a representative of the A.I.E.E. on American Engineering Council Assembly, was elected chairman of the finance committee of American Engineering Council at its meeting held in Washington, D. C., January 11–13, 1934.

W. L. Winter (A'21) sales engineer in the central station department of the San Francisco (Calif.) office of the Westinghouse Electric and Manufacturing Company, has been transferred to the Salt Lake City, Utah, office to succeed the late E. L. Morris. Mr. Winter joined the San Francisco office of the company in 1920.

Paul Doty (A'04, M'12) chairman of the Minnesota State Board of Registration for Architects, Engineers, and Land Surveyors, St. Paul, Minn., and also president of The American Society of Mechanical Engineers, was recently elected a vice-president of American Engineering Council, to serve for the 2-year term 1934–35.

Arnold Roth (A'26) former technical director of the Ateliers de Constructions Electriques de Delle, Villeurbanne, Rhone, France, has recently been entrusted with the direction of the Fabrique d'Appareillage Electrique Sprecher & Schuh, Aarau, Switzerland.

J. A. Walls (A'03, F'13) vice-president and chief engineer of the Pennsylvania Water and Power Company, Baltimore, Md., since 1914, and of the Safe Harbor Water Power Corporation since its founding, has been elected president of both of these organizations.

F. A. Allner (A'12, M'14) general superintendent of the Pennsylvania Water and Power Company, Baltimore, Md., was recently elected a vice-president of that company. Mr. Allner has been associated with the Pennsylvania Water and Power Company since its organization in 1910.

Melville Eastham (A'19, M'26) president of the General Radio Company, Cambridge, Mass., has been appointed a member of the board of directors of the Institute of Radio Engineers for the year 1934.

W. G. Cady (M'19) professor of physics, Wesleyan University, Middletown, Conn., and junior past-president of the Institute of Radio Engineers, continues as a member of the board of directors of this organization during 1934.

William Wilson (M'23) assistant director of research, Bell Telephone Laboratories, Inc., New York, N. Y., has been elected a member of the board of directors of the Institute of Radio Engineers for the years 1934–36.

E. L. Nelson (A'20, M'26) radio development engineer, Bell Telephone Laboratories, Inc., New York, N. Y., continues as a member of the board of directors of the Institute of Radio Engineers for the year 1934.

E. R. Shute (M'17) general superintendent of traffic, Western Union Telegraph Company, New York, N. Y., has been appointed a member of the board of directors of the Institute of Radio Engineers for the year 1934.

J. V. L. Hogan (A'11, M'20) consulting engineer, New York, N. Y., has been appointed a member of the board of directors of the Institute of Radio Engineers for the year 1934.

A. N. Goldsmith (M'15, F'20, and life member) editor of the Institute of Radio Engineers, has been elected a member of the board of directors of this organization to serve for the 3-year term 1934–36.

L. M. Hull (M'27) Aircraft Radio, Boonton, N. J., and junior past-president of the Institute of Radio Engineers, becomes a member of the board of directors of this organization for the 2-year term 1934–35.

O. H. Caldwell (A'13, M'22) editor of *Electronics*, New York, N. Y., continues as a member of the board of directors of the Institute of Radio Engineers for the year 1934.

R. A. Heising (A'15) radio engineer, Bell Telephone Laboratories, Inc., New York, N. Y., continues as a member of the board of directors of the Institute of Radio Engineers during the years 1934–35.

L. C. F. Horle (A'20, M'22) consulting engineer, Newark, N. J., has been appointed a member of the board of directors of the Institute of Radio Engineers for the year 1934.

F. A. Kolster (M'19) International Communications, Inc., New York, N. Y., continues as a member of the board of directors of the Institute of Radio Engineers for the years 1934–35.

H. M. Turner (A'20) associate professor of electrical engineering, Yale University, New Haven, Conn., continues as a member of the board of directors of the Institue of Radio Engineers for the years 1934–35.

C. T. Mess (A'27, M'29) assistant engineer of the California State Railroad Commission, has been appointed valuation engineer of that organization.

C. M. Jansky, Jr. (A'20, M'32) consulting radio engineer, Washington, D. C., has been elected president of the Institute of Radio Engineers for the year 1934.

Obituary

Giuseppe Faccioli (A'04 M'11, F'12, and past vice-president) former works engineer and associate manager of the Pittsfield, Mass., works of the General Electric Company, died in Pittsfield, Mass., January 13, 1934. He was born at Milan, Italy, in 1877. In 1899 he graduated from the University of Milano, as a mechanical and electrical engineer, obtaining the gold medal assigned by the Society of Italian Engineers for the highest scholarship. For the following year he was with the Societa Elvetica of Milano, manufacturers of locomotives, engaged in changing the motive power of the factory from steam to electricity. From 1900 to 1901 he was with the Tecnomasio Brown Boveri Company of Milano, being at first in the testing room and later in charge of the design of induction motors and alternators. From 1901 to 1902 he engaged as a consulting engineer. In 1902 he came to the United States, being in the testing laboratory of the New York Edison Company for the first few months. During the year 1903 he was with the Interborough Rapid Transit Company, New York, in L. B. Stilwell's office as inspector in the installation of the lighting system in the New York subway. During 1904 he was with the Crocker-Wheeler Company as designing engineer, mainly assisting William Stanley in the development of his new type of induction alternator. Early in 1905 he became assistant

to Mr. Stanley in his Great Barrington, Mass., laboratory, engaged in the development of several types of equipment. In 1906, with Mr. Stanley, he entered the employ of the General Electric Company, continuing work at the Great Barrington laboratory until 1908 when Mr. Faccioli was transferred to the railway department at Schenectady, N. Y. Later the same year he was transferred to the transformer department as advisory engineer, and in 1911 was appointed assistant engineer of the transformer department. Later he was transferred to the Pittsfield works, and in 1913 was appointed works engineer of the Pittsfield plant. In 1927 he became associate manager. He retired because of ill health in 1930. The Institute's Lamme Gold Medal for 1931 was presented Mr. Faccioli during the summer convention at Cleveland, Ohio, in 1932, "for his contributions to the development and standardization of high-voltage oil-filled bushings, capacitors, lightning arrestors, and numerous other features in high voltage transformers and power transmission." Mr. Faccioli had served the Institute as manager 1918–22, and as vice-president 1922–24. He also had served on the following committees of the Institute: board's committee on technical activities 1919–20, Edison Medal 1919–21 and 1922–24, electrical machinery 1919–27, electrophysics 1916–17, protective devices 1916–17, transmission and distribution 1918–19, and code of principles of professional conduct 1921–34. Mr. Faccioli was the author of many papers on engineering subjects.

Everett Morss (A'11, M'11, F'13) president of the Simplex Wire and Cable Company, Boston, Mass., died in that city December 27, 1933. He was born in Boston in 1865. In 1885 he received the degree of bachelor of science from Massachusetts Institute of Technology, Cambridge, and in that year undertook to manufacture insulated wire for the predecessor of The Simplex Electrical Company; after nearly a year of experimenting he developed the Simplex T. Z. R. weatherproof wire. In 1889 he started the manufacture of rubber insulated wire, the business gradually developing into the manufacture of all varieties of rubber insulated wire and cable. In 1895, upon the incorporation of The Simplex Electrical Company, Mr. Morss became its vice-president, and in 1903 became president. Throughout the history of The Simplex Electrical Company and its predecessors, he had charge of the manufacture, including the development of all processes, building of factories, and all technical and engineering problems. In 1895 he took charge of the manufacture of electric heating apparatus for the American Electric Heating Corporation, but after 2 or 3 years was obliged to give up direct charge of this work because of insufficient time to devote to it. In 1902 he became vice-president of the Simplex Electric Heating Company, upon its incorporation, and for a number of years he had much to do with the development and manufacture of its products, although not actively in personal charge. Upon the incorporation of the Simplex Wire and Cable Company, Mr. Morss became president, continuing in this capacity until his death. He also was president of the Franklin Foundation, and was a trustee and director in several concerns. During the War he was a member of the priorities committee of the War Industries Board 1917–18, and chief of its brass section 1918. He was a member of the corporation of Massachusetts Institute of Technology, having served as treasurer and a member of the executive committee, and has been president of the Boston Chamber of Commerce 1921. He was a member of The American Society of Mechanical Engineers and of Theta Zi fraternity. In 1923 Tufts College conferred upon him the degree of master of arts. He was a member of the following clubs: Metropolitan (Washington); Union, University, Exchange, St. Botolph, Algonquin (Boston); Engineers', Bankers (New York); and Country (Brookline).

William Bancroft Potter (A'96, M'96) formerly consulting engineer of the transportation department of the General Electric Company, Schenectady, N. Y., and for many years the engineer of the company's railway department, died January 15, 1934. He was born in 1863 at Thomaston, Conn. From 1881 to 1887 he was a machinist for E. H. Judd and Son, Hartford, Conn. From 1887 he became engineer for the Thomson-Houston Electric Company, Lynn, Mass. In 1894 he was transferred to Schenectady, being chief engineer of the railway department of the General Electric Company between 1895 and 1930. In the latter year he retired from active service. During the early years of his career he devised the series-parallel controller for street cars, which for many years has been the underlying principle of most methods of street car control systems. He also was active in the promotion of gas-electric rail cars and oil-electric locomotives, and directed several railroad electrifications. Some 134 patents had been granted him. He has written many articles for technical societies and was a member of the American Society of Civil Engineers, The American Society of Mechanical Engineers, and the Society of Naval Architects and Marine Engineers. He was a member of the following clubs: Engineers', Transportation, Railroad (New York); Mohawk, Mohawk Golf, Edison (Schenectady); and Griswold (Erie). For the Institute, Mr. Potter served as a member of the traction and transportation committee 1916–17, 1919–21, and 1923–24; transportation committee 1925–32; and education committee 1933–34.

Joseph Dufferin Peters (M'25) general manager and engineer for the National Light and Power Company, Moose Jaw, Saskatchewan, Canada, died November 27, 1933. He was born in Perth County Ontario, in 1884. He studied for 2 years at the Collegiate Institute, Stratford, Ontario. Up to 1907 he was engaged in the operation and construction of steam plants and distribution systems for the following organizations: Thames Dairy Company, London, Ontario; Canadian Milk Products Company, Brownsville, Ontario; Barkey Bros., Tillonsburg, Ontario; and London Electric Company, now Ontario Hydro Electric Power Commission, London, Ontario. From 1907 to 1908 he installed the electric plant for the Moore Milling and Electric Company, Qu'Appelle, Saskatchewan. From 1908 to 1909, he was operating engineer of the Municipal power plant at Moose Jaw. In the latter year he became manager of the municipal light and power department for the city and Moose Jaw, remaining in this capacity until 1930; here he designed and redesigned equipment and supervised construction and operation of the system during its development from 600-kw to 11,000-kw capacity. From 1930 until his death he was general manager for the National Light and Power Company, Ltd., purchasers of the Moose Jaw plant. During this period he supervised further additions to the plant to a total capacity of 21,000 kw. He had served the Institute as a chairman of the Saskatchewan Section. Mr. Peters also was a member of the Registered Professional Engineers' Society, Province of Saskatchewan, and was an associate member of the Engineering Institute of Canada, having been chairman of its Saskatchewan Branch.

Arthur A. Brown (A'10, M'13) assistant to vice-president, Westinghouse Electric and Manufacturing Company, New York, N. Y., died December 19, 1933. He was born at Three Creeks, Ark., in 1873. After serving as an apprentice in the foundry and machine shop of the H. B. Smith Company, Westfield, Mass., he entered the mechanical engineering department of the University of Illinois in 1898. At the end of 3 years he went to work with the Bethlehem Steel Company, South Bethlehem, Pa., as machinist. A few years later he returned to the H. B. Smith Company as assistant superintendent, 2 years later becoming general superintendent of the Richmond Company of Norwich, Conn., manufacturers of house heating apparatus. A short time later he became general manager of the Rarig Engineering Company of Columbus, Ohio, manufacturers of blowing engines and blasting furnaces. In 1904 he gave up industrial work and entered the sales department of the Westinghouse Machine Company, Pittsburgh, Pa. In 1907 he was made Pittsburgh district manager for the Westinghouse-Church-Kerr Company. Two years later he was placed in charge of all syndicate operations of the Westinghouse Electric and Manufacturing Company, with headquarters in New York, holding this position continuously from 1909 to 1926, when he was appointed assistant to vice-president. He was a member of the former National Electric Light Association, and the Engineers' Club, The Railroad Club, and the Bankers' Club, all of New York, and Siwanoy Country Club.

Clare Nowlen Stannard (A'28) vice-president and general manager of the Public Service Company of Colorado, Denver, and one of the most prominent executives in the Henry L. Doherty organization, died in Denver on January 2, 1934, after a short illness. Born in Friendship, N. Y., in 1869, he attended public and high schools in Binghamton, N. Y., then obtained training for special work in 7 years as a cadet with the Binghamton Gas and Electric Company, including training in banking, street railway,

gas, electric, and water utility work. In 1897 he entered the employ of the Denver Tramway Company, transferring to the Denver Consolidated Electric Company in 1898. This company was merged to form the Denver Gas and Electric Light Company, and later the Public Service Company of Colorado. Mr. Stannard became commercial manager of the company, and in 1921 was made vice-president and general manager and was active in this office until his death. During his administration the company developed rapidly and extended its services to cover a large portion of the state. He was prominent in the civic activities of his city and state, and was a member of many clubs and organizations, including the Denver Club, Rotary, Denver Country Club, Denver Athletic Club, Cherry Hills Club, Wigwam Club, Illuminating Engineering Society, and was past vice-president of the American Gas Association and past president of the National Commercial Gas Association. He also had served as president of the Rocky Mountain division of the National Electric Light Association.

Membership

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before January 31, 1934, or March 31, 1934, if the applicant resides outside of the United States or Canada.

Aggers, C. V., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Armstrong, G. C. (Member), Westinghouse Elec. Mfg. Co., E. Pittsburgh, Pa.
Aycock, W. C., N. Y. & Queens Elec. Lt. & Pwr. Co., Flushing, L. I., N. Y.
Bayer, M. H., East End Music Co., N. Y. City.
Bond, E. Jr., Union Carbide Co., Niagara Falls, N. Y.
Bozak, E. M., C. J. Crowley Elec. Co., Torrington, Conn.
Brabson, R. M., Jr., N. Y. & Queens Elec. Lt. & Pwr. Co., Flushing, L. I., N. Y.
Brooks, W. W., Ill. Water Survey, Mason City.
Brunn, R. B. J., Savil Radio Engr. Corp., N. Y. City.
Brunner, C., Metropolitan Device Corp., Bklyn., N. Y.
Burke, T. A., N. Y. State Dept. of Health, Albany, N. Y.
Burton, W. R., Ohio Bell Tel. Co., Cleveland.
Campbell, D. L., Okla. Gas & Elec. Co., Sapulpa.
Canepa, T. T., 1415 No. Bdway., Milwaukee, Wis.
Carson, R. J., Bklyn. Edison Co., Inc., Bklyn., N. Y.
Clark, H. W. (Member), Potomac Elec. Pwr. Co., Washington, D. C.
Cluver, H. J., 161 W. 100 St., N. Y. City.
Cottony, H. V., 317 W. 124 St., N. Y. City.
Cowan, J., Bronx Gas & Elec. Co., N. Y. City.
Davis, A. F., 123 W. Houston St., Tyler, Texas.
Dewey, C. S., Natl. Equip. Co., Springfield, Mass.
Driver, P. C., 1607 Opal St., Pullman, Wash.
Dunn, A., 470 Ontario St., Albany, N. Y.
Edwards, L. T., Main St., East Hampton, L. I., N. Y.
Eldred, W. N., 527 Almer Rd., Burlingame, Calif.
Emery, G. W. (Member), The Froehlich & Emery Engg. Co., Toledo, O.
Emery, J. R., (Member), The Froehlich & Emery Engg. Co., Toledo, O.
Ensmann, B., N. Y. Edison Co., N. Y. City.
Ensor, A. H., 14 Tilton Ave., Brockton, Mass.
Farber, L. M., Fisher Body Corp., Leeds, Kansas City, Mo.
Finkenauer, F. J., Jr., c/o Samuel Bell, Jr., Inc., Germantown, Phila., Pa.
Fleshler, A. D., Transit Commission, N. Y. City.
Caballe, C. A., N. Y. Edison Co., N. Y. City.
Gabel, G. H., Pa. Dept. of Highways, Selinsgrove.
Gagnier, C. E., Carnegie Steel Co., Youngstown, O.
Goodsell, E. M., Meriam Co., Cleveland, O.
Gordon, G. (Member), 31 So. Miller St., Newburgh, N. Y.
Grauch, W. F., Pa. Dept. of Highways, Upper Darby.
Green, H. A., The Green-Mills Const. Co., Bedford, O.
Grossfeld, C., 1634 80th St., Bklyn., N. Y.
Guinther, G. LaV., Defiance Paper Co., Niagara Falls, N. Y.
Halamka, G. L., 1419 Douglas Ave., Racine, Wis.
Harmon, E. B., Mountain States Tel. & Tel. Co., Denver, Colo.
Harries, K. R., Potomac Elec. Pwr. Co., Washington, D. C.
Hart, N. L., 10275 Pico Blvd., Los Angeles, Calif.
Hoff, H. B., Am. Dist. Tel. Co., Cleveland, O.
Hoffman, K. B., N. Y. Edison Co., N. Y. City.
Hostetter, J. W., N. Y. Edison Co., N. Y. City.
Hulswit, W. H., Jr., Northwestern Univ., Evanston, Ill.
Iaskip, L. S., Am. Tel. & Tel. Co., N. Y. City.
Job, B. W., 2634 South Troy St., Chicago, Ill.
Kazine, I. A., 46 Downing St., Bklyn., N. Y.
Kennedy, H. E., 105 Tunnel Rd., Berkeley, Calif.
Kime, R. M., N. Y. Edison Co., N. Y. City.
Kinzelman, G. W., 6553 Newgard Ave., Chicago, Ill.
Kisch, J. P., Pub. Serv. Elec. & Gas. Co., Irvington, N. J.
Kloeblen, E. M., J. G. White Engg. Corp., N. Y. City.
Knight, K. T., Carolina Pwr. & Lt. Co., Marion, S. C.
Kopper, J. M., The Garey School, Aberdeen, Md.
Kuelthau, W. A., Pub. Serv. Commission of Wis., Madison.
Kuyper, W. W., Gen. Elec. Co., Schenectady, N. Y.
Larson, S. D., 614 E. St. Vrain St., Colo. Springs, Colo.
Lattin, W. J., Columbia Univ., Univ. Heights, N. Y. City.
Lindemuth, H. F., N. Y. Edison Co., N. Y. City.
Loustaunau, J. J., 218 W. Johnson St., San Antonio, Texas.
Lovelace, C. K., Okla. Gas & Elec. Co., Enid.
Lowe, R. E., Gen. Elec. Co., N. Y. City.
Marceau, J. P., 5073 Bourbonnieve Ave., Montreal, Quebec, Can.
Meador, J. R., Gen. Elec. Co., Pittsfield, Mass.
Montgomery, W. N. (Member), Missouri Chiropractic Col., St. Louis, Mo.
Mulholland, R. A., East 3rd St., Lampasas, Texas.
Murphy, L. W., 12 Stedman St., Hartford, Conn.
Naldoff, F. R., U. S. Bureau of Reclamation, Almira, Wash.
Newman, W. W., Great Falls, S. C.
Olsen, M. L., Southwestern Bell Tel. Co., Okla. City, Okla.
Parks, C. E., Jr., Northern Ind. Pwr. Co., Kokomo, Ind.
Payne, W. T., Y.M.C.A., Springfield, Mass.
Persio, L. N., 224 W. 4 St., Williamsport, Pa.
Philipps, R. J., Kenyon Transformer Co., Inc., Bronx, N. Y. City.
Polisco, J., 423 Chadwick Ave., Newark, N. J.
Potter, F. M., Worcester Poly. Inst., Mass.
Powell, J. R., Jones & Laughlin Steel Corp., Aliquippa, Pa.
Quesu, H. J., 106 Utica Ave., Bklyn., N. Y.
Reid, J. O., United Elec. Lt. & Pwr. Co., N. Y. City.
Reid, W. S., Potomac Elec. Pwr. Co., Washington, D. C.
Richards, H. N., Pa. Elec. Repair Co., Pittsburgh.
Schulz, E. L., N. Y. & Queens Elec. Lt. & Pwr. Co., Flushing, N. Y.
Seidman, S. M., Ohio Bell Tel. Co., Cleveland.
Shaw, F. W., Kansas City Pwr. & Lt. Co., Mo.
Siedler, F., Pa. R.R., Phila.
Slinger, R. N., Gen. Elec. Co., Schenectady, N. Y.
Smith, W. H., 124 W. Glenarm St., Pasadena, Calif.
Smith, W. S., S. C. State Highway Dept., Kershaw, S. C.
Spielman, S. C., Philco Radio Co., Phila., Pa.
States, F. P., Emaks Battery Corp., Belleville Pike, Kearny, N. J.
Stringer, G. L., 26 Middagh St., Bklyn., N. Y.
Thompson, A. I., 62 Summit St., Ridgefield Park, N. J.
Titgemeyer, J. C. (Member), The Froehlich & Emery Engg. Co., Toledo, O.
Toole, M. G., Clark St., Maryville, Tenn.
Toombs, J. E., 224 W. Centennial Ave., Muncie, Ind.
Triest, R. M., John Wiley & Sons, N. Y. City.
Tutwiler, J. W., N. & W. Ry., Portsmouth, O.
Urquhart, A. R., Broad River Pwr. Co., Columbia, S. C.
Wells, E. R., Ohio Pwr. Co., Newark.
White, J. L. (Member), Appalachian Electric Pwr. Co., Roanoke, Va.
Young, R. Z., Pacific Tel. & Tel. Co., San Francisco, Calif.
Young, S. G., Averill Park, N. Y.
Zittel, T. O., Civil Works Assn., Buffalo, N. Y.

108 Domestic

Foreign

Ducati, A. C., Societa Scientifica Radio, Bologna, Italy.
Golding, E. W. (Member), Univ. Col., Nottingham, Eng.
Guha, S. K., Pub. Works Dept., Burma, India.
Hahlbeck, H. A., United River Plate Tel. Co., Buenos Aires, Argentina.
Hamid, A., Pub. Works Dept., Batala, Dist. Gurdaspur, Punjab, India.
Jan, S. K., Kashmir Hydro Elec. Installation, Baramulla, Kashmir, India.
Romanovsky, V. B., Electroapparat, W. O. 24 Linia, Leningrad, U. S. S. R.
Stanbridge, C. H. (Member), P. O. Box 1280, Cape Town, South Africa.

8 Foreign

Recommended for Transfer

The board of examiners, at its meeting of January 17, 1934, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Clarkson, Albert J., supt. of electric equipment, N.Y.C. R.R. Co., Harmon-on-Hudson, N. Y.
Davis, Ernest W., Chief E.E., Simplex Wire & Cable Co., Cambridge, Mass.

To Grade of Member

Breece, Charles A., commercial survey engr., Indiana Bell Tel. Co., Indianapolis.
Burbank, Jerome, elec. and radio engr., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Coolidge, Wm. D., director of research lab., Gen. Elec. Co., Schenectady, N. Y.
Davidson, Roy J., asst. chief engr., Pacific Pwr. & Lt. Co., Portland, Ore.
Everson, Walter A., pres., Everson-Leidy Elec. Co., Allentown, Pa.
Fairburn, A. J. B., instructor in E.E., Cooper Union Inst. of Tech., New York.
Fuhs, Raymond H., transformer engr., Indianapolis Pwr. & Lt. Co., Ind.
Kitchen, W. A., asst. supt. of elec. dept., Oklahoma Gas & Elec. Co., Oklahoma City.
Kummer, Ludwig, acting chief engr., Trinidad Leaseholds, Ltd., Pointe-a-Pierre, Trinidad, B. W. I.
Pilkington, John H., division engr., Bklyn. Edison Co. Inc., Bklyn., N. Y.
Ralston, Emmet G., operating vice-pres., Indianapolis Pwr. & Lt. Co., Ind.
Schleicher, George B., technical asst., meter div. Phila. Elec. Co., Pa.
Sullivan, George L., asst. engr., Bklyn. Edison Co Bklyn., N. Y.
Tasker, Homer G., chief engr., United Research Corp., Long Island City, N. Y.
Van Why, Forbes, W., control and transmission engr., KMTR Radio Corp., Hollywood, Calif.
Watts, Thomas R., research engr., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Wolfe, Fred I., manager, industrial pwr. serv., Metropolitan Edison Co., Easton, Pa.
Zimmerman, Andrew G., technical man, The Pacific Tel. & Tel. Co., San Francisco, Calif.

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Blackhall, Harold J., Postlagernd, Essen, Germany.
Bugnion, Frank E., 14 Clinton St., Cambridge, Mass.
Code, F. L., 6061 Trafalgar St., Vancouver, B. C., Can.
Darcy, Harris B., 305 M. & M. Bldg., Houston, Texas.
Dean, George H., Corrie, Old Shoreham Road, Shoreham-by-Sea, Eng.
Gentilini, Celso, 1512 Wood St., Wilkinsburg, Pa.
Griffith, Geo. M., R. no. 1, Tucker, Ga.
How, John H., 42 Wai Oi Road East, Canton, China.
Kahale, N. A., Box 434, W. Lafayette, Ind.
Lober, Charles, K. C. P. & L. Co., 1330 Baltimore Ave., Kansas City, Mo.
Mathisen, Karsten, V., 912 Noyes St., Evanston, Ill.
Panton, H. D., Phoenix Utility Co., c/o Kansas Gas & Elec. Co., Wichita, Kans.
Shifrin, Leonard I., c/o Tanenbaum, 12 Pinehurst Ave., New York City.
Soskin, Samuel B., 1225 S. Calif. Ave., Chicago, Ill.
Sparks, Losey D., 1507 Sherwin Ave., Chicago, Ill.
Talbot, H. L., 55 Pine Ave. E., Montreal, Que., Can.
Weber, George A., 537 Addison Ave., Palo Alto, Calif.
Whittemore, J. D., 126 State St., Albany, N. Y.

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, during December are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

FORSCHUNGSHEFT 362. KURZSCHLUSSERWÄRMUNG von KABELN. By A. Hecht. Berlin, VDI-Verlag, 1933. 25 p., illus., 12 x 8 in., paper, 5 rm. This, according to the author, is the first study to be made of the heating of insulated cables during short circuits. The question is here subjected to a theoretical and experimental investigation. Formulas for practical use are developed.

HANDBOOK of CHEMISTRY and PHYSICS, 18 ed. Edit. by C. D. Hodgman. Cleveland, Ohio, Chem. Rubber Pub. Co., 1933. 1818 p., illus., 7 x 4 in., lea., $6.00. Intended to provide the physical and chemical tables and formulas needed by engineers and scientists. This edition has been thoroughly revised and enlarged by the addition of numerous new tables and the extension of former ones.

INTRODUCTION to THEORETICAL PHYSICS. By J. C. Slater and N. H. Frank. N. Y. and Lond., McGraw-Hill Book Co., 1933. 576 p., illus., 9 x 6 in., cloth, $5.00. Presents the classical and the more modern parts of theoretical physics as a coherent whole. Intended to familiarize the reader with the methods and principles of the subject, and enable him to read advanced books on its various branches. A knowledge of descriptive physics and of mathematics through the calculus is assumed.

(The) INVENTOR and HIS WORLD. By H. S. Hatfield. N. Y., E. P. Dutton & Co., 1933. 269 p., diagrs., 8 x 5 in., cloth, $2.40. Indicate the temperament characteristic of the inventor, shows how he works, explains why it is so difficult for him to get his invention adopted, and indicates promising directions for his efforts. Mechanical, chemical, electrical, biological, and psychological inventions are discussed quite fully, and the workings of patent law are considered.

McDONALD'S ELECTRICAL DICTIONARY. By G. McDonald. Boston, Meador Pub. Co., 1933. 178 p., 8 x 5 in., lea., $1.50. Over 2,000 electrical terms are defined. The definitions are simple and, in most cases, clear, and cover adequately the ordinary needs of the student of electricity.

PRACTICAL ACOUSTICS for the CONSTRUCTOR. By C. W. Glover. Lond., Chapman & Hall, 1933. 468 p., illus., 9 x 6 in., cloth, 25s. For the architect or engineer in search of practical information. The theory of acoustics is presented clearly and its application to the design of buildings illustrated. Sound insulation, noise, and vibration reduction, the use of sound absorbents, and aircraft noise are discussed. Typical specifications for acoustical work are given. Appendices include a useful bibliography, tables of acoustical coefficients for 700 materials, and particulars of many representative materials for damping sound and vibration.

Les REDRESSEURS de COURANT, Construction, Caractéristiques, Utilisation des Valves Bleuques. By R. de Bagneux. Paris, Étienne Chiron, 1933. 124 p., illus., 9 x 6 in., paper, 10 frs. The principles, properties, and uses of the various types of rectifiers are presented in a practical, nonmathematical fashion in this book, intended for amateur radio operators and electrical workers. Special attention is given to questions of maintenance.

RÉSEAUX de DISTRIBUTION d'ÉNERGIE ÉLECTRIQUE. (Memento d'Electrotechnique, v. 3). By A. Curchod. Paris, Dunod, 1934. 655 p., illus., 8 x 5 in., cloth, 138 frs. A comprehensive, concise reference work to which the electrical engineer may turn for definite information upon current practice. The present volume is devoted to the production, transformation, transmission, and distribution of electricity. French legislation affecting the distribution of electricity is included.

THEORIE der ELEKTRIZITÄT Bd. 2, ELEKTRONENTHEORIE. By R. Becker. 6 ed. Leipzig and Berlin, B. G. Teubner, 1933. 400 p., illus., 9 x 6 in., cloth, 17 rm. This, the second volume of a thorough revision of Max Abraham's text on the theory of electricity, discusses the electron. While based upon the classic theory of the electron, the text also considers it from the viewpoint of the quantum theory. In addition to general principles, the volume discusses the elastically constrained electron, field equations in static and moving media, the electronic theory of metals and the theory of radiation in empty space.

(The) THEORY of ATOMIC COLLISIONS. By N. F. Mott and H. S. W. Massey. Oxford (Eng.), Clarendon Press; New York, Oxford University Press, 1933. 283 p., illus., 10 x 6 in., cloth, $6.00. The sixth volume of the international series of monographs on physics. Develops the quantum mechanical theory of collisions between electrons, alpha particles, nuclei, and atomic systems generally. The complete theory is given and the way is shown to draw many important deductions about the properties and structure of the nucleus. Special attention is paid to collisions between particles moving with relatively small velocities.

THEORY of FUNCTIONS as Applied to Engineering Problems. Edit. by R. Rothe, F. Ollendorff and K. Pohlhausen, authorized translation by Alfred Herzenberg. Cambridge, Technology Press, Massachusetts Institute of Technology, 1933. 189 p., illus., 10 x 6 in., cloth, $3.50. Based upon a series of lectures. The first half of the volume deals with the theory from the point of view of pure mathematics and gives a general knowledge of the methods of function theory. The second part consists of 5 lectures upon specific applications, chiefly to problems of electrical engineering; the construction of electric and magnetic fields by means of source-line potential, 2-dimensional fields of flow; the field distribution in the neighborhood of edges; the complex treatment of electric and thermal transient phenomena; and the spreading of electric waves along the earth.

THOMAS ALVA EDISON, the Youth and His Times. By W. K. Wise. Chicago, N. Y., San Francisco, Rand McNally & Co., 1933. 252 p., illus., 8 x 6 in., cloth, $2.00. The story of Edison's youth, ending with the sale of his stock ticker, at the age of 23. The author has collected many stories of Edison's life as a train boy and telegrapher, which he weaves into an interesting record that will appeal to boys. There is a bibliography.

UNTERNEHMUNGSFORM und VERKAUFSPOLITIK der STROMVERSORGUNG. By H. Kirchhoff. Berlin, Julius Springer, 1933. 188 p., tables, 10 x 9 in., paper, 8 rm. A critical study of electrical public utilities in Germany, with emphasis upon problems of organization and tariffs. The economic effects of public and private ownership upon the production of electricity are considered at length, and the relations between tariffs, costs, and consumption discussed.

Die WIRTSCHAFTLICHKEIT der FERNSPRECHANLAGEN. By F. Lubberger. 2 ed. Munich and Berlin, R. Oldenbourg, 1933. 124 p., illus., 10 x 7 in., paper, 6.80 rm. Because the operating data of the 1927 edition of this study of telephone economics are out of date, a new edition has been prepared, based upon current figures. At the same time scope of the work has been enlarged to include long-distance and automatic telephony.

BAIRD of TELEVISION, the Life Story of John Logie Baird. By R. F. Tiltman. London, Seeley Service & Co., Ltd., 1933. 220 p., illus., 9 x 6 in., cloth, 10s 6d. This biography includes the early struggles and the achievements of Baird, written in an easy style, emphasis being upon the inventor's life, not upon the technicalities of his invention.

Der SELEKTIVSCHUTZ nach dem WIDERSTANDSPRINZIP. By M. Walter. Munich and Berlin, R. Oldenbourg, 1933. 172 p., illus., 10 x 7 in., paper, 8.50 rm. A comprehensive, systematic presentation of the subject of selective relaying on the resistance principle, intended for practicing engineers as well as students. The method of operation and the planning of typical systems of protection are presented simply and practically.

WORLD RESOURCES and INDUSTRIES. By E. W. Zimmermann. N. Y. and Lond., Harper Bros., 1933. 842 p., illus., 10 x 6 in., cloth, $5.00. An important, timely appraisal of world resources. The agricultural and industrial resources of the world are reviewed, stress being laid upon their relativity and functional nature. Future prospects are discussed. The book has much of interest to economists, manufacturers, and business men.

CHEMICAL PATENT INDEX, [United States] 1915–1924. Vol. 3, Subject Index F–L. By E. C. Wordon, N. Y., Chem. Cat. Co., 1933. 1004 p., 10 x 7 in., cloth, $25.00. Covers the entire field of chemical technology and that of chemical development. Over 22,000 patents issued in the decade 1915–1924 are indexed under patentees and under all possible subjects. Volume 3 comprises letters F to L of the subject index. It contains approximately 160,000 subject entries.

CRYSTALLINE STRUCTURE in relation to FAILURE of METALS, especially by Fatigue. (Edgar Marburg Lecture 1933.) By H. J. Gough. Phila., Am. Soc. for Testing Materials, 1933. 111 p., illus., 9 x 6 in., paper, $1.00. Discusses the knowledge of deformation and fracture under mechanical forces which has resulted from extensive studies of single metallic crystals. The lecture summarizes in an effective way what is known of the nature of solid bodies. It should interest chemists and physicists, as well as engineers and metallurgists.

Die DREHZAHLREGELUNG von ASYNCHRONMOTOREN durch WECHSELSTROMKOMMUTATORHINTERMASCHINEN. By H. Zabransky. Berlin, Carl Heymanns Verlag, 1934. 208 p., diagrs., 10 x 7 in., paper, 16 rm. An exhaustive account of the use of a-c commutator machines to control the speed of induction motors. The material is classified by purposes and is complete to the end of July 1933. Patent numbers are given throughout, and a subject index is provided.

GEOLOGY of CALIFORNIA. By R. D. Reed. Tulsa, Okla., Am. Assn. of Petroleum Geologists, 1933. 335 p., illus., 9 x 6 in., cloth, $5.00. A sketch of the stratigraphy, structure, and geologic history of California, with particular reference to post-Triassic events in the coastal province. Brings into relief some of the major unsolved problems of California geology; and furnishes geologists in general with an introductory account of the present status of geologic work in this state.

INTERNATIONAL ACETYLENE ASSOCIATION PROCEEDINGS, 33rd Annual Convention, 1932. N. Y., The Assn., 1933. 201 p., 9 x 6 in., cloth, not for sale. The papers presented deal with the uses of oxy-acetylene cutting and welding processes. The use of welded piping in power plants and residences, welding in the aircraft industry and in railroad and truck maintenance, weld testing, etc., are discussed. The reports of the Association and a list of its members are also included.

MITTEILUNGEN des HYDRAULISCHEN INSTITUTS der TECHNISCHEN HOCHSCHULE MÜNCHEN. Heft 7, 1933. By D. Thoma. Munich and Berlin, R. Oldenbourg, 86 p., illus., 11 x 8 in., paper, 5.80 rm. Contains 4 papers. The first describes investigations of the lubricating capacity of oils and fats. The second treats of flow over weirs. The effects of sudden stoppage upon turbine pumping plants are discussed in the third paper, based upon experiments with large and small pumps. The final paper describes a new hot-wire instrument for determining the direction and magnitude of the velocity of turbulent water.

THEORETICAL PHYSICS. Vol. 2, Electromagnetism and Optics. Maxwell-Lorentz. By W. Wilson. Lond., Methuen & Co.; N. Y., E. P. Dutton & Co., 1933. 315 p., illus., 9 x 6 in., cloth, $5.75. The second volume of this text is devoted to electricity and optics. In it, as in the preceding volume, the subject matter has been selected to present physical theory as a coherent logical unity. Electrostatics, magnetostatics, the fundamentals of electrodynamics, thermoelectricity, Maxwell's theory, electron theory, dispersion, scattering of radiation, etc., are discussed.

Engineering Societies Library

29 West 39th Street, New York, N.Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

G-E Reports Business Increase in 1933.—Orders received by the General Electric Co., during the year 1933 amounted to $142,770,791, compared with $121,725,772 for 1932, an increase of 17 per cent, according to a recent announcement. Orders for the quarter ended December 31 amounted to $37,985,790, compared with $27,351,658 for the last quarter of 1932, an increase of 39 per cent. The company continued to experience an increase in the number of its stockholders during 1933. The gain was considerably smaller than in recent previous years, but it nevertheless enabled the company to close the year with the largest number of stockholders it has ever had—188,316.

New Canadian Agency for Brown Boveri.—A new company, the Swiss Electric Co. of Canada, Ltd., has been formed, which has an exclusive arrangement to distribute in Canada the products of Brown Boveri & Co., Ltd., of Switzerland, the Micafil A.-G., and other companies. Headquarters will be temporarily in the offices of Griswold & Co., Ltd., the former distributors of Brown Boveri products.

Asbestos Companies Merge.—The Ambler Asbestos Shingle & Sheathing Co. and the Keasbey & Mattison Co., both of Ambler, Pa., have merged, and a controlling interest has been acquired by Turner & Newall, Ltd., of Great Britain. The latter firm and subsidiaries constitute one of the largest factors in the asbestos and magnesia business in the world. The enlarged business will retain the name of Keasbey & Mattison Co., remain under American management, and American capital will continue to be largely represented, according to the announcement.

New Insulating Materials Agency.—S. T. Rodgers, for the past 16 years connected with the Sherwin Williams Co. in the capacity of insulation engineer for the development and sale of insulating varnishes and compounds, has established a manufacturers' sales agency at 3351 Norwood Road, Cleveland, and will handle a complete line of electrical insulating materials. The territory covered will consist of Ohio, western Pennsylvania and eastern Indiana and Michigan.

Incandescent Lamp Sales Increase in 1933.—A preliminary estimate of the number of lamps sold in the United States during 1933 indicates a total of 616,000,000 for both large and miniature lamps, representing an increase of more than 11 per cent over the sales in 1932. The use of carbon filament lamps, as in previous years, continued to decrease. Among the developments of the year in lighting equipment noted by the General Electric Co., were the introduction of a three-light Mazda lamp, a high-powered "movie flood" lamp, new sizes in photoflash lamps, sodium-vapor lamps for highway lighting, hot-cathode positive-column lamps for color floodlighting and the spectacular illumination of the Century of Progress at Chicago.

New Laboratory Super Centrifuge.—The Sharples Specialty Co., 23rd & Westmoreland St., Philadelphia, has developed a new laboratory supercentrifuge which makes available an extremely high, efficient separating force for the sedimentation of solids from liquids, the clarification of liquids and the separation of immiscible liquids occurring as mixtures and emulsions. These operations are performed continuously. Liquid material is introduced into the rotating bowl of the machine where it is subjected to a separating force as high as 62,000 times the force of gravity. It is then discharged continuously. The frame of the new models is similar to the large size Sharples commercial centrifuges so that the turbine head or motor drive head can be installed. The new machine can be equipped for either steam or compressed air turbine drive or motor drive. It has wide application in industry, in laboratory control work, research work for the development of new processes, etc.

Voltage Adjusting Device for Electrical Appliances.—Designed and manufactured by The Acme Electric & Mfg. Co., Cleveland, the "variable voltage adjustor" permits the regulation and adjustment of the primary line voltage from either below or above normal to the proper operating voltage of electrical appliances, radio receivers, refrigerators, etc. Similar in construction and appearance to an ordinary step-down transformer, a series of taps has been created within the case and a manually operated dial provides the necessary regulating medium for control. A sensitive and extremely accurate instrument indicates the secondary voltage in connection with the regulation from the operating dial. The variable-voltage adjustor is well suited for service shop use being light, handy, and affording a means of testing appliance and electrical products under a series of low-voltage and over-voltage conditions.

Old Engineering Company Changes Name.—The name of W. S. Barstow & Co., Inc., has been changed to E. M. Gilbert Engineering Corp., according to an announcement from the company's headquarters, Reading, Pa. E. M. Gilbert, whose name is given to the corporation, entered the public utility field in 1907. In 1916 he became vice-president and chief engineer of W. S. Barstow & Co., and in 1929 was elected president. The Barstow company was incorporated in 1906 to function as a centralized engineering, construction and management company for various utilities, and has acted also in a general consulting capacity in a wide variety of construction and operating problems. Except for its change of name, the corporation will continue with its same policies, and personnel. It has to its credit the completion of many outstanding power plants, including the Gilbert steam station on the Delaware River near Holland, N. J., unusual because of its low fuel consumption—.877 pound of coal per kilowatt hour; also the hydroelectric development on the Saluda River near Columbia, S. C., a project involving the building of the largest earth dam in the world for power purposes.

Trade Literature

Suspension Insulators.—Bulletin 604-H. Describes important developments in suspension insulators. In addition to the more technical data the booklet contains complete catalog listings of the entire O-B line of transmission products. Ohio Brass Co., Mansfield, O.

Hoists. Bulletin RH-1. Describes applications of hoists for every plant and purpose, treating both general and specific problems. Installations are illustrated and diagrams explain simplified design, construction and operation. The Harnischfeger Corp., 4400 West National Ave., Milwaukee.

Arc Welding Handbook.—The seventh edition of this book by C. J. Holslag has been brought up to date with chapters on shielded arc, hammer annealing, flux covered, normalizing electrodes and others. It also contains, in the words of the author "a very interesting explanation of why fusion welding fusions and why steel holds together anyway." Electric Arc Cutting & Welding Co., 152 Jelliff Ave., Newark, N. J.

Motors.—Bulletin 3085, 4 pp. Describes type S, improved split phase motors, with steel field rings, smaller dimensions and quieter in operation, for small pumps and compressors, oil burners, fans, blowers and air conditioners, drill presses, etc., available in $^1/_6$ and $^1/_4$ hp, 1,725 rpm, and $^1/_3$ and $^1/_8$ hp, 1,140 rpm, with resilient or rigid base mountings. The Emerson Electric Mfg. Co., 2018 Washington Ave., St. Louis.

Circuit Breakers.—The Square D Co. has added to its line of industrial circuit breakers a 600-ampere frame, making it complete from 15 amperes to 600 amperes. These breakers are available for 230 volts, alternating current, and 125–250 volts, direct current, as well as in 3 and 4-wire solid neutral and in 575 volts alternating current and 250 volts direct current. The complete listing of the new industrial circuit breaker line will be carried in the company's standard catalog, to be reissued shortly. Square D Co., Detroit.

Cables.—Bulletin, 4 pp. Describes four types of "Trenchlay" cable-power, for all power circuits up to and including 5,000 volts grounded neutral and not over 3,000 volts ungrounded neutral; concentric, for rural extension and series street lighting up to and including 11,000 volts between phase conductors to ground; control, for multiple control and signal circuits not over 600 volts; railway signal, for all types of railway signal service up to and including 750 volts. Trenchlay is a non-metallic cable, designed and developed for direct earth installation. General Cable Corp., 420 Lexington Ave., New York.

Published Monthly by

American Institute of Electrical Engineers

(Founded May 13, 1884)

Electrical Engineering

Registered U. S. Patent Office

March 1934
Volume 53
No. 3

The Official Monthly Journal and Transactions of the A.I.E.E.

J. B. Whitehead, President
H. H. Henline, National Secretary

Publication Committee
E. B. Meyer, Chairman
R. N. Conwell — H. H. Henline
W. S. Gorsch — H. R. Woodrow

Publication Staff
G. Rou Hennings, Editor
C. A. Gisel, Advertising Manager

PUBLICATION OFFICE, 20th and Northampton Streets, Easton, Pa.

EDITORIAL AND ADVERTISING OFFICES, 33 West 39th Street, New York, N. Y.

ENTERED as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918.

SUBSCRIPTION RATES—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii and the Philippine Islands, Central America, South America, Haiti, Spain and Spanish Colonies; $13 to Canada; $14 to all other countries. Single copy $1.50.

CHANGE OF ADDRESS—requests must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered due to incorrect address cannot be replaced without charge. Be sure to specify both old and new addresses and any change in business affiliation.

ADVERTISING COPY—changes must be received by the fifteenth of the month to be effective for the issue of the month succeeding.

STATEMENTS and opinions given in articles appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters.

REPUBLICATION from "Electrical Engineering" of any Institute article or paper (unless otherwise specifically stated) is hereby authorized provided full credit be given.

COPYRIGHT 1934 by the American Institute of Electrical Engineers.

ELECTRICAL ENGINEERING is indexed in Industrial Arts Index and Engineering Index.

Printed in the United States of America. Number of copies this issue—

17,500

This Month—

Front Cover

Interior of one of the transmitters built in the Bell Telephone Laboratories, Inc., for the Central America radiotelephone service.

Educational Series—No. 4

Electric Discharges in Gases—II Ions in Dense Gases 388
By KARL K. DARROW

Special Articles

The Story of the Institute Budget . . . 375
By E. B. MEYER

Scientific Thought and Social Reconstruction 381
By C. E. KENNETH MEES

Social Aspects of the Engineering Approach 395
By HENRY A. WALLACE

Actions on Electric and Magnetic Units 402
By A. E. KENNELLY

Steam Ejector Systems for Car Conditioning 406
By C. M. ASHLEY

A.I.E.E. Papers

Experiments in Fatal Electric Shock . . 399
By A. G. CONRAD and H. W. HAGGARD

Shunt Resistors for Reactors—II 411
By F. H. KIERSTEAD and L. V. BEWLEY

Transients in Magnetic Systems 418
By C. F. WAGNER

Theory of Primary Networks—Part II . . 426
By F. M. STARR

The Theory of Incremental Rates and Their Practical Application to Load Division—Part I 432
By M. J. STEINBERG and THEODORE H. SMITH

News of Institute and Related Activities 496

Many Sections and Branches to Celebrate the Institute's 50th Anniversary in May 496

North Eastern District Meeting to Be Held in May 497

1934 Yearbook Now Available . 497

Reports of Committee Meetings Held During Winter Convention 498

Letters to the Editor 500

Membership 505

Engineering Literature 507

Industrial Notes 508

Employment Notes (See Advertising Section)

Officers and Committees (For complete listing see p. 658-81, September 1933 issue of ELECTRICAL ENGINEERING)

—Turn to Next Page

Discussions of A.I.E.E. Papers

Communication

Auditory Perspective—Amplifiers—Scriven 461
Auditory Perspective—Basic Requirements—Fletcher 461
Auditory Perspective—Loud Speakers and Microphones—Wente & Thuras 461
Auditory Perspective—Physical Factors—Steinberg & Snow . 461
Auditory Perspective—System Adaptation—Bedell & Kerney . 461
Auditory Perspective—Transmission Lines—Affel, Chesnut & Mills 461
Stabilized Feed-Back Amplifiers—Black 461

Education

The Pitt-Westinghouse Graduate Program—Dyche & Hellmund 446

Electric Furnaces

Cast Iron and Its Production—Healey 452, 455
Electrical Equipment for Induction Furnaces—Levy 452
Electrodes—Carbon and Graphite—Vosburgh 452
High Frequency Induction Furnaces—Adams, Hodge & MacKusick 452, 455
Rocking Indirect Arc Electric Furnaces—Crosby 452, 454
The 3-Phase Electric Arc Furnaces—Arnold 452, 453
Transformers for Electric Furnaces—Stephens & Schell . . 452, 454

Electric Power Switching

Electric Power Switching—Lovell 456
Switching at the Connors Creek Plant—Fugill 456
Switching at the Hudson Avenue Station—Gilt 456
Switching at Long Beach Plant No. 3—Kroneberg, Bulkley & Andree 456
Switching at Richmond Station—Bailey & Ford 456
Switching at State Line Station—White 456

Electrical Machinery

An Experimental Ignitron Rectifier—Ludwig, Maxfield & Toepfer 488
Effects of Rectifiers on System Wave Shape—Blye & Kent . . . 483
Equivalent Reactance of Synchronous Machines—Crary, March & Shildneck 484
Protecting Machines From Line Surges—Calvert 488
Simultaneous Control of Voltage and Power Factor—Blume & Woods 483

Instruments and Measurements

Cross Potential of a 4-Arm Network—Seletzky 478
Heavy Surge Currents—Generation and Measurement—Bellaschi 481
Portable Schering Bridge for Field Tests—Hill, Watts & Burr . 478

Power Distribution

An Economic Study of Suburban Distribution—Sweetnam & Corney 489
Fundamentals of Design of Electric Energy Delivery Systems—Johnson & Henry 489, 493
Joint Use of Poles with 6,900-Volt Lines—Bullard & Keyes 489, 491
Radial Versus Primary Network Distribution—Wulfing . . 489, 492

Power Transmission

Attenuation and Distortion of Waves—Bewley 471
Corona Losses From Conductors of 1.4-Inch Diameter—Carroll, Cozzens & Blakeslee 470
Counterpoises for Transmission Lines—Fortescue 467
Power Limit of a Transmission System—Peterson 477
Power Limits of Synchronous Machines—Clarke & Lorraine . 475
Power Limits of 220-Kv Transmission Lines—Kroneberg & Macferran 473
Steady State Stability of Composite Systems—Crary 475

Protective Devices

Automatic Reclosing of Oil Circuit Breakers—Anderson . . . 466
Control of Distance Relay Potential Connections—Warrington 465
Lightning Measured on 4-Kv Overhead Circuits—Halperin & McEachron 465
Petersen Coil Tests on 140-Kv System—North & Eaton . . . 462

Transportation

Investigation of Rail Impedances—Trueblood & Wascheck . . 450
Pantograph Trolleys I—Design Features—Schaake 451
Pantograph Trolleys II—Operating Features—Pickens . . . 451
Trolley Wire Lubrication Improved—Lamson 449

WINTER CONVENTION DISCUSSIONS. Discussions of the winter convention papers received before February 5 and which have been approved appear in this issue. Discussions subsequently received up to March 1, and which have been approved, together with the authors' complete closures if received by March 15, will be published in the April issue. This will constitute the bulk of the winter convention discussions. Subject to review and approval, contributions received after March 1 may subsequently be published provided they are sufficiently pertinent, but they may not be included within the authors' closures.

BACK ISSUES WANTED. Copies of the November and December (1933) issues of ELECTRICAL ENGINEERING are required to meet the demand for these back numbers. If you care to dispose of your copies of these issues please mail them to American Institute of Electrical Engineers, 33 West 39th St., New York, N. Y., printing your name and address upon the enclosing wrapper. Twenty-five cents will be paid for each copy returned.

The Story of the Institute Budget

A Presentation of Facts and Figures

By E. B. MEYER
FELLOW A.I.E.E.

Chairman A.I.E.E.
Finance Committee

THROUGHOUT the past several years, as a result of the general depression in business which has affected practically every activity, the matter of control of expenditures has required most careful consideration. To both individuals and organizations, the general curtailment of income has presented most perplexing problems, the proper solutions of which have been found only through painstaking analysis of all items of expense and the effecting of economies, where possible, in regular operating costs.

The American Institute of Electrical Engineers, in company with all such professional societies and like institutions, has been confronted with the many difficulties that have arisen out of this situation. On the finance committee and the board of directors has rested the responsibility for budgeting the total annual expenditure on such a basis that it would come within the limitations of the anticipated income and, at the same time, give the greatest possible latitude to those who were directing Institute activities that are essential to the furthering of its aims and in the interest of the members and their professional work.

In such periods of business recession, it is absolutely essential that everything that is done contribute to a strengthening of the foundation upon which will be laid future plans. At no time in its history has the Institute indulged in extravagances; but if, under such economic conditions as exist at present, the maximum contribution is to be made to its members who support it, every policy and every procedure must undergo the critical scrutiny of those who are endeavoring to retain those activities which are the most significant.

Such a subject is controversial and frequently the cause of much discussion on the part of the membership. In all such situations, lack of a complete understanding of facts and figures leads to misunderstanding and sometimes to complaints on the part of some who have at heart only the best interests of the Institute. Therefore, some of the problems as they have been presented to the board of directors, together with a brief outline of the steps toward solution as taken by the finance committee, are set forth for the purpose of acquainting the membership with items of major consideration and to show the effort that consistently is being made to maintain the high standard of service which the Institute always has striven to render to its members.

The extent of the contribution that can be made by any organization such as the Institute is determined by the soundness of its business policies. The furtherance of its aims, to promote technological advancement and the best interests of its membership, is predicated upon its ability so to manage its affairs that it may foster uninterruptedly those activities that are consistent with the purposes for which it exists. It is important that its members be qualified technically, if advances in the electrical art are to be made, but it is just as important that the members have knowledge of the financial aspects of the Institute's affairs if they would be equally qualified to promote the well-being of the institution which concerns itself not only with technical matters, but also with the improvement of the professional status of those engaged in electrical engineering.

Annual Budget and Income Statement

The nature and relative importance of the various items that make up the annual budget perhaps are known to but few members not actively identified with the Institute's financial affairs. In Table I, therefore, are presented the actual expenditures for the year 1931 and the budget of expenditures for 1934, respectively, and this, in addition to listing the items of which the budget consists, makes a comparison which shows the effectiveness of the steps that have been taken consistently since 1931 to make reductions wherever possible.

It may be noted that in the last 3 years there has been a falling off of more than 40 per cent. Of importance, therefore, is the comparison between the anticipated income for 1934 and the budgeted expenditures, and whereas no attempt has been made to analyze every one of the latter items in detail the following discussion of the more important activities is presented in order that the members not only may be acquainted with the conditions, but also may know what purpose guides those who are directing the affairs of the Institute.

Furthermore, it is believed that such knowledge will lead to the conviction that if the Institute is to continue to render service, those activities which promote the accomplishment of its purposes cannot be curtailed unduly, and that it is incumbent upon every member to do all within his power that will in any

way contribute to the successful operation of Institute affairs.

Reserve Capital Fund

This fund had its inception in 1921 when the board of directors voted that 5 per cent of the annual income should be reserved, if possible, as a working capital fund to be used in certain contingencies. The plan was not unanimously approved, there being some members who questioned the justification for a reserve capital fund at any time and who believed that the Institute was obligated to expend each year its entire income for those activities considered to be of major interest to the membership. Fortunately, this view was not general, with the result that the Institute has been able to contend with the contingencies which have developed during the past several years.

A factor with reference to the fund which should be mentioned is that its existence is largely due to the profits derived from the advertising section of the official monthly publication, which since 1921 have amounted to $450,000. The very great decrease in the amount of advertising revenue during the period of the business depression is therefore directly related to the withdrawals from the reserve capital fund.

The book value of this fund, as of September 1930, amounted to $218,847.88. During the ensuing period the fund was reduced by the sum of $64,319.63, leaving a net book value on May 1, 1933 of $154,528.25.

Of this reduction, $19,673.75 represents a reserve within the fund that has been created to offset doubtful investments which are in default of interest payments; $7,492.27 comprises losses in exchange or sale of securities; the remainder of approximately $37,000 is the actual withdrawal from the fund to cover deficits from operations and special appropriations authorized by the board of directors.

It is gratifying to note, however, that the ratio of market value to book value is more than 70 per cent, indicating the very conservative attitude on the part of those responsible for creating this investment fund, as many other funds have depreciated in value to less than 50 per cent.

Changes in Publication Policy

There is perhaps no other single activity of the Institute that concerns the individual member in so intimate a way as does the publication policy, which determines the character of the official monthly publication, Electrical Engineering.

The adverse effect of recent economic conditions upon the revenue producing phases of the Institute's operations is clearly shown in the foregoing statement on income. The falling off in membership and the considerable decrease in the return from advertising have necessitated a substantial reduction in the appropriation for publication purposes. Advertising, one of the largest of income producing items, dropped from approximately $85,000 in 1930 to less than $17,000 in 1933, a reduction of 80 per cent.

The problem which is constantly before the responsible committees, therefore, concerns the determination of a publication policy that will give the greatest and most tangible return to the members for the dues that they pay. About a year ago a comprehensive survey was undertaken to find out what modifications might be made in the publication policy that would enable the Institute to serve its membership most effectually and at the same time keep the cost within the limitations of the restricted budget. As a result of this study the publication committee proposed at the June convention in Chicago, last year, a unified program which subsequently was approved by the board of directors at its meeting in August 1933.

Beginning with the September 1933 issue and in subsequent issues of Electrical Engineering this new publication policy was presented in detail. Briefly, the new plan will afford practically a 100 per cent increase in the amount of technical material supplied to the membership at large, at a considerable reduction in the actual gross total cost.

The publication budget, it may be noted, is less

Table I—Comparison of Expenditures for Year Ending September 30, 1931, and Budget for Year Ending September 30, 1934

The results of steps taken to reduce expenses are shown, but unless present estimates of 1934 income are exceeded a portion of the reserve fund, as indicated, will have to be used to maintain membership activities at the present standard

Expenses	Expended Year Ending 9/30/31	Budget for Year Ending 9/30/34	Per Cent Decrease
Publications			
Text matter	$116,611.58	$67,000.00	42.5
Advertising section	24,518.58	10,500.00	57.1
Year Book	9,381.07	5,600.00	40.3
Institute meetings	15,594.45	10,000.00	35.8
Institute Sections			
Appropriations	23,573.24	14,000.00	40.6
Convention and other expenses	13,549.04	7,800.00	42.4
Institute Branches	13,174.17	6,700.00	49.1
Administration			
Headquarters' salaries	48,640.32	31,000.00	36.2
General (postage, printing, supplies, etc.)	15,218.55	12,000.00	21.1
Membership	8,507.19	6,000.00	29.4
Traveling expenses, general	10,212.86	4,250.00	58.3
United Engineering Trustees			
Building assessment	5,713.56	3,000.00	47.4
Engineering Societies Library	10,420.23	8,380.00	19.5
Engineering Societies Employment Service	1,226.22	4,000.00	+226.0
American Engineering Council	17,615.25	7,625.00	56.7
Standards committee	7,824.70	5,825.00	25.5
Other committees and miscellaneous expenses	16,887.71	9,335.00	44.7
	$358,668.69	$213,015.00	40.6
Income			
Dues	$209,402.16	$129,500.00	38.1
Students' fees	13,159.50	6,500.00	50.6
Entrance fees	7,841.75	2,400.00	69.3
Transfer fees	1,565.00	800.00	48.8
Advertising	67,195.97	20,000.00	70.2
Electrical Engineering subscriptions (nonmember)	9,478.23	8,000.00	15.5
Transactions subscriptions	12,058.12	3,500.00	70.9
Miscellaneous sales	9,634.56	4,500.00	53.2
Revenue from badges	2,706.50	1,000.00	63.0
Interest on securities	11,791.40	8,800.00	25.3
	$344,833.19	$185,000.00	
Withdrawal from reserve capital fund	13,835.50		
Cash available from sale of securities, authorized by the board of directors in January 1933		15,665.00	
Amount which may have to be drawn from reserve capital fund unless income estimate is exceeded		12,350.00	
	$358,668.69	$213,015.00	40.6

than 60 per cent of the amount 3 years ago, and is lower than it has been at any time since 1919–1920. In spite of this, however, the new policy will increase tremendously the effective publication service to the individual member.

In recognition of the forthcoming celebration of the Fiftieth Anniversary of the Institute on May 13, of this year, it is planned to enlarge the May issue of ELECTRICAL ENGINEERING and to develop it into a suitable memorial volume. It is intended that this issue shall record the life and activities of men prominent in Institute affairs, as well as the electrotechnical advances of the period. The issue will probably contain approximately 200 pages and, to achieve the desired results, a special appropriation of $2,000 over and above the normal publication budget has been provided. Such additional expense will, it is anticipated, be more than offset by the return from special advertising which should find this issue attractive because of its character and permanent reference value.

REDUCTION IN SECTION APPROPRIATIONS

With the presentation of the budget for 1931–32, the board of directors suggested to the Sections that they accept a voluntary reduction of 10 per cent and thus contribute to the effort to allocate equitably the anticipated income to the various activities planned for the year. In the 2 ensuing years the increase in the suggested voluntary reduction to 20 per cent was similarly caused by financial circumstances and was, in effect, the alternative to a revision of Institute by-laws to provide for smaller appropriations.

Section 48 of the by-laws has provided since 1922 that each Section shall receive in the aggregate a sum not to exceed $175 plus $1 for each member who resides within its territory at the beginning of the administrative year. During the past several years of economic stress, the board of directors has not wished to amend that section, as it has been hoped that the appropriations to the Sections might soon be restored to the full amounts. It therefore invited the Sections to coöperate and thus make unnecessary the establishing of a mandatory limitation.

It has been the desire at all times to support Institute Sections as liberally as circumstances would permit, and this is evidenced by the fact that a comparison of the average Section appropriation, taken from the most recent financial statements of 3 other national engineering societies with similar Section organizations, shows the Institute's average appropriation to be larger by 30 per cent, 125 per cent, and 225 per cent, respectively. The reductions in Sections appropriations since 1931 have, therefore, been suggested by the board of directors in a sincere effort to allocate the funds to all important activities on a fair basis.

ADMINISTRATION

There has been developed at headquarters a highly trained and efficient working staff which has made possible an expansion of the activities from year to year without the corresponding necessity for increasing the number of employees on the staff. Already it has been established as a fact that the routine work incidental to the maintenance of membership under the present conditions and the recent changes in publication policy have called for even more clerical work than was required in former years.

The records indicate that during the past years of prosperity, only moderate increases in compensation have been granted, and that almost 40 per cent of those now employed have been connected with the Institute for a period of from 12 to 29 years.

Details of administrative expense are given in the following items:

Salaries includes the full salary of the national secretary and the office manager, and a proportion of the total salaries paid to other employees of headquarters' staff.....	$31,000
GENERAL EXPENSES	
Postage is charged with cost of mailing communications to the general membership, such as dues, bills, and statements, election ballots, routine correspondence, miscellaneous announcements, committee notices, etc.....	5,000
Stationery and Printing is charged with cost of all stock, plain and printed, used in carrying on routine activities; also for miscellaneous supplies not chargeable against specific appropriations.....	3,000
Office Equipment absorbs part of the replacement cost of office furniture and equipment.....	500
Miscellaneous Expense absorbs such charges as telephone service, telegrams, insurance, cartage of mail, typewriter supplies and inspection, engrossing diplomas, check tax, and miscellaneous office supplies and headquarters' expenses..	3,500
Total appropriation.....	$43,000

As a result of a decrease in the personnel and a reduction in salaries, the total annual expenditures for headquarters' payroll has decreased from $112,452, as of October 1, 1931, to $71,290 at present, a reduction of 36 per cent. As a matter of fact, the payroll of the headquarters' staff 7 years ago was $3,000 more than it is at present in spite of the fact that in 1926 the editorial staff consisted of 3 people at an annual salary of $8,640, whereas the editorial staff consists today of 5 people at a total annual expenditure of $15,506, the latter total being $2,500 less than that authorized by the board of directors when certain changes in publication policy were approved.

MEMBERSHIP COMMITTEE

The membership committee, under the active and enthusiastic leadership of the chairman, Everett S. Lee of Schenectady, N. Y., is quite optimistic of the results which it expects to accomplish during the year; not only in stimulating new member applications, but in bringing back into the fold those who, having found it necessary to drop out for a time during the past few years, are now finding that they are in a position where they can restore to themselves their Institute standing.

Under present conditions the membership committee is called upon to exert even greater efforts than formerly to maintain the membership, but, despite this fact, the expenditures of the committee for the present appropriation year will have to be less than in

previous years. The committee is engaged diligently in carrying on the usual campaign to obtain new members, and notwithstanding existing conditions has succeeded in obtaining an appreciable number of new applications.

The detailed estimated expenses of the membership committee for the 1934 budget are as follows:

Printing of application and endorsement forms; national, Section, and committee stationery, etc.	$ 500
Pamphlet list of Members and Fellows	75
National committee notices to membership	500
Follow-up correspondence to members in arrears, prospective applicants, Enrolled Students	800
Notifications of election	50
Payments to Institute Sections for portion of entrance fees of new members	900
Miscellaneous postage and other expenses	525
Salaries of clerical force	2,650
Total appropriation	$6,000

Reduction in Traveling Expenses

In the adoption of the 1934 budget, which again provides for a mileage rate less than that which has been allowed in earlier years, the board of directors was influenced by the following considerations:

1. The decrease in the amount of funds available for this purpose.
2. The probable general adoption by the railroads of a lower mileage rate.
3. The desire to provide traveling expenses for the maximum number of Institute activities. The 1933–34 budget contemplates the expenditure of 21.8 per cent more for traveling expenses incurred for Section and Branch work than was expended in 1932–33.

The budget provides for one meeting of each District executive committee to be held within the district, and to be attended by the vice-president, the district secretary, and either the chairman or the secretary of each Section within the District, or, if neither can attend, an alternate chosen by the Section executive committee. Provision is also made for occasional visits of the vice-presidents of the Institute to the Sections and Branches within their geographical Districts.

To afford a proper understanding of the various allowances for traveling expenses in the budget, the items are tabulated below and show the totals on the basis of 5 cents per mile, with the exception of the appropriation for the national nominating committee, approved on the basis of 10 cents per mile:

Section delegates to summer convention	$ 3,100
Counselor delegates to summer convention	550
Conference on student activities in each geographical District	4,000
Geographical District executive committees	750
Vice-presidents	500
Board of directors	2,000
National nominating committee	1,000
Total appropriation	$11,900

At the conference of officers, delegates, and members held during the summer convention in Chicago, June 1933, the following resolution was adopted:

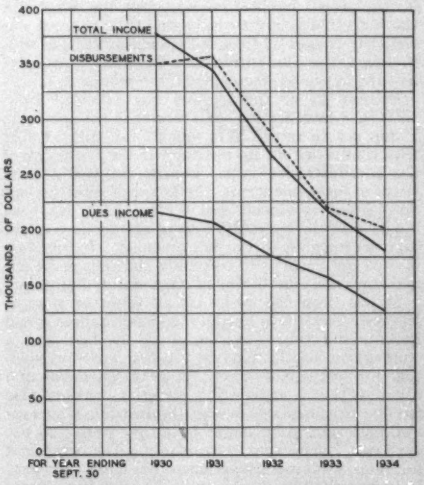
Resolved: That it be recommended to the board of directors that in each future annual budget sufficient funds be allocated to insure the continuance of the annual District student activities conferences, and that the travel allowance to such meetings in any year, for one student chairman and one counselor from each Branch, be made at the same rate as may be in force for the Section delegates and others to whom travel allowances are granted.

The board of directors, at its meeting held on June 28, 1933, voted to refer this resolution to the finance committee for consideration. Upon receipt of the finance committee's favorable recommendation, the board of directors authorized a special appropriation of $4,000 to permit, at the 5-cent mileage rate, of a conference in each of 9 geographical Districts.

At the October meeting, the board of directors resolved that during the year beginning October 1, 1933, the number of meetings of the board of directors be decreased in order to reduce expenditure for traveling expenses to such meetings, and that meetings of the executive committee may be substituted at the discretion of the president.

Engineering Societies Library Maintenance

The Engineering Societies Library is one of the most important coöperative activities of the 4 national societies of civil, mining, mechanical, and electrical engineers. As a composite, thoroughly indexed, and conveniently arranged library developed



Annual Institute income and disbursements since 1929

The extent to which the annual revenue from dues and from other sources has been reduced in the four years since 1929, and the probable income from these sources for 1934, call for vigorous effort on the part of membership committees and others who may render assistance in this most important matter. It is expected that general business improvement will, before long, have a favorable effect on the character of this chart. The consistent lowering of annual operating costs each year since 1930 is indicative of steps taken to keep such costs within close approximation of the funds provided by the total annual income.

from the individual libraries of these 4 societies, it is well prepared to serve effectively in virtually the entire field of engineering.

Each society, in the development of its technical publications, constantly has endeavored to supply to its members the most desirable technical material originating in its own division of engineering, and thus has enabled them to keep in close touch with technical progress of the types in which they are especially interested. However, even in its own division, no society can hope to supply all the technical material which its members may desire. By their coöperative support and development of a single library of large proportions, the engineering societies have made readily accessible to their members the world's best engineering books and periodicals, and yet the total cost to each society has been moderate.

The service bureau of the library is prepared to supply information in written form, such as photostats, reports on searches, and translations. Thus it meets the needs of many members, regardless of their location, who do not have access to a good engineering library or who do not find it convenient to do their own library work.

The book lending service of the library enables members located anywhere to borrow virtually any current American engineering book at a charge of 5 cents per day plus transportation charges.

A library agreement approved in 1928 by the Founder Societies and the United Engineering Trustees, Inc., provides for the apportionment of contributions for the support of the library among the 4 Founder Societies on the basis of an equal contribution from each plus an additional contribution from each society based upon its membership. The Institute budget for the present appropriation year contains an allotment of $8,380 for the library.

American Engineering Council

The majority of the members are familiar, it is believed, with the development of American Engineering Council from the time that a joint body, Engineering Council, was created by the 4 Founder Societies in 1917 for the purpose of establishing an agency to deal with matters of common interest to engineers and to serve as an instrument for contact between engineers and the general public in so far as such matters concern the engineering profession and the public welfare. Fundamentally, this body provides the means whereby unified action may be taken when necessary either to promote a more enlightened public opinion or to safeguard in a proper way the interests of the members of the engineering profession.

The original body, having headquarters in New York, received financial support from each of the societies to the extent of $4,000 annually; reference to the printed records of the Council for the years 1918 to 1920 will reveal the extent of the achievements which were possible with this organization.

The organization of American Engineering Council in Washington and the transfer to this body of Engineering Council activities occurred in 1920, at which time the 4 constituent societies agreed to contribute financial support on a membership basis of $1 per member. The payments made by the Institute since that time to and including 1933 have averaged $16,500 annually. The budget for 1934 provides for an appropriation of $7,625. Of this amount $3,125 represents the obligation for the last quarter of 1933 and the balance is for the nine months of the budget year of 1934.

Council has, over the past 2 years, sharply curtailed expenses and the reorganization plans for 1934 contemplate still further curtailments. President Whitehead, in a letter to the chairman of the A.I.E.E. finance committee, under date of January 13, 1934, wrote as follows:

> I have just returned from the meeting of the Assembly of the American Engineering Council and have been more than ever impressed by the importance of the work that it has done in the past and the functions planned for it for the future. There was unanimous recognition by all of those present that the best interests of the profession of engineering are being well conserved within Council and that it is at present most representative as well as a most efficient mouthpiece.

That there are many exceedingly important movements which require engineering guidance is evident to anyone conversant with present day affairs, both economic and political. That these movements may have an exceedingly important influence upon the future of the engineering profession is obvious to any student. Perhaps never before in the history of the profession did it need, more than at this time, a central, authoritative, coöperatively supported agency which can deal effectively with public questions and all similar matters which concern the engineering profession.

Only through the deliberations of such a body can the best interests of the great profession of engineering and of its members be served and procedure formulated under which engineers may make their greatest contribution to all constructive and forward-looking national movements. To Council, therefore, both moral and financial support should be given. If this is done, Council will be enabled to exert its influence properly toward maintaining the integrity and well-being of the profession to the ultimate benefit of all of its members.

Standards Committee

From the original position of having practically complete control of electrical standardization work (which was held from 1906 to 1924 approximately) the Institute's responsibility now has developed into that of both originator of new and desirable standardization projects and guide in the development of such projects up to the point where they are ready for approval as American Standards.

Practically all American Institute of Electrical Engineers' projects are developed, however, under the direction of the Institute's standards committee or its various technical committees, with the knowledge and coöperation of the standard-making bodies of other engineering organizations. By such a development procedure, carried on entirely under the auspices of the Institute, it proves possible in many instances eventually to offer and to obtain approval

as American Standards for many specifications, standards, and codes, which otherwise would be held up for long periods if forced into the necessary formal procedure which governs the activities of sectional committees of American Standards Association. The current series of test codes now in process of development under American Institute of Electrical Engineers' procedure is an example of this nature.

The preliminary work of compilation necessarily involves appropriations by the originator and by the sponsor organization sufficient to cover the clerical and production expenses of each new project throughout the various stages preceding final adoption, whether the project is carried forward by an agency, a sectional committee, or by a subcommittee of the Institute's standards committee.

At its meeting held January 22, 1934, the board of directors of the Institute adopted a resolution urging that ". . . provision be made for the necessary and adequate technical standardization and research activities of the [U.S.] Bureau of Standards in the electrical field so that it may continue its valuable contributions to the art and industry. . . ." This resolution was published on page 357 of the February issue of ELECTRICAL ENGINEERING.

ENGINEERING SOCIETIES EMPLOYMENT SERVICE

The amount appropriated for Engineering Societies Employment Service over the past 4 years has had, of necessity, to be materially increased. Under normal conditions this service has practically paid for itself, but with the decline in the number of placements made, due to the lack of positions available, the Institute has been forced to accept a larger share of the expense of providing this employment facility. The appropriation of $1,200 in the 1931 budget has been increased to $4,000 for 1934.

MISCELLANEOUS EXPENSE

The details of the item of $9,335 for other committee and miscellaneous expenses in the 1934 budget are as follows:

American Standards Association	$1,125
President's appropriation	1,250
Finance committee (expense of audit)	400
Code committee	60
Technical committees	150
Edison Medal committee	100
Membership badges—inventory account	750
U.S. National Commission, I.C.I.	300
Miscellaneous printing	2,500
Retirement salary	2,700
Total appropriation	$9,335

YEAR BOOK

For economic reasons it was not deemed advisable to publish the year book in 1932 or 1933, the last edition having been published in 1931. In spite of this, however, during each of the 2 years it has been necessary to expend approximately $2,000 to cover the clerical cost of maintaining (whether or not a year book is published) the mailing and business records of the membership.

Although the omission of 2 editions of the year book has not appeared to have caused any general dissatisfaction on the part of the membership (the reason for omission no doubt being understood) an average of 100 requests monthly has been received during the past several months for copies of an edition later than 1931.

As the headquarters staff was not in a position to furnish a membership list to applicants for membership who requested this for use in selecting their sponsors (and this naturally affected the work of the national membership committee) nor to furnish such lists in convenient form for the use of Institute committees and officers of Institute Sections, it was the belief of the board of directors that to remedy this situation a year book should be published this year to give a list of members with business and mailing addresses as recorded on January 31, 1934.

This year book will be new in style and will contain an alphabetical list of members with reference to the state and town in which the desired complete entry of each member can be found. Under this arrangement the catalog of members appears in geographical order, which style conforms more nearly to the requirements of Institute committees and Section officers, affording an opportunity to determine readily the business affiliations of members in any particular locality.

MEMBERS' RESPONSIBILITY

The foregoing discussion brings to the attention of the membership the nature of the problem that ever is before the members who constitute the managing bodies of the Institute, and also the studious effort that is being made to give the various phases of Institute life the degree of emphasis that each deserves. The responsibility that rests on those Institute members who, in their official capacities, direct such matters and strive to maintain a sound financial status of the Institute certainly is, in some respects, greater under present economic conditions than ever before. It is, therefore, all the more important that the individual members realize this, and give serious thought to possible ways in which they may render assistance to their officers and committee heads.

What then should be the attitude of a member of the Institute? As was pointed out by President Whitehead in his recent message to the membership (2nd cover, ELECTRICAL ENGINEERING, Nov. 1933) the concern of a member should be "*what can I do for the Institute?*"; with assurance he may expect to participate in full measure in those benefits that will come to each member as a result of a concerted effort on the part of all to contribute in every possible way.

The respect in which any particular member may render assistance to the general welfare of the Institute is not easily definable and will vary with circumstances and with the opportunities that may present themselves to any given member. In one case it may be seeking out new members, or stimulating renewed interest on the part of those who are indifferent or apathetic. In another, advantage may be taken of opportunities to induce members who are inactive to take a more prominent part in activities

for which they are fitted. Again, a constructive suggestion may be made with regard to some respect in which economies might be effected.

Over and above all of these things which may be regarded as specific contributions, however, do we find the question of *attitude* as the one major responsibility. The professional and material welfare of every member is, as President Whitehead has pointed out, "intimately bound up with that of the Institute. The work of the Institute cannot be curtailed, its resources cannot be impaired, without ultimate detriment to the professional and material well-being of each of its members." If, then, the attitude of each member is all that it should be and evidences acceptance of the fact that "the American Institute of Electrical Engineers is an organization through which electrical engineers are united for conserving and expanding the opportunities open in the profession, for the elevation of its standards, and for the stimulation and improvement of the professional equipment of the individual member," then will the Institute be enabled to go forth with assurance to meet whatever new problems may be presented by future conditions.

Scientific Thought and Social Reconstruction

By C. E. KENNETH MEES Director in Charge of Research and Development, Eastman Kodak Company, Rochester, N. Y.

CONCERNED AS HE WAS with the design and production of industrial machinery, Doctor Steinmetz realized that the increasing use of that machinery must have a profound effect on the social, economic, and political relations of men, and he was speculating constantly as to the future of our machine civilization. In commemorating his work, therefore, at this crisis in human affairs, it seems appropriate to turn for a short time from the consideration of technical scientific progress and to dwell on the reaction that progress is having upon the life of mankind and upon the relation of the scientist to that reaction.

In the change that recently has come over our theories of the nature of the physical universe, nothing is more striking than our abandonment of the necessity for continuity in physical phenomena. We no longer insist on the representation of all phenomena by differential equations, and we are content to accept the view that many phenomena are essentially discontinuous in their nature. Discontinuous phenomena, however, often have their origins in continuous phenomena that are antecedent to them. For instance, the slow changes that occur in the earth's crust, involving the rise of one portion of the crust in relation to another, produce steadily increasing strains which suddenly are relieved by a slip which produces an earthquake.

Scientific men cannot stand aside and ignore the vast political and social experiments being conducted during the present period of accelerated social change. It is not necessary or even desirable, however, that professional scientific men abandon their laboratories and attempt to deal with executive problems; but it is necessary that they expound insistently the nature of scientific thought and study its application to social and political problems. Engineers and scientists are urged to deal with problems of social reconstruction as they deal with other problems, pinning their faith on those methods of reasoning that have proved so successful in analyzing all types of natural phenomena.

In the same way, the steady changes in knowledge and technique that occur in human society from time to time produce a state of strain which can be relieved only by a transition period of rapid change. Such transition periods have occurred often in the history of the world, and there have been rapid changes both in relation to the material control that man has over his environment and also in relation to the economic and social structure of society. Frequently, these changes have been accompanied by great mass movements of peoples, resulting in the destruction of nations and the erection of new empires on the ashes of the old. Between the fourteenth and the twelfth centuries B. C., such a great change resulted in the destruction of the oldest stable empires of which we have any record. The origin of that change we do not know. It was quite possibly the culmination of climatic changes in the great plains of Eastern Europe and Western Asia. In the course of it, Crete lost her control of the northern Mediterranean and finally vanished from the list of the empires. The Archaean Greek civilization which Crete had founded disappeared in its turn. The Hittite Empire, attacked in the north, pressed through to the south, came into conflict with Egypt and finally with the new power of Assyria, and was destroyed. Assyria conquered Babylonia and expanded its new empire, which was eventually to overrun Egypt itself. It was perhaps at that time that the predecessors of the

Full text of the Eighth Steinmetz Memorial Lecture delivered before the A.I.E.E., Schenectady (N. Y.) Section, Jan. 10, 1934. *Not published in pamphlet form.*

Romans swept into Italy, and that the great Celtic invasions of Britain and Gaul occurred.

In the fifth century after Christ, a similar rapid change in the organization of world power and consequently in the economic and social life of the civilized world took place. The Gothic invasion of Italy, with the transfer of the empire from Rome to Constantinople, terminated the domination by Rome of the western world.

At the present time, the rate of change is greater than any in the previous experience of man, and it appears still to be accelerating.

In the fifteenth century again, feudalism came to its end, and the social system that had ruled the world for a thousand years deliquesced and changed before the eyes of man. At the same time, the people of Northern Europe largely abandoned the traditional religion of their forefathers and established a new church, which carried with it altogether new and different social relations.

Portentous as these changes were, and rapid as they seemed at the time, they were, nevertheless, extremely slow in comparison with the changes we have seen and now are witnessing. The 2 earlier changes mentioned took several centuries to accomplish, and even the more rapid change at the close of the Middle Ages took more than a hundred years to complete. Compared with any of these, the great industrial revolution of the nineteenth century, when machinery and factory organization took the place of hand labor and the home industry, was extremely rapid; but that whole century saw less change in the life of man than the first third of the twentieth, and within our own lifetimes we have seen changes in method and technique that will affect the economic and social organization of society to perhaps as great an extent as the whole of the changes made from the neolithic period to the beginning of the twentieth century.

At the present time, the rate of change is greater than any in the previous experience of man, and it appears still to be accelerating. The origin of this change is, of course, the development of our knowledge of nature, that knowledge which we classify under the general heading of "science"; and so long as our increase in scientific knowledge continues to accelerate, the resulting change in social and economic conditions also will accelerate. At the present time, the proportion of human effort devoted to the acquisition of new scientific knowledge is increasing each year; but it is still only an infinitesimal part of the activities of mankind and only a very small part of the amount of energy that might be expended upon the development of science if that were thought generally to be worthwhile.

The production of scientific knowledge causes changes of great importance in our economic and social life; these changes lag very much behind the production of science so that as a general rule the science being applied today is not the science produced today, but the science of which the fundamentals were discovered a number of years ago. As the rate of production increases, the period between a scientific discovery and its application diminishes, and whereas it took us 50 years to apply Faraday's discovery of electromagnetic induction, such discoveries as the electronic tube have been applied on a world wide scale within 2 decades; and at the present time perhaps we may be considered as applying generally scientific discoveries of only 10 years ago. The much greater production of scientific knowledge at the present time, however, means that the application of science to industry and, still more, its effects on our economic and social life will continue to increase even if the amount of scientific discovery in the near future does not; and there is every probability that the latter also will continue to increase.

This rapid change that is going on in human affairs, having the curious characteristic that it is continuously increasing in rate, may be compared with an autocatalytic reaction in chemistry. An autocatalytic reaction is one in which a product of the reaction increases its rate, so that if you put all the materials into a vessel and start the reaction going, it will begin slowly and then increase in rate and go faster and faster as the products accumulate. Such a reaction ends in a complete conversion of the system into a new form. Sometimes, the rate increases so much that the reaction becomes explosive and the new form is entirely different from the original system. Sometimes, after a period of violent reaction, the system settles down into a new and stable form. No system that is changing at an increasing rate, and especially no system in which the product of the reaction increases the rate of change, can be stable.

The conditions that made necessary adjustments and changes in the social order arose from the growth of science; scientific men must feel that they have a special responsibility for the correct orientation of the social system toward those conditions.

In our present system, it seems that the very scientific knowledge produced tends to increase the rate of change; and it is therefore probable by analogy, although it is not at all certain, that our social system is in an unstable stage and that after a period of rapid change it will settle into a new and stable phase which will endure until some new cause provokes another period of change. What that stable system may be and how it can be stabilized, since we must assume that scientific discovery will continue, is impossible for us to foresee; but certainly that change cannot continue to occur at an ever increasing rate.

During the period of activity in which we find ourselves at the present time, many experiments are being conducted; new social systems are being evolved, and new economic methods are being tried. The corporate state under a fascist dictatorship and the corporate state under a communist dictatorship are only 2 of the more striking experiments that are being conducted at the present time, with mankind at large as the subject of the experiment and with the happiness and lives of mankind dependent upon the success of the experiments.

It is clear that scientific men cannot stand aside from these vast political and social experiments and ignore them, restricting their interest merely to protests when such experiments are likely to affect their personal interests. The conditions that made necessary adjustments and changes in the social order arose from the growth of science, and scientific men must feel that they have a special responsibility for the correct orientation of the social system toward those conditions. Moreover, there is a technique of experiment and that technique must be learned. It is not a natural gift of mankind. Any one who has watched experiments carried out by men untrained in the methods of science will know how costly and wasteful such experiments are likely to be; and if social reconstruction is to be undertaken as a series of vast experiments, it is desirable, at any rate, that those who conduct the experiments will have been trained in the technique of experimentation. It was this that led Professor Miles Walker in his address to the engineering section of the British Association in 1932 to call on the engineers to manage the world. He felt that if the engineers—in which term for brevity he included all scientific men—took a greater part in world management, they would make a greater success of it. He suggested that actual experiments in the form of self-supporting colonies consisting of groups of 100,000 people should be formed under the auspices of engineers and economists. Again, Sir Frederick Gowland Hopkins in his presidential address to the British Association at Leicester this year reminds us of the indictment that the command of nature has been put into man's hands before he knows how to command himself, but he suggests that this is an indictment of mankind and not an indictment of science.

To me, however, an indictment of mankind seems quite useless. If we cannot indict a nation, how can we indict a species? We must play the game with the cards that are dealt; we must reconstruct society with men as they are. We must assume the probable behavior of mankind as we assume the properties of any other material we have to use, and we must find our solution assuming that the behavior will continue. The scientist, then, as I see it, cannot retire into his shell like a medieval monk or, as the classical Latin grammar story put it, "Balbus, having tweaked the dragon's tail, went away." Nor do I agree with Professor Walker that it would be wise for the scientist to attempt to take up the burdens of the politician or the statesman. It is imperative that he continue to carry out his own work, from which may come the salvation of mankind. The special work of the scientist is the creation of ordered knowledge which is then available for use by all mankind; but in this special work he employs a special method and he approaches his problems in a special spirit, and this method and spirit constitute, I believe, the special contribution of science toward social reconstruction.

It is imperative that the scientist continue to carry out his own work, from which may come the salvation of mankind.

In the last 20 years, a great change has come over the technical industries of the world and especially of the United States. That has been ascribed, probably with justice, to the great expansion of industrial scientific research. However, I do not believe it is the actual work done in the industrial research laboratories that has produced the change; it is rather the growth of the scientific spirit in all sections of the industrial organization. Executives of modern technical industry have been trained in the methods of science and they face their problems with a scientific attitude. In order that the scientific spirit should be used in government, it is not necessary or even desirable that professional scientific men abandon their laboratories and attempt to deal with executive problems; but it is necessary that they expound insistently the nature of scientific thought and study its application to our social and political problems.

Once before in history, the application of scientific methods to the theory and practice of government almost was realized. In the golden age of Greece, the great group of philosophers, of whom the most perfect expression was to be found in the work of Aristotle, had made a truly scientific approach to the problems of nature. Then, the destruction of the philosophic spirit during the period following the wars of Alexander, the rise of the materialistic military empire of Rome, and finally the destruction of almost all the culture of the old world, with the downfall of the classical pagan religion, brought the advance of scientific thought to an abrupt end.

Throughout the Middle Ages, the authority of the written word almost completely displaced first-hand observation and experiment in the search for truth. The revolt against authority arose in the early sixteenth century; Galileo and Kepler in astronomy, Gilbert in electricity, and Harvey in physiology made great contributions to scientific knowledge. Francis Bacon, nobleman, politician, and lawyer, while himself not practiced in experimental methods and while ignorant apparently of the great work of his contemporaries, had a wonderful gift in his trenchant pen and his facility of expression; and he carried the popular imagination with him in his emphasis on observation and experiment as against blind acceptance in the written word. The following passage accredited to him illustrates admirably the irony and sarcasm he could use to emphasize his contentions:

"In the year of our Lord 1432, there arose a grievous quarrel among the brethren over the number of teeth in the mouth of a horse. For 13 days the disputation raged without ceasing. All the ancient books and chronicles were fetched out, and wonderful and ponderous erudition, such as was never before heard of in this region, was made manifest. At the beginning of the fourteenth day, a youthful friar of goodly bearing asked his learned superiors for permission to add a word, and straightway, to the wonderment of the disputants, whose deep wisdom he sore vexed, he beseeched them to unbend in a manner coarse and unheard of, and to look in the open mouth of a horse and find answer to their questionings. At this, their dignity being grievously hurt, they waxed exceedingly wroth; and, joining in a mighty uproar, they flew upon him and smote him hip and thigh, and cast him out forthwith. For, said they, surely Satan hath tempted this bold neophyte to declare unholy and unheard-of ways of finding truth contrary to all the teachings of the fathers. After many days more of grievous strife the

dove of peace sat on the assembly, and they as one man, declaring the problem to be an everlasting mystery because of a grievous dearth of historical and theological evidence thereof, so ordered the same writ down."

Bacon put exclusive emphasis upon the inductive method, that is, direct observation of natural and inferences drawn therefrom as against the written words of the past.

In the year of Bacon's death, 1626, a Frenchman who some years before had left the army because of his interest in philosophy, returned to Paris to begin the definite study of mathematics as the basis of a system of philosophy; and 11 years afterward Descartes published a system of coördinate geometry which for the first time linked together the old mathematical sciences of geometry and algebra. In Descartes' philosophy of science, he emphasized the development of theories obtained intuitively and the deduction of conclusions from those theories.

For many years the 2 methods—the inductive method of Bacon based upon pure experiment, and the deductive method of Descartes based upon intuitive reasoning—have found themselves opposed to each other. Even today it is common for philosophers to discuss the relative value of inductive and deductive methods, but it seems to me that such discussion is like an argument as to which part of the body is most important to a man: Does he need most his head, his heart, or his intestinal tract? The answer is, of course, that he needs them all; he cannot live without them. To find out something about nature, we need facts first of all, and second, a linking idea that will enable us to get into one picture all the facts we are considering. This linking idea we call a hypothesis. Then, from the hypothesis we deduce consequences; these consequences must follow from the hypothesis and they must also be of the type we can verify. It is of no use to deduce consequences that are impossible for us to verify when we are searching for evidence as to the validity of a hypothesis. If all the consequences we can deduce and all the facts we can find fit the picture we form, then we term that picture a theory and grant it validity until we meet well attested facts that will not fit it.

The fundamental purpose of scientific research is to make an orderly picture of nature, so that we can understand it and thus be able to predict for ourselves without actually determining all the facts.

It may be seen that the scientific method involves both the inductive method of Bacon and deductive method of Descartes. Bacon laid the greater stress on the experimental work leading to the facts that a hypothesis was formed to fit. Descartes laid the greater stress upon the intellectual leap by which a hypothesis was invented to fit the facts, but both are necessary. We must get the facts by experiment, and we must deduce a hypothesis by instinct. A great experimenter perhaps will accumulate many facts before finding a fitting hypothesis. A great thinker may leap intuitively at a hypothesis before he has many facts. In one case, the experimenter must search for his hypothesis; in the other, the thinker must find an experimenter to supply him with the facts. Sometimes the completed theory must be abandoned entirely because facts are found that are quite incompatible with the theory, so that it is necessary to construct an entirely new picture; at other times, and perhaps more generally, a theory may have to be modified or extended in detail as new facts become available.

The fundamental purpose of scientific research is to make an orderly picture of nature, so that we can understand it and thus be able to predict for ourselves without actually determining all the facts directly.

The following is perhaps a rough picture of the way in which man has proceeded in his conquest of nature. Suppose that a man entered the door of a vast room which was a storehouse of information—a library, in fact; but suppose that instead of books each fact or statement was written on a piece of paper and that these pieces of paper, of all sizes and kinds and written in all languages, were piled up higgledy-piggledy so as to reach to the ceiling; and, moreover, suppose that the room was unlimited in extent: The first impulse of a man entering such a room would be to go away, but the man I am speaking of is the human race, and the difference between the human race and other animals is that it did not go away; it set to work to sort the facts. Very, very slowly at first, but faster later as it gained experience, the human race started to sort out that library of facts and to place together the facts that seemed to be of the same kind so that they could be classified. At first, when man took up the slip of paper and read it, it meant nothing to him because he had never seen the same fact before, and so he put it down and went on to the next; but presently he began to find that many slips had the same or similar facts on them and he began to put them together and regard them as in the same classification or, as he put it, due to the same cause. Quite often man was wrong in this belief and his association of facts proved later to be incorrect; such incorrect associations have persisted through the ages. When such incorrect associations have been held by many men for many years, we call them superstitions, and they become so rooted in our minds that they are very hard to eradicate. Perhaps the most interesting systems of incorrect associations of facts are those known as *magic* and *religion*.

One of the earliest facts of which an animal becomes conscious is that its own body is not functioning normally. Usually the trouble corrects itself and the animal recovers. As soon as man began to reason, he must have tried to find remedies for his bodily disorders, and those remedies would be associated with his daily routine and especially perhaps with food. If a plant can make you ill, cannot the same plant or another make you well? When primitive man ate the same plant, he was using a homeopathic medicine; when a different plant, an allopathic medicine. When he simply hung the plant around his neck, he was employing magic. Among primitive peoples, magic always has played a great part, and it is perhaps a little difficult for us to

realize how deeply the principles of magic are entrenched in the thought and history of man.

Frazer analyzes into 2 the principles on which magic is base: first, that like produces like or that an effect resembles its cause; and, second, that things which once have been in contact with each other continue to act on each other at a distance. From the first of these principles, which he calls the "law of similarity," is inferred that a man can produce any effect he desires merely by imitating it, so that if a savage, for instance, wants a good crop, he will take care to have it sown by a woman who has many children; or if a witch doctor wants to hurt a man, he will make an image of him and then destroy it in the belief that just as the image suffers, so does the man, and when it perishes, he must die. From the second principle, it is inferred that whatever is done to a material object will affect any person with whom the object was once in contact, so that most savages are very careful to burn any hair they cut off or the parings of their nails lest an enemy might use them to do them harm; and in some African tribes, anything once touched by the king must be carefully destroyed.

The negative principle corresponding to the principle of similarity is the great widespread law of taboo which governs the things a man abstains from doing lest, on the principle that like produces like, they should spoil his luck. The Eskimo boys, for instance, are forbidden to play cat's cradle because if they do so, their fingers in later life might become tangled in the harpoon line. The principles of magic are so widespread that almost all the lives of primitive peoples have some relation either toward acts intended to produce luck or toward things refrained from lest they produce ill luck. These widespread roots are by no means extinct among us today, so that on careful analysis many of our beliefs will be found to be essentially magical in origin although generally we are no longer conscious of the sources from which those beliefs have sprung.

An even greater factor than magic in the history of man has been the development of religion. Very early man observed that his food and well-being were connected closely with natural phenomena, such as the cycle of the seasons, which we know to be due to the movement of the earth around the sun. He, however, catalogued the facts that he knew under the hypothesis that natural phenomena were due to the operation of intelligent beings made in his image, and gave these invented beings jurisdiction over groups of natural phenomena so that there were gods of the earth, the sky, the sea, and minor gods of trees, rivers, and mountains. Sometimes psychological facts were classified in the same way, and there were gods of love and war, or terror and sorrow; and thus was built up the structure of religion. When the great prophets came, Buddha, Jesus, and Mohammed, their philosophy drew on this structure and their followers incorporated much of the earlier religious belief in the systems of philosophy that were founded on their teachings; thus today in the vast mass of what we term religious beliefs we come continually on groups of associations that started as hypotheses to be used in the classification of natural phenomena. Many Christian hymns still repeat the belief that the crash of sound following the discharge of electricity from a cloud is the voice of a god.

Unquestionably, the development of magic and religion as pseudosciences, which provided a systematic classification of phenomena, tended to retard the development of scientific thought; but this probably was not so much because the classifications they provided were incorrect as because of their attitude toward the method by which such classifications should be made. From the beginning, the insistent note was heard from priests and prophets that it was the duty of their followers to have faith, to accept, and to follow authority.

The acceptance of authority is the very antithesis of the scientific method of thought. Step by step, man has established his claim to deal with phenomena directly, without the acceptance of any authority; but signs are not lacking that today this claim is being challenged, and challenged sharply.

Now, the acceptance of authority is the very antithesis of the scientific method of thought. Step by step, man has established his claim to deal with phenomena directly, without the acceptance of any authority; but signs are not lacking that today this claim is being challenged, and challenged sharply. The troubled time through which we are passing has enabled men to seize authority who have no desire that independent decisions shall be made by those whom they rule, and who believe (in most cases sincerely) that rule by authority is necessary. In Italy, in Germany, in Russia today authority is the only voice to be heard. It may appear that this has no relation to technical science, that the suppression of adverse political opinions has no importance for the future of engineering; but science is all one, its method and its spirit are one, and the age-old foe of that method and that spirit is authority.

Certain characteristics of scientific thought distinguished it very sharply from many other methods of thought. I have already dealt with its neglect of authority as such and with its direct appeal to experiment and to the classification of demonstrated facts; but in the political sphere, and I am afraid in the sphere of sociology and economics, the absence of emotion, which is characteristic of scientific thought, is an even more striking distinction. In most political matters we do not think, we feel. Some years ago I reminded a friend of mine who was praising a certain national statesman that though he might be, as my friend claimed, the wisest and noblest of mankind, he yet was a man and not a god; and when a few years later my friend had changed his political views, I had to remind him that that statesman might be the vilest and basest of mankind, but he was a man and not a devil.

The following quotation from Bertrand Russell's "Skeptical Essays" seems to me to express better than I could the difference in methods of thought:

"We have had in recent years a brilliant example of the scientific temper of mind in the theory of relativity and its inception by the

world. Einstein, a German-Swiss-Jew pacifist, was appointed to a research professorship by the German Government in the early days of the war; his predictions were verified by an English expedition which observed the eclipse of 1919, very soon after the Armistice. His theory upsets the whole theoretical framework of traditional physics; it is almost as damaging to orthodox dynamics as Darwin was to Genesis. Yet physicists everywhere have shown complete readiness to accept his theory as soon as it appeared that the evidence was in its favor. But none of them, least of all Einstein himself, would claim that he had said the last word. He has not built a monument of infallible dogma to stand for all time. There are difficulties he cannot solve; his doctrines will have to be modified in their turn as they have modified Newton's. This critical undogmatic receptiveness is the true attitude of science.

No engineer will object to better planning; but it is essential that before we adopt a new system of industry on a nation wide scale, we should have reason to believe that it is a better system.

"What would have happened if Einstein had advanced something equally new in the sphere of religion or politics? English people would have found elements of Prussianism in his theory; anti-Semites would have regarded it as a Zionist plot; nationalists in all countries would have found it, tainted it with lily-livered pacificism, and proclaimed it a mere dodge for escaping military service."

In the brilliantly written introduction to that book, Russell points out that the amount of emotion felt by any thinker upon a subject is a measure of the uncertainty he has with regard to that subject. A denial that the logarithm of 2 is 0.30103 arouses absolutely no anger in any breast. When, as is reported probably without truth, a legislature ordered that the ratio of the circumference of a circle to its diameter shall be considered for convenience as equal to 3, or when a statesman states in a court of law that he doesn't believe that man is a mammal, no sense of indignation arises; it is the risible faculties only that are stirred. However, when we become less certain, we become more emotional. An attack on one's personal character easily may stir us to anger because of internal doubts as to whether that character is unassailable, while the wild enthusiasm with which a nation will undertake to destroy that nation is a measure of the complete ignorance that exists as to the nature of the matter at issue. It is very unfortunate that in recent discussions of social reconstruction and of economics a large amount of emotion has entered, so that it becomes of greater importance to consider the attitude of the Russian government toward religion or toward marriage than to study dispassionately the possible success of the gigantic economic and social experiment in which they are engaged; or to criticize the relations of statesmen to certain bankers who stand as symbols, than to discuss whether or not their views on finance relate to facts.

We are told often nowadays that our economic system has failed and that the individualistic control of production and distribution must be replaced by another more centralized system. No engineer will object to better planning; but it is essential that, before we adopt a new system of industry on a nationwide scale, we should have reason to believe that it is a better system. Now, the atmosphere in which the existing discussion of economics and sociology is being carried on is singularly unsuitable for such a discussion. There is a story of a preacher who lost his place in his sermon when Henry Ward Beecher was in the congregation. He afterward asked his distinguished colleague what he did when he found himself in a similar difficulty. "Oh," said Beecher, "I do what you did; I yell." At the present time many of the lesser bureaucrats and politicians seem to meet difficulties by yelling. Against this spirit it is the duty of those who have had the advantage of a scientific training to set their faces sternly.

Unfortunately, so long as men's actions are controlled by their emotions, an objective thinker who discussed every proposition without emotion would have no part in modern political life, since a politician must understand the effect of emotional thought and must be prepared to utilize emotional appeal if he is to obtain popular support. A successful political leader must tend therefore either to believe his own emotional appeal or to become a cynic and to some extent a hypocrite if he exerts that appeal without belief. It is this difficulty that makes even the greatest democratic leaders seem insincere in many of their actions; the appeal to emotion is unavoidable if popular sanction is to be obtained, and yet their critics and often they themselves in retrospect feel that appeal to be false and unwarranted. It seems to me that for this reason alone the political arena is unsuitable for the scientific man and that those who believe most fully in the value of the scientific spirit should be prepared to understand and sympathize with leaders who must obtain general popular approval for their actions.

The cleavage in intellectual outlook and mental habits between the political leader and the scientist, the engineer, or, for that matter, the industrialist, is a very real and fundamental one and by no means is to be dismissed summarily. It is common for scientists and industrialists to discuss the methods of the politician as if they were either merely stupid or deliberately wicked, while the views of the political expert as to the "intellectuals" are often scornful in the extreme. In practice, the adoption of political methods controlled by pure reason could succeed only if they involved a dictatorship and the rule of the majority of the people by a small minority. For this reason, the modern dictatorships, whether fascist or communist, can be far more objective and direct in their methods than can democracies. This does not mean that dictators are necessarily, or even probably, exponents of the scientific spirit—indeed, their constant appeal to *ex-cathedra* authority is essentially unscientific; but it does mean that the leaders of a democracy cannot be truly scientific in their attitude and that scientific men must choose between the path of pure reason, which leads directly to oligarchy, and democracy, which involves a certain amount of compromise and confusions.

Leaders of a democracy cannot be truly scientific in their attitude and scientific men must choose between the path of pure reason, which leads directly to oligarchy, and democracy, which involves a certain amount of compromise and confusions.

In 1916, Doctor Steinmetz published a brief paper entitled "Industrial Efficiency and Political Waste" (*Harpers Magazine*, v. 133, 1916, p. 925) in which he warned of the necessity for a change in the political system, taking as a model the efficiency of great industrial organizations. This change he felt was necessary because "The economic development of the world, accelerated by the World War, has made a coöperative industrial organization of our nation a necessity for self-preservation. Such a coöperative industrial organization," said Steinmetz, "presupposes a powerful, centralized government of competent men remaining continuously in office." Doctor Steinmetz felt that such a political change, however desirable, was unlikely to occur since it was incompatible with the democratic temperament of the American people.

If the democratic system of government cannot change to meet the requirements of the changing world system, it must give way inevitably to other systems. That this is so is the claim of many leaders of political thought and, notably, of Mussolini. Only a few years ago, however, it seemed impossible that industry ever should be organized to use scientific methods. The industries of the last century were, with few exceptions, utterly remote from the methods of thought current in the laboratories of the universities, and were controlled largely by "self-made" autocrats. Within our lifetimes all that has changed and the leaders of our modern industries are often technically trained experts, completely removed from their predecessors as to their outlooks and habits of thought.

In order to attain a similar result in the field of politics, we need no revolution; we require only an orderly evolution of the same type. As Janssen says, "There are very few difficulties which cannot be surmounted by a will strong enough or by study sufficiently profound." It is not at all impossible that in a few years the political demagogue may be as rare as the industrial autocrat has become. In order to achieve this result, we must improve the methods of thinking of the public so that they will select suitable governors and then will require from them real leadership and accurate thought. It is both our duty and our right to select for ourselves those who govern us, and the necessary changes can be effected by the proper exercise of that duty and right. The art of government is exceedingly difficult, and it is of the utmost importance, especially in such times of transition as the present, that the men chosen as administrators should be selected with the utmost care.

If the democratic system of government cannot change to meet the requirements of the changing world system, it must give way inevitably to other systems.

The selection of the best methods of procedure in government, as in science, depends eventually upon judgment; and judgment depends upon the natural capacity of the judge and of his training and experience. It should be accepted that in any judgment there will be error and that errors will occur in accordance with the laws of probability. The judgment will be better as the probable error is smaller, but there always will be some error. The administrator, moreover, will suffer from bias. If he is sufficiently objective in mind and sufficiently experienced, he will recognize that and will attempt to make a correction for it just as we correct precision measurements for the "personal equation." Therefore, we should so select our methods of government that there is a maximum chance of arriving at the best judgment, a minimum opportunity for bias, and a probability that the best judgment that can be arrived at will be applied.

Let us accept and consider all proposals, of whatever kind, for a better method of operation; let us refuse absolutely to accept authority as such; let us ignore emotional appeals; and let us pin our faith to those methods of reasoning that have proved so successful in the analyses of all types of natural phenomena.

In so far as our present methods do not meet these requirements, they should be changed, but the most important matter is that we must be prepared to seek out specifically for the functions of government the best men that we have, not necessarily the best in quality, but often the best in character, since a man might have first class judgment and yet be so biased by his ambitions that his decisions would be affected.

In addition to selecting the most suitable leaders, however, the public must be willing to accept their leadership, to value the expression of intelligent thought, and to discount all appeals to emotion and to sectional interests.

In order to attain this result, it is the duty of scientific men everywhere to insist on the value of the scientific spirit and method of thought. My plea today, therefore, is that we deal with the problems of social reconstruction as we do with all other problems. Let us accept and consider all proposals, of whatever kind, for a better method of operation; let us refuse absolutely to accept authority as such; let us ignore emotional appeals; and let us pin our faith to those methods of reasoning that have proved so successful in the analyses of all types of natural phenomena.

The scientific method of thought is not applicable to only one class of phenomenon nor is its use confined in any way to those who have been specifically trained in technical science. The scientific habit of mind and the scientific methods should be understood and cultivated by the community as a whole.

I think that all of us must desire that we honestly could say of ourselves, as Francis Bacon felt justified in saying:

"For myself I found that I was fitted for nothing so well as for the study of Truth; as having a mind nimble and versatile enough to catch the resemblance of things (which is the chief point) and at the same time steady enough to fix and distinguish their subtler differences; as being gifted by nature with desire to seek, patience to doubt, fondness to meditate, slowness to assert, readiness to reconsider, carefulness to dispose and set in order; and as being a man that neither affects what is new nor admires what is old, and that hates every kind of imposture. So I thought my nature had a kind of familiarity and relationship with Truth."

Electric Discharges in Gases—II

Ions in Dense Gases

By KARL K. DARROW
ASSOCIATE A.I.E.E.

Bell Telephone Laboratories, New York, N. Y.

LIKE CAESAR'S GAUL, the vast domain of electrical phenomena in gases may be divided conveniently into 3 parts. Of these the wildest and the hardest to penetrate by far is that of the self-sustaining discharges, the various forms of arc and glow and spark. In these the gas is swarming with free electrons and ionized atoms and excited neutral atoms and corpuscles of light, appearing and disappearing and changing state and interacting with one another and with the electrodes and the walls of the containing tube in such a tumultuous variety of ways that the phenomena are very difficult to understand. At the other extreme is the best ordered of the 3 divisions, comprising the experiments in which beams of free electrons or ionized atoms or photons are carefully produced so as to consist of particles of a single kind with a single energy and a single velocity, and are admitted into tubes of gas so rarefied that the encounters of individual particles with individual atoms can be studied. These are the provinces of the other two articles of this series, written respectively by Dr. Joseph Slepian and R. C. Mason (scheduled for the April issue of ELECTRICAL ENGINEERING) and by Dr. Tonks (February issue). In this article I take the intermediate division, comprising the experiments in which ions of various kinds are produced in intelligible ways and then are set to wandering through "dense" gases—meaning by this, gases so dense that an ion cannot traverse the experimental tube, or pass from one to another electrode thereof, without making hundreds or thousands of collisions with atoms.

This article is a review of some of the established facts and accepted theories pertaining to the behavior of ions in dense gases, supplementing the article that appeared in last month's issue reviewing current knowledge concerning ionization and excitation, and preparing the way for next month's article which will discuss various types of electric discharges in the light of the basic processes set forth in this and the preceding article. This is the fourth of a series of special articles developed under the sponsorship of the A.I.E.E. committee on education, and the second of three devoted to the major divisions of the general subject of electric discharges in gases. Full details concerning this series of articles are given on p. 238 of ELECTRICAL ENGINEERING for February 1934.

—Editor.

DRIFTING OF ELECTRONS THROUGH A GAS PERVADED BY A FIELD: THEORY

Let us form a mental picture of a simple scheme of apparatus: a pair of parallel plates, "cathode" and "anode," the former pouring out a quantity of electrons which are drawn by a field, of uniform strength E throughout the interspace, to the latter. The cathode plays the part of the hot filament so frequently figuring in experiments on gases of low density. It may be a heated plate, or a slab of cold metal from which electrons are elicited by ultraviolet light; or it may be a metal wall with a hole or holes, through which electrons wander from some source behind it into the interspace between it and the anode. If the distance between the plates is of the order of centimeters, the pressure of the gas (supposing it to be near room temperature) should be hundreds of baryes at least.

The electrons emerge from the cathode with relatively small speeds; the field picks them up at once, and accelerates them. Before they have gone more than a small fraction of the way toward the anode, they collide with atoms, or with molecules if the gas is a molecular gas such as air. In order not to have to say "atoms or molecules" constantly, I will henceforth use "atom" to stand for either. *In their collisions with atoms the electrons suffer losses of speed which are small, but deflections which are great.* Consequently, when they have receded far enough from the cathode to have experienced a few collisions apiece, they have nearly as much kinetic energy as though they had fallen unchecked through the field to the place which they have reached, but instead of following the lines of force they are darting about in every direction like particles of a gas. The atoms have converted what in a vacuum would be a rain of electrons, falling in nearly straight lines from cathode to anode, into a chaos of random flights. *The gas composed of neutral atoms is now mingled with an electron-gas.*

We now make 2 specific assumptions, for convenience rather than for necessity: (a) that the collisions between electrons and atoms are strictly elastic, and (b) that the average angle of deflection suffered by an electron at a collision is 90 deg. To ensure the validity of the former, we must keep the field strength in the experiment so low that no electron ever acquires enough energy to ionize or excite an atom (see "Electric Discharges in Gases—Ionization and Excitation," by Dr. Tonks, p. 239–43, ELECTRICAL ENGINEERING, February 1933); this is not a severe limitation, as we can produce many important phenomena while obeying it. In an elastic collision, the electron transfers to the atom a fraction—call it

ϵK—of its kinetic energy K which is indeed small, ϵ being less than $4m/M$; here m and M stand for the masses of electron and atom, respectively, and M is always thousands of times as great as m.[1] The second assumption we know to be sometimes incorrect, for physicists are now making immediate observations of the deflections of electrons by atoms, experimenting with the technique in which an electron beam is sent across an extremely rarefied gas. Before long, people will begin to undertake the task of modifying assumption (b), but for the present it satisfies much better than one might perhaps expect, and it will always be the simplest picture of the fundamental doctrine, that the motion of electrons through a gas is an alternation of sudden impacts with unimpeded flights.

From these assumptions it follows, as I said before, that when the electrons have gone a little way from the cathode their speeds are nearly the same as though they had fallen unchecked through the field, but their directions of flight are random. As the electrons continue onward through the material gas, accelerated constantly by the field and impinging on atom after atom, the first of these conclusions becomes untrue. This is because of the fact that the energy loss at a collision is proportional to the kinetic energy of the electron. Eventually—that is to say, far enough out in the gas—the mean kinetic energy $\overline{K}$ of the electrons becomes so great that the average loss at collisions (we put it at half the maximum loss, $2(m/M)\overline{K}$) balances the average gain from the field during the free flights between the collisions. It is as though at every impact a tax were levied upon the electrons, proportional to the capital which they have already amassed; this increases steadily as they enrich themselves, until it swallows up their fixed income. Thus beyond a certain distance from the cathode there exists a close approximation to the so-called "terminal" condition, in which the mean kinetic energy $\overline{K}$ of the electron-gas does not vary from place to place, but has a constant value depending upon the field strength. Nearly all experiments are performed in tubes so proportioned and filled with gas of such density, that practically this terminal condition prevails throughout the region of the observations; and we shall consider it henceforth as so prevailing.

One other and most important aspect of this electron-gas remains to be considered. Each of the "free paths" of an electron from one impact to the next, being performed in the applied electric field, is bent or swerved by that field; though the *initial* directions of the free paths may be distributed isotropically or quite at random, their *final* directions will depart by a little from the isotropic distribution, tending to favor the direction of the field. It may be shown that the net effect is the same as though the electron gas were steadily drifting through the material gas with a constant "drift speed," superposed on isotropic zigzag motions of its particles. The drift speed is very much smaller than the average speed of these random motions, and the drifting electron gas may be likened to a wind or a moving cloud, things which also move with a mass-motion much slower than the random motions of the molecules or atoms which compose them. This drift speed is one of the most frequently measured quantities in this department of physics. I denote it by u; the mean speed of the random motions of the electrons by ω; the mean kinetic energy of the electrons by $\overline{K}$; the mean free path of the electrons by l; the mean free time or average interval between successive collisions (of an electron with atoms) by τ; the field strength by E; and quote the customary formulas.

The formula for u is this:

$$u = \frac{1}{2}(eE/m)\tau = \frac{1}{2}eEl/m\omega \qquad (1)$$

One may derive it by considering that, during the mean free time, an electron is always experiencing the acceleration eE/m (e = charge, m = mass of the electron) in the applied field; that, as a result, its speed in the field-direction is on the average greater by $(eE/m)\tau$ at the end than at the beginning of its free path; that this comes to the same as saying that its *average* speed along the field-direction during its free time is greater by $\frac{1}{2}(eE/m)\tau$ than it would be if there were no field; and finally, that this average excess speed which has just been evaluated is entirely responsible for the drift, and is in fact the drift-speed, because if there were no field there would be no drift at all.

The formula for $\overline{K}$ is this:

$$\overline{K} = \sqrt{M/8m}(eEl) \qquad (2)$$

M standing for the mass of an atom of the gas. One may derive it by considering that the kinetic energy which an electron acquires from the field during its free flight is on the average[2] $\frac{1}{2}m(eE/m)^2\tau^2$; that the kinetic energy which an electron loses at an impact against an atom is on the average $2(m/M)\overline{K}$, as mentioned above; and that in the terminal condition these two quantities are equal. It is also assumed that $\overline{K}$ is equal to $\frac{1}{2}m\omega^2$, and here the reader may well object that this amounts to identifying the mean speed and the square-root-of-mean-square speed of the electrons, which certainly is wrong. There are other examples of impeachable averaging in the arguments leading to eq 1 and eq 2, but it is not worth while to make an elaborate attempt to better them, for even if we could make them unassailable (which we could not) there would still be the uncertainties of assumptions (a) and (b). It is best to consider that the right-hand members of eq 1 and eq 2 are both to be multiplied by unknown factors, which we have

1. If the reader is willing to assume that a central impact is the most efficient in transferring energy, he may simply suppose that the electron approaches along the x-axis with speed u, and the electron and the atom depart along the same axis with speeds u' and U', respectively; the result is then obtained by solving for (U'/u) the two equations of conservation-of-momentum ($mu = mu' + MU'$) and conservation of kinetic energy ($mu^2 = mu'^2 + MU'^2$). It is assumed that the atom is initially stationary, an assumption nearly always acceptable because electrons (owing to their lesser mass) are usually moving much faster than atoms.

2. This is not so obvious as it may seem. An electron which starts with speed v on a free path inclined at angle θ to the field-direction possesses, at the start, kinetic energy equal to $\frac{1}{2}mv^2$; at the end of time t the kinetic energy has increased to $\frac{1}{2}m(v^2 + 2atv\cos\theta + a^2t^2)$, where a stands for (eE/m). The second term however vanishes in the averaging, leaving only the third to express the mean increment of kinetic energy.

fairly strong grounds for believing not very different from unity—between $\frac{1}{2}$ and 2, quite probably. (In eq 1 this factor often is assigned the value 1.63.)

Eliminating l between (1) and (2) we obtain the relation:

$$\bar{K}/u^2 = M \tag{3}$$

an equation convenient for experimental test.

It often is desirable to speak of the temperature T of the electron gas, or simply the "electron temperature"; this quantity is equal to the mean kinetic energy $\bar{K}$ multiplied by a universal constant; the relation between $\bar{K}$ in ergs and T in degrees is the following:

$$\bar{K} = \frac{3}{2}kT \tag{4}$$

where k is the "Boltzmann constant," equal to $1.37 \cdot 10^{-16}$. Putting T into eq 2, one notices that the temperature of the electron gas, far from being equated to the temperature—T_0, say—of the atom gas with which the electrons are mixed, is equated to an expression which does not involve T_0 at all. Indeed eq 2 shows that, under customary conditions of field strength and pressure, the field should maintain the electron gas at temperatures many times higher than T_0. This striking consequence of the theory is fully verified by experiment, as we shall see.

Diffusion of Electrons Through Gases: Theory

There is a very important theorem that a gas with a nonuniform density tends to flow or drift along the direction of its density gradient, with a drift speed proportional to that gradient. This theorem is applicable to electron gas; and we may say that a density gradient, or "concentration gradient" as it is more commonly called, is equivalent to a field—that is, to the field strength that would produce the same drift. It may be shown[3] that a concentration gradient G—to be written as dn/dz, n standing for the concentration or the number of electrons per unit volume—and the equivalent field strength E are linked by the equation:

$$E = kTG/ne = (kT/ne)(dn/dz) \tag{5}$$

It will be seen that this relation makes it possible to measure the electron temperature and so verify the striking consequence aforesaid of the theory:

Drift and Diffusion of Ions of Atomic Mass: Theory

Not all of the ions to be found in conducting gases are free electrons. All of the positively charged ions are, at the least, individual atoms which have become ionized through the loss of one electron (or more than one); they may be clusters of several atoms, one of which is ionized. Some or all of the negative ions may be atoms or clusters of atoms to which an extra electron has attached itself.

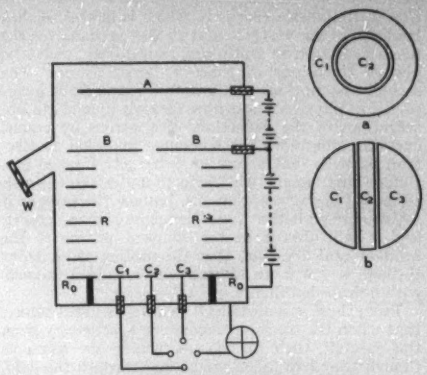


Fig. 1. Scheme for observing drift speed and diffusion conjointly

The ions drift in a uniform field directed from A toward C_1 and C_3 (sketched above "a") and after passing through the hole in B the ion stream widens laterally by diffusion. (The arrangement "b" of the electrodes serves for measuring drift speed separately, a magnetic field being applied.) (Townsend)

Ions such as these will form an "ion gas" mixed with the atom gas, having (when a field prevails) a temperature and a drift speed. There are, however, notable differences from the electron gas above described. In the electric field, the electron gas of the previous case is raised to a much higher temperature than the atom gas, and this is essentially because an electron gives up so small a fraction of its kinetic energy to an atom at an impact—the energy-transfers between electrons and atoms are, we may say, very inefficient because of the great disparity of masses. In the present case the masses of atom and ion are equal, or at least of the same order of magnitude; the transfers are very efficient, and the temperature of the ion gas is practically the same as that of the atom gas. Equations 2 and 3 thus have no validity. Equation 1 retains its general appearance, with ω in the denominator of the expression for u; but now ω, like $\bar{K}$ and T, is independent of field strength, and instead of $\frac{1}{2}m$ there is a factor depending on both m_i and m_a, the masses of ion and atom, respectively. Equation 6—in which c_a and c_i stand for the square-root-of-mean-square speeds of atoms and ions, respectively, and r for the ratio m_a/m_i—is based on the assumption that atoms and ions alike behave like elastic spheres. I append to this the appropriate forms of eq 3 and eq 4:

$$u/E = 0.812(1 + r)^{1/2}(el/m_a c_a) = 0.812\left(\frac{1 + r}{r}\right)^{1/2}(el/m_i c_i) \tag{6}$$

$$\bar{K} = \frac{1}{2}m_i c_i^2 = \frac{1}{2}m_a c_a^2 = \frac{3}{2}kT_0 \tag{7}$$

$$E = (kT_0/ne)(dn/dz) \tag{8}$$

3. Many readers will remember the theorem that in a fluid exposed to gravity, equilibrium prevails when the pressure-gradient dp/dz is equal to the force exerted on unit volume of the fluid by gravity. If the fluid is a perfect gas, the pressure p is equal to nkT (n = number of atoms per unit volume, T = temperature, k = Boltzmann constant), and hence the pressure-gradient is equal to the concentration gradient multiplied by kT. The force per unit volume exerted by gravity is nmg, and this, when we go over to the case of an electron gas subjected to a field strength E (gravity being negligible by comparison) is replaced by neE.

Drift and Diffusion of Electrons: Experimental

Return now to eq 5. It shows that if one can determine both the concentration gradient G and the field strength E which separately produce a given drift speed u, one can deduce from their ratio the electron temperature T. Since T depends on the field strength, the former measurement must be made in the presence of the same applied field as the latter; it is not, however, necessary to adjust G until the drift speed due to the concentration gradient becomes the same as that which E separately would produce, for we may make the measurement for any convenient value of G and then assume that this drift speed is proportional to G/n. Actually there is a very ingenious method in which a stream of ions is passed through a hole into a chamber of gas (Fig. 1); the stream is drawn across the gas by a field parallel (say) to the X axis, and simultaneously the ions diffuse sidewise in the YZ plane so that the stream widens steadily as it proceeds. The widening which the stream has undergone by the time it reaches the far side of the chamber is affected by the forward drift in the field and by the lateral diffusion jointly, and from an analysis of the data the electron temperature may be obtained. By a slight modification of the apparatus the drift speed due to the field may be separately measured.

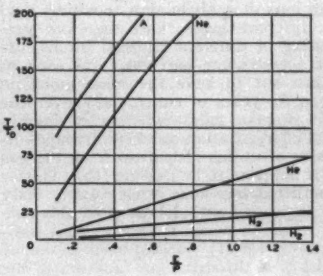


Fig. 2. Ratio T/T_0 of electron temperature to neutral gas temperature, plotted for argon, neon, helium, nitrogen, and hydrogen as a function of ratio E/p of field strength to gas pressure (Townsend)

By this procedure, values of electron temperature *200 and more times* as high as the temperature T_0 of the atom gas are observed (Fig. 2). No extravagant field strength is needed to produce such values: in pure dry argon the ratio T/T_0 is about 200 when the field strength is 0.5 volt per cm and the pressure is one millimeter of mercury. In the glowing gas which fills the tube of a mercury vapor arc, electron temperatures of 60,000 deg C or 80,000 deg C are observed (by a different method, the "Langmuir probe method," which Slepian and Mason probably will consider in their article of this series) although the vapor itself is not sufficiently hot even to soften the glass walls of the tube.

For several gases u and T have both been measured under identical conditions, this making possible a test of eq 3 and therefore of the fundamental assumption of elastic impacts. The assumption is found to be excellently confirmed for several gases, so long as T is not too great; for instance, it is verified for hydrogen, nitrogen, and helium when $\bar{K}$ is not more than 0.5 electron-volt (T about 6,000 deg C) and for argon its validity holds up as far as $\bar{K}$ = 5 electron-volts. The discrepancies which occur at higher values of $\bar{K}$ (and at low values also, in chemically active gases) may be taken as a measure of the mean departure from perfect elasticity of the impacts.

The mean free path l of the electrons may be determined from eq 1 if u and $\bar{K}$ have both been measured; or if one fully accepts both of the assumptions (a) and (b)—perfect elasticity of impacts, average deflection at a collision equal to 90 deg—one may determine l by measuring either T by itself or u by itself (using in the former case eq 2, in the latter the equation obtained by eliminating $\bar{K}$ between eq 1 and eq 2.) For some gases l is nearly constant, while for others—argon is a conspicuous example—it varies rapidly with $\bar{K}$ (Fig. 3). This puts somewhat of a strain on the otherwise convenient picture of the atoms as elastic spheres, inasmuch as it becomes necessary to imagine that the size of the sphere depends on the speed of the electron which is approaching. It is perhaps more comfortable to imagine that there is a certain chance of the electron traversing the sphere instead of rebounding from it, this chance varying rapidly with the speed of the electron. Such compromises are often necessary when one wishes to avail oneself of the advantages of a simple and pictorial model. In this case the necessity is inescapable, for these results are sustained by those of a great many experiments in which narrow streams of electrons are projected across thin strata of rarefied gases, and their mean free path is determined by measuring the number either of those which are deflected by collisions or of those which manage to cross undeflected.

Finally, suppose that on the constant applied electric field E there is superposed another at right angles to it, which second field is oscillatory (alternating); denote this latter by $F \sin nt$. Experiments show that on the steady drift along the direction of the

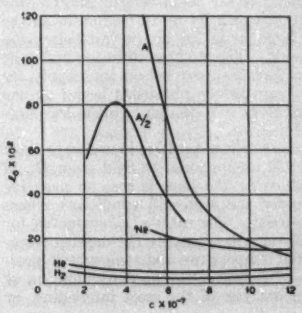


Fig. 3. Mean free path l of free electrons in argon, neon, helium, and hydrogen at a gas pressure of 1 mm of mercury, plotted as a function of c, the root-mean-square speed of the random motion of the electrons (Townsend)

constant field there is now superposed a sidewise to-and-fro motion of the electron gas; there is what may be called an "oscillating drift," in phase with the field which produces it. Up to frequencies of the order 10^8 (cycles per sec) this mass vibration of the electron gas is found to have the amplitude which is to be expected from eq 1, if for the factor multiplying E in that equation we put the value μ derived from experiments with steady fields, and assume that the sidewise drift speed is equal to $\mu F \sin nt$. In this substitution the value put for $\bar{K}$ is that corresponding

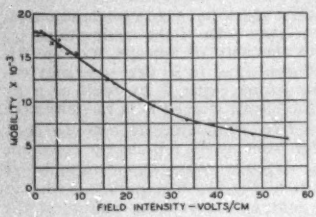


Fig. 4. Mobility of free electrons as a function of field strength, in nitrogen at atmospheric pressure (Wahlin)

Mobility means ratio of drift speed to field strength

to the steady field strength E prevailing in the experiment, the ratio of F to E being intentionally kept so small that the alternating field does not appreciably affect the electron temperature.

Diffusion and Drift of Massive Ions: Experimental

Measurements of diffusion of positive ions always show that their temperature is indistinguishable from that of the neutral gas: T is equal to T_0, as we expect from the fact that no kind of positively charged particle is known which is not a charged atom or cluster of atoms. Measurements of diffusion of negative ions usually show the same, which implies that electrons do not long remain free in ordinary gases, but quickly attach themselves to atoms or atom clusters. For electrons to remain free in a dense gas it is necessary that the gas should be inert, or at least chemically inactive, and that it should be well dried and well freed of organic vapors such as those of stopcock grease; or else that the current density or the field strength (strictly, the product of field strength by mean free path) in the gas should be large, as in the arc or just before the passage of a spark. The study of diffusion and drift of massive ions had been carried on intensively for more than 10 years before physicists began to dry and purify their gases well enough to make free electrons observable.

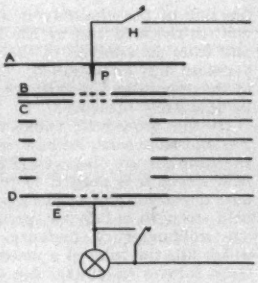
Measurements of drift of positive ions always show that drift speed is proportional to field strength, in accordance with eq 6; the same is true for negative ions, except under the aforesaid conditions where free electrons persist. The ratio u/E, evaluated for standard density of a gas (usually the density corresponding to room temperature and atmospheric pressure), is termed "mobility." The determination of mobility values was one of the most interesting, or anyhow one of the most widely studied, problems of physics during the first 20 years of this century, and is still cultivated.

The methods of measurement are legion; I will mention only a very late one (Fig. 5). A flock of ions is drawn by a field through a pair of consecutive shutters mounted a distance D apart, which are opened for brief moments separated by a time interval T; they pass to the electrometer beyond the second shutter if, and only if, their drift speed u is equal to D/T. Actually the shutters, as I have called them, are transverse electric fields which are applied by a high frequency generator, in such a way that the ions can reach the electrometer only if they traverse the distance D during an integer number of half-cycles of the frequency (5 half-cycles, in some actual instances). On plotting electrometer current against frequency, a curve is obtained with a peak for each kind of ion present, and from the location of the peak u may be evaluated. In most cases the ratio u/E lies between 1 and 10 when u is expressed in cm per sec and field strength in volts per cm.

The situation with respect to theory has been confused through nearly all of the third-of-a-century of experimental research by a remarkable fact of experience: when ions of a given sign (positive, say) originating in different gases, and therefore presumably consisting of different charged atoms, are caused to drift across some particular gas such as air, they all turn out to have the same mobility! There have been 30 years of controversy over the meaning of this singular rule: whether it signifies that the original charged atom quickly surrounds itself with a cluster of atoms picked up from the gas through which it happens to be passing (the "cluster theory") or whether it has some other cause. Only within the last 3 years have violations of this rule been observed: cases in which it appears that positive ions of a known variety (ionized atom of one of the alkali metals) drift through a gas (any one of the

Fig. 5. Scheme for measuring drift speed of ions in manner described in accompanying text

Ions drift in uniform field directed from P toward E, but when they reach the planes of the gauzes they are drawn to the wires thereof by a transverse alternating field, unless they happen to reach these planes at the moments when the alternating field is nearly zero (Van de Graaff)



noble gases) clear across the experimental chamber without losing their initial and distinctive values of drift speed. This has been achieved by intensive drying and purification of the gas, coupled with the use of the method described above, which permits of observing the drift speed in the first few ten-thou-

sandths of a second of the existence of the ion. In argon the mobilities of positive ions of sodium, potassium, rubidium, and caesium are found to vary as $(1 + r)^{1/3}$, in accordance with eq 6. The simple elastic-sphere theory is nevertheless inadequate, and it is necessary to introduce a new feature into it by postulating forces of attraction between the ions and the atoms; these may be considered as arising because the charge on an ion polarizes the neighboring atoms.

Recombination

When a gas filled with equal numbers of ions of opposite signs is left to itself the ions rapidly disappear, because positives and negatives in their wanderings through the gas meet with those of the opposite sign and combine with them into neutral particles: the process known as "recombination." The disappearance is completed much more rapidly than it would be if the ions of both signs were elastic spheres having

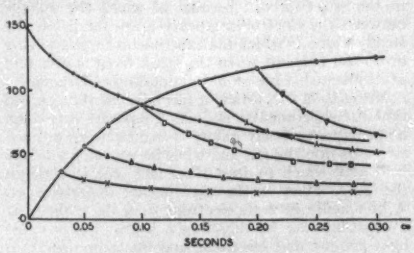


Fig. 6. Illustrating recombination

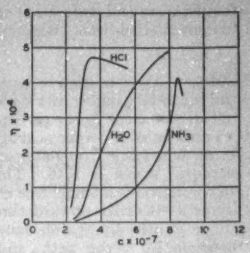
The rising curve shows the number of ions in a sample of air as function of time during a continuous exposure to ionizing rays, and the falling curves show the number as function of time after the rays are shut off. (The curve descending from the left is the fall after a 30-sec exposure.) (Schemel)

about the same radii as the atoms. This phenomenon, like the phenomena of mobility, suggests that the ions are clusters of atoms, or that they exert on one another forces which at close distances are even greater than the electrostatic attractions between them. The rate of disappearance depends in peculiar ways on temperature and pressure, and this possibly signifies that 2 ions of opposite sign must give away some of their kinetic energy in collisions with atoms shortly before they combine with each other, as otherwise they are likely to rebound from one another without combining. There are, however, many ill-understood phenomena in this field.

Attachment

The massive negative ions mentioned in the 2 preceding sections come into being because free electrons are captured by, or "attach" themselves to, neutral molecules or atoms. If a stream of free electrons drifts across a dense gas, some of its individuals are captured *en route*. Say that the gas is at pressure

Fig. 7. Probability of attachment of electrons to molecules (see text) in hydrogen chloride, water vapor, and ammonia as function of root - mean - square speed c of the random motion of the electrons. (Bailey and Ducanson)



p, and is bounded by screens at $x = 0$ and $x = L$, and pervaded by a field of field strength E directed parallel to the x-axis; then if N_0 electrons emerge per unit time from the first screen and drift across the gas, the number which arrive at the second screen per unit time as *free uncaptured electrons* may be written as $N_0\ exp(-aL)$. The coefficient a is a sort of a measure of the tendency of the gas to capture the electrons; it depends on the electron temperature T, and therefore on E and p which control T. A better measure is the ratio of a to the number of collisions which an electron makes in going from $x = 0$ to $x = L$ if it escapes capture all the way. This may be termed "probability of attachment at a collision of an electron with an atom" though this usage is rather loose and should be analyzed carefully by any one making a study of the subject. With field strengths (or rather, with values of E/p) such as have been considered up to now in this article, it is rather surprising to learn that, even in gases such as oxygen where it is difficult to maintain a supply of free negative electrons, this probability is of the order of 10^{-6}; in the noble gases it is lower than 10^{-9}. It varies with T in strange and intricate ways which have not yet been sufficiently studied.

Self-Amplified Ionization

Return now to the scheme of apparatus proposed in the second paragraph of this article, and imagine that the anode is gradually drawn back so as to vary the distance d between cathode and anode, the potential difference V between these electrodes being always so adjusted that the field strength E remains the same. Let N_0 electrons, composing a current of strength $i_0 = N_0e$, enter the gas per unit time from the cathode. We have heretofore assumed that E is so low that all collisions between electrons and atoms are elastic; in such conditions the current i will be constant and equal to i_0, whatever the value of d. If, however, the field strength (it is really the field-strength-to-pressure ratio E/p which matters, as heretofore) is sufficiently increased, it is found that *the current increases exponentially with d: extra current carriers are arising in the gas* (Fig. 8). The electrons emerging from the cathode and drifting through the gas occasionally make impacts of such violence against atoms, that these are separated into free electrons and positive ions. "Secondary" electrons thus set free are quick to attain the electron

temperature and drift speed of the primary ions, and to ionize in their turn: the exponential relation

$$i = i_0 \exp(\beta_2 d) \tag{9}$$

is due to the cumulative ionizing action of primary and secondary and tertiary and all other electrons.

The coefficient β_2 in eq 9 depends on E and p. To get an idea of its order of magnitude, take the value for air when $E = 700$ volts per cm and $p = 4$ mm of mercury, which is 8.16. This implies that under such conditions a single free electron ionizes about 8 atoms as it drifts onward through a centimeter (of course it actually travels much more than a centimeter in its zigzag path, and makes an enormous number of collisions during this interval). Owing to the high value of the ratio E/p, attachment is probably rare, so that the negative ions in the gas are actually free electrons as is taken for granted in the foregoing passage. It is, however, an unfortunate fact that when the field-strength-to-pressure ratio is so high as it is in these experiments, the advent of the extra ionization impedes very greatly or precludes altogether the use of the classical methods of measuring attachment and recombination and drift speed and electron temperature, so that we remain largely ignorant of these important phenomena in just the conditions where exact knowledge of them would be of major importance.

When d is increased sufficiently, eq 9 ceases to be exactly valid, the curve rising too rapidly (Fig. 8); it appears that the current is enhanced by something additional to the ionizing power of the free electrons. When d is still further increased, something startling presently happens. With parallel plane electrodes such as have hitherto been postulated, this startling event is the occurrence of a *spark*. With cylindrical or spherical electrodes, it may be the advent of a glow or corona, a so-called "self-sustaining discharge." Paradoxical as the statement sounds, the spark itself is properly to be regarded as a self-sustaining discharge. True, it ceases almost immediately; but that is for a secondary reason having nothing to do with the phenomena in the gas: the immense current which flows in the spark has effects in the outer circuit, because of which the voltage between the electrodes quickly drops far below the steady value V which the experimenter was applying up to the moment when the spark burst across, and at its lowered value cannot maintain the discharge.

Hitherto in this article it has been tacitly assumed that the experimenter is doing 2 separate acts when he provides a steady inflow of free electrons or massive ions into the gas and when he provides a steady field with which to draw these ions onward through the gas. Thus in the experiments underlying eq 9, he usually extracts electrons from the cathode at a constant rate by directing a beam of ultraviolet light against that electrode, and this is an operation entirely separate from his other operation of keeping a steady voltage applied between anode and cathode. In a self-sustaining discharge, however, it is sufficient for him to attend to the second operation only, and maintain the voltage; the internal processes of the discharge itself attend to the other task of maintaining the outflow of primary electrons from the cathode. There is a gradual transition between these 2 extreme cases, covering the range where the discharge is not self-sustaining, but the current is greater than that computed from eq 9; for in this range the processes occurring in the gas are responsible for a part, though not the whole, of the primary electron stream.

Several ways are known in which these processes may act to produce the required result. Thus, if the electrons traversing the gas acquire energy enough to ionize its atoms, they also inevitably acquire energy enough to cause these atoms to send out ultraviolet light; now, ultraviolet light falling upon a metal ejects electrons from that metal; so that in the experiment just pictured, some of the electrons emerging from the cathode must be due not to the separate beam of light which the experimenter directs against it from outside, but to light generated by the passage of the previously ejected electrons through the gas itself. In this case one may say that the primary electrons receive energy from the field and give it to the atoms, which absorb it and subsequently reëmit it in the form of photons (corpuscles of light) which

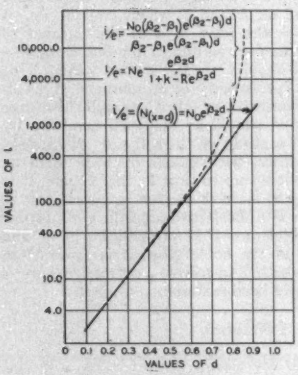


Fig. 8. Semilogarithmic plot of current vs. electrode distance (i vs. d) in air between plane parallel electrodes

Pressure, 4 mm of mercury; field strength, 700 volts per cm. Straight line, graph of eq 9. Curve agrees with either of the annexed formulas. (Data from Townsend)

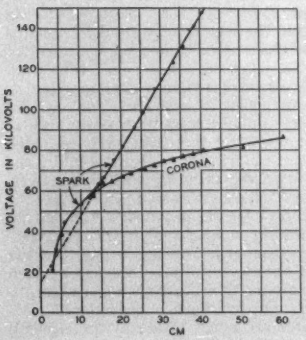


Fig. 9. Relation between breakdown potential (kv) and distance (cm) between parallel wires of 8.25-mm diameter

Beyond about 12 cm the advent of the spark is preceded by the advent of a corona discharge, and there is a range of voltages in which the latter is self-sustaining and stable. (Peek, "Dielectric Phenomena in High Voltage Engineering," McGraw-Hill)

carry it over to the cathode and there employ it in extracting fresh electrons. It may also happen that the atoms, instead of reëmitting this energy which they receive, keep it stored up within themselves until they happen to wander over to the cathode surface itself and impinge against the metal, whereupon their stored energy is taken over from them and employed to the same end. Such a thing is especially likely in certain kinds of gases, including the noble gases, of which the atoms or molecules are peculiarly able to retain their energy for long periods without emitting it in the form of light; during the retention they are said to be "metastable atoms." Likewise the positive ions formed in the gas and drawn to the cathode by the field may expel electrons from the metal when they strike it. Yet another possibility is, that the positive ions on their voyage through the gas may themselves split some of the atoms which they meet into free electrons and additional positive ions. In a mixture of gases, metastable atoms of the one may ionize atoms of the other.

It is probable that in actual cases where the current is greater than eq 9 admits, the current flow is contributing to its own support in 2 or more of these ways simultaneously. To ascertain what actually is happening in any case is a problem of research of which the importance is matched only by the difficulty. Its importance is largely due to its bearing on the phenomenon of "breakdown" (that is, the advent of the spark or other form of self-sustaining discharge); for breakdown comes about when these processes (together, it may be, with others as yet unrecognized) are acting powerfully enough to replace all the ions which go to the electrodes or otherwise disappear by an unceasingly equal supply of fresh ions. After breakdown has occurred and the self-sustaining discharge is established, these processes have the field to themselves. However the phenomena then differ extraordinarily from those of the gentle current-flows which have been the topic of this article; the differences being traceable in part to the great current densities, in part to the high field strengths which are accentuated by the presence of space charge.

References

No names have been mentioned in this article, as it is impossible to apportion credit properly in so succinct a treatment. I should mention at least that many of the experimental methods and much of the theory in this field of physics are due to J. S. Townsend, and that eq 6 is due to Langevin. Fuller accounts, with references to the original papers, may be found in the following books and articles:

1. K. T. Compton and Irving Langmuir, Electrical Discharges in Gases. *Reviews of Modern Physics*, v. 2, 1930, p. 123–242, and v. 3, 1931, p. 191–257.
2. Karl K. Darrow, Electrical Phenomena in Gases. Williams & Wilkins, 1932. High-Frequency Phenomena in Gases. *Bell System Technical Journal*, v. 11, 1932, p. 576–607, and v. 12, 1933, p. 91–118. Mobilities of Recognizable Ions, *Review of Scientific Instruments*, v. 4, 1933, p. 6–8.
3. K. G. Emeleus, Conduction of Electricity Through Gases. Methuen, 1929.
4. L. B. Loeb, Kinetic Theory of Gases. McGraw-Hill, 1927.
5. J. J. Thomson and G. P. Thomson, Conduction of Electricity Through Gases. Cambridge University Press, 1928–32.
6. J. S. Townsend, Electricity in Gases. Clarendon Press, 1915. Motion of Electrons in Gases. Clarendon Press, 1925; *Journal of the Franklin Institute*, v. 200, 1925, p. 563–590.
7. F. W. Peek, Jr., Dielectric Phenomena in High-Voltage Engineering, McGraw-Hill, 3d ed. 1929.
8. S. Whitehead. Dielectric Phenomena, D. Van Nostrand & Co., 1927.

Social Aspects of the Engineering Approach

Social advantages and disadvantages of the engineering-scientific approach to civilization are discussed in this article, which includes full text of an address delivered at a meeting of the American Association for the Advancement of Science held in Boston, Mass., December 8, 1933. The engineer is urged to apply the precision of his thinking and his honesty in facing facts to the more complex situations that concern living organisms and our social life.

By
HENRY A. WALLACE
U. S. Secy. of Agriculture, Washington, D. C.

I SUPPOSE you are all more or less familiar with that concept of the cyclical rhythm of civilization which has been popularized in recent years by Petrie, the Egyptologist, and Spengler, the German philosopher. According to this analysis, a civilization takes its origin in a profound, but as yet unexpressed, new attitude on the part of a virile, agricultural people toward the Universe. This profound, original feeling gives the bias to subsequent events throughout the life of the civilization. First, it manifests itself in great cathedrals and sculpture; next in painting, literature, and music, followed by science, mechanics, and wealth; and finally it manifests itself in dissolution which comes because of a lack of faith in the worthwhileness of the original attitude toward the universe and because of disgust with the material results which finally have been inspired by that attitude. According to this analysis we have now come to the late fall, the eventide of this civilization, and the coming of the engineer is like the coming of Indian summer in late October just before the cold and dreary days of winter.

Philosophical analysis of this sort, even when backed up by archeological research, can be, of course, merely suggestive; but after our experience with the World War and the depression of the past 4 years, we are led to question the American credo, based as it has been on faith in progress unlimited, derived from endless mechanical invention, improved methods of mass production, and ever-increasing profits. Without accepting either the implicit pessimism of the Spenglerian twilight philosophy or the Pollyanna optimism of the old-fashioned American "go-getter," I would ask you to examine superficially with me the contributions of science and

engineering, the dilemma thereby created, and a possible way out.

Productivity Increases Annually

For 100 years the productivity of the so-called civilized world has increased at the rate of about 3 per cent annually. Correcting for increase in population, the output *per capita* has increased at the rate of about 1 per cent annually. In the United States the rate of increase of material wealth perhaps has been a little faster than this; but everywhere there has been apparent a little slowing down during the World War, and especially since 1930. So we have, on the one hand, those people who proclaim that inevitably the predepression trend will be resumed, and those who, on the other hand, say that the time of the quantitative expansion of man's control over nature is now coming rapidly to a close.

Engineering and science, combined with the division of labor, have made it possible for an hour of man-labor on the farm to produce several times as much as it did a hundred years ago. In company with the rest of you I have marveled from time to time over the tremendous contribution of the reaper, the binder, the combine, the truck, the tractor, and the gang-plow; but inasmuch as we have come now to days of real soul-searching about all the things that we hitherto have called progress, I think it is high time for all of us to analyze these various labor saving devices a little more critically. Do they really save as much as appears on first glance?

True it is that the farmer puts in only a mere fraction of his own labor in producing wheat, as compared with 100 years ago, but what about the labor of the men who made the combines and the plows and the tractors? What of the labor of the men who transport the wheat the thousand miles to market, of the vast distributing and advertising machinery which seem to be necessary if we are to operate on the broad scale apparently required by the modern adaptations of engineering and scientific discoveries? I am inclined to think there is a real net gain, but it is a gain of a sort which easily can be lost altogether unless certain social adaptations very rapidly are perfected.

There Should Be More Time to Enjoy Life

The change from the back-breaking cradle of our forefathers to the modern combine ought to mean a tremendous release of human energy on the farm for something besides growing and harvesting a crop. The days when wheat was broadcast by hand, perhaps from a saddle horse, in retrospect seem quite romantic; but to the farmer who had to spend days at seeding-time where he now spends hours, the romance probably wore pretty thin. The grind of the harvest of years ago, the sweat of men in the field and women in the kitchen, were honorable things, and even were celebrated in song and story; but it did not leave much time for living. Engineers and scientists have given us the instruments and the methods whereby we can escape much of the grind; theoretically, there ought to be far more time for living and far more with which to enjoy life. Yet the reverse seems to be poignantly true.

The man who invented our labor saving machinery, the scientists who developed improved varieties and cultural methods, would have been bitterly disappointed had they seen how our social order was to make a mockery of their handiwork. No doubt they felt that they were directing their talents to free mankind from the fear of scarcity, from the grind of monotonous all-absorbing toil, and from the terrors of economic insecurity. Things have not worked out that way.

I do not mean to imply that there have been no gains. Of course there have been net gains, even if incommensurate with the hopes and promise of science. Plainly we must hold those gains, and add to them rapidly and extensively; but I think we can do this only if the planning of the engineer and the scientist in their own fields gives rise to comparable planning in our social world.

Productivity Could Be Doubled in 30 Years

So far as science and engineering themselves are concerned, I see no reason why the rate of expansion that characterized the "Century of Progress" should not be increased, at least for a time. While there are certain ultimate limitations in our supplies of coal, iron, petroleum, and soil fertility, it is obvious to most of us who are close to any particular phase of scientific research or technical organization that there are imminent discoveries which, when applied, will increase *per capita* output enormously. Nearly every technical man knows in his heart that from a purely scientific engineering point of view the most amazing things could be done within a relatively short period. Of course, in the world of hard fact the full effect of any revolutionary invention is not felt typically for 15 or 20 years; but I feel safe in saying that our scientists and inventors today have enough new stuff within their grasp or just around the corner so that the world 30 years hence easily could have a total productive power twice that of today.

It is almost equally possible that the total wealth-producing power of the world a generation hence will be less than it is today. The trouble, if it comes, will not be in the inability of scientists and technologists to understand and to exploit nature, but in the ability of man to understand man and to call out the best that is in him. In solving this limitation scientists and engineers all too often have been a handicap rather than a help. They have turned loose upon the world new productive power without regard to the social implications. One hundred years ago the power looms of England destroyed the cottage weaving industry, and during the early years of that impact misery strode over the countryside of England in proportion as the *nouveaux riche* gained capital to exploit their gains over the entire world. That kind of thing has been done again and again, and we have called it progress because the power of man over nature was increasing and because in the long run the common man shared in this increase. What happened to the common man in the shortrun, of course, could be of no concern to a *laissez faire* society.

Until recently, most of us, whether scientists, business men, or laborers, have looked back on the Century of Progress and called it good; but today the afflictions of Job have descended upon us and of necessity we must argue with Bildad, the Shunite, and set ourselves right with our God before we go forward into a prosperity 7 times that which we enjoyed before.

Acting perhaps in the capacity of Bildad, I would like to suggest that the very training which made possible the enormous material expansion of the past century may have made impossible to some extent the building of a just social system for the prompter and more uniform distribution of the wealth produced by the system. Most of the scientists and engineers were trained in *laissez faire*, classical economics, and in natural science based on the doctrine of the struggle for existence. They felt that competition was inherent in the very order of things, that "dog eat dog" was almost a divine command.

The power discovered by scientists and inventors was applied in the United States by a race of men who had developed a concentrated individual will power and an extraordinary thriftiness as a result of several generations of pioneer agricultural training and Protestant churchgoing. As a result, human power of high spiritual origin, but debased by the sophistication of the "devil take the hindmost" economics of the colleges, took command of the exploitation of the discoveries made by the scientists and inventors. Scientists and inventors have an intense kind of religion of their own—certain standards to which they like to be true—and as long as they could get enough money to pursue their researches, why should they care how some one else handled the social and economic power derived from these researches? Perhaps that is putting the matter unkindly, but other explanations that might be advanced are not much more flattering. Those who delved too deeply into social and economic problems got into trouble, and many of the best scientists felt that it was not good form to do things which to certain types of mentality seemed impractical and which might endanger science's financial support.

Technical Efficiency Vs. Culture

It is my observation that previous to 1933 more than $^3/_4$ of the engineers and scientists believed implicitly in the orthodox economic and social point of view. Even today I suspect that more than half of the engineers and scientists feel that the good old days soon will be back when a respectable engineer or scientist can be an orthodox standpatter without having the slightest qualm of conscience. It is so nice to feel that there are great supermen from whom directly and indirectly you draw your own sustenance, who, sitting Jove-like above us lesser mortals, make possible the free functioning of the law of supply and demand in such a way that their profits enlarge at the same rate that our research expands. Like most of you in this audience, I rather like that kind of a world, because I grew up in it: in some ways, I wish we could get back to it; but both my mind and my instinct tell me that it is impossible for any length of time. Of course, if prosperity returns within the next year or 2, it is possible for us to think that we are back in that old world again; but unless the people who make profits and direct capital allocation to different productive enterprises have seen a great light, or unless we move forward into certain highly centralized forms of industrial and governmental control, we shall sink back into our former trouble.

There ought to be more than a little hope in the fact that our engineers have demonstrated so successfully their skill in planning. In many great industries, the engineers have been able to mark out the contours of expansion and development 10 to 15 years ahead. If in the past they seemed to be guided by purely material and mechanical considerations, that doubtless has been because such considerations were necessarily the chief ones so long as we were conquering a continent. Today it is becoming increasingly evident that we must take into account the qualitative as well as the quantitative expansive aspects. This would suggest that in the engineering courses of the future, engineers should be given an opportunity really to enrich their minds with imaginative, nonmathematical studies such as philosophy, literature, metaphysics, drama, and poetry. Of course, so long as an engineer is burdened with the necessity of putting in 18 hours a day mastering calculus, mechanics, and the complex theories of electricity, he simply cannot give any effective attention to the cultural aspects of life; and if by accident an engineer, exposed to studies of this sort, should be enthused by them, he might for the time being become somewhat less effective as an engineer. We thus are exposed to a dilemma, which I would be tempted to solve by saying that probably no great harm would be done if a certain amount of technical efficiency in engineering were traded for a somewhat broader base in general culture.

Social Problems Crying for Solution

It is difficult to see how the engineer and the scientist can preserve much longer a complete isolation from the economic and social world about them. A world motivated by economic individualism has come repeatedly to the edge of the abyss, and this last time possibly came within a hair's breadth of plunging over. Yet science, all this time, has been creating another world and another civilization that simply must be motivated by some conscious social purpose, if civilization is to endure. Science and engineering will destroy themselves and the civilization of which they are a part, unless there is built up a consciousness that is as real and definite in meeting social problems as the engineer displays when he builds his bridge. The economist and the sociologist have not yet created this definite reality in their approach; can you, trained in engineering and science, help in giving this thought a definite body?

Today when the industrial nations of the world have skimmed most of the cream off the backward nations and the backward classes, and when there are no longer any challenging geographical frontiers

to be conquered, it becomes apparent that we must learn to coöperate with each other instead of joining together in the exploitation of some one else. This means the building of a social machinery as precise and powerful as an automobile engine. How extraordinary is the patient vigor of thought that enables a group of engineers to blue-print and execute a new design; and how sloppy is our economic blueprinting and execution by comparison!

It must be said in defense of the economists, however, that their problem is infinitely more difficult than that of the engineer. The economic engineer never has had any excuse to exist until recently because no one gave him any orders for blueprints. Even yet the objectives are so loosely defined, the popular will is in such a state of flux, that the designing of the economic engineer is about like that of an automotive engineer who discovers after he has completed his engine that it was to go into a tractor instead of an automobile.

A Coöperative State Not Impractical

As I have said to many farm audiences, we are children of the transition—we have left Egypt, but we have not yet arrived at the Promised Land. We are learning to put off the hard boiled language of the past, but we have not yet learned to speak the coöperative language of the future. One is as different from the other as a human being is different from an animal. There need be nothing impractical, there need be nothing foolishly idealistic about a Christian, coöperative, democratic state; but I fear it will take us as long to build a public consciousness fitted to run such a state as it is taking the Russians to build efficient factories and train their people to run them.

We know that there must be a balance between productive power and consumptive power, and that excessive profits used to expand productive power beyond consumptive power are sure to lead to a breakdown. We know that the continued insistence on heavy exports in excess of imports by a creditor nation is bound to lead to disaster. We know today that the great unemployment is in the so-called heavy industries, and that this could be remedied if faith in a profound new excitement swept the country like the railroad building boom of the early Eighties, or the automobile boom of the Twenties. This boom might take the form of totally new railroad equipment, or the popularization of new and better airplanes, or the making fashionable of winter homes and winter industries for every one in the South and a duplicate summer set in the North. In any event, whatever is done to stimulate the heavy industries, it is to be hoped that the bonds issued to pay for the stimulation will be on a long term, amortized, low-interest basis.

We know that we must have a monetary system that will bring about a better balance between debtor and creditor and between productive power and consumptive power. These things can be measured and social machines can be built to deal with them; but before success can be expected, there must run through the rank and file of the people a feeling that amounts to a profound determination to deal with social problems.

The Engineer and the Mathematics of Life

There is something about engineering that tends to lay emphasis on logical, cold, hard, lifeless facts. Nearly all engineers have suffered the common punishment resulting from the remorseless discipline of higher mathematics, physics, and mechanics. No man has to work as hard in college as the engineer. As a result, the engineer sometimes imputes a value to precise mathematical reasoning that it does not always have. There is such a thing as life, and the mathematics of life is as far beyond the calculus as the calculus is beyond arithmetic.

We can see in Mendelian genetics a complex algebra that has proved to be of some analytical use in determining the mechanism of heredity. Nevertheless, from the standpoint of producing superior plant and animal organisms, the engineering mathematical approach to life has not yet been especially successful. It seems to me that the emphasis of both engineering and science in the future must be shifted more and more toward the sympathetic understanding of the complexities of life, as contrasted with the simple, mathematical, mechanical understanding of material production.

The quantitative answers produced by the science of the past hundred years are not enough. They merely increase the speed of life without increasing the quality. Would that we had someone with the imagination of Sir Isaac Newton to develop the higher calculus of the engineering of life which is so necessary if our increased productive power is to increase total human happiness!

Have you not sometimes wondered whether this whole Century of Progress might not be just a superficial and temporary phenomenon after all? The increase of physical output in 3 generations is so extraordinary that we have tended to think that this is what man is meant for. It seems to me a terribly inadequate yardstick of civilization. A man has food, clothing, and shelter; wherein does he differ from the beasts of the field? Surely these are not the things that distinguish the civilized from the uncivilized. Food and shelter and the other necessaries in any rational order ought to go without saying. They ought to be as automatic, and as universal, in this day of technological achievement, as the air we breathe. It is from this point on that life begins.

Engineers! Apply Yourselves to Social Problems

A characteristic of the engineer is his willingness to face the cold truth about the task to which he addresses himself. Engineers have brought to their jobs a more fully developed intellect than any other class of our citizenry. Sloppy, opportunistic thinking is simply inexcusable in the engineering world. I would be the last to suggest that the engineer abandon the precision of his thinking and his honesty in facing facts. I am merely asking that the same

qualities be brought to bear in so far as possible on the more complex situations which have to do with living organisms and our social life. I fear, however, that in our social and economic life the objectives always must come from that mysterious realm which all engineers and scientists should treat with the greatest respect, but with which engineering and scientific methods are totally unable to grapple.

In brief, then, we wish a wider and better controlled use of engineering and science to the end that man may have a much higher percentage of his energy left over to enjoy the things that are nonmaterial and noneconomic; and I would include in this not only music, painting, literature, and sport for sport's sake, but I would include particularly the idle curiosity of the scientist himself. Even the most enthusiastic engineers and scientists should be heartily desirous of bending their talents to serve these higher human ends. If the social will does not recognize these ends, at this particular stage in history, there is grave danger that Spengler may be proved right after all, and a thousand years hence a new civilization will be budding forth after this one has long laid fallow in a relative Middle Ages.

Experiments in Fatal Electric Shock

In the experiments reported here the authors have studied the relations involved in the maximal effect of electric shock, which is death. These experiments were conducted on rats; the relations of duration, current intensity, and frequency were studied. The results afford an explanation of the common observation that death from high voltage usually is cardiac in origin, and from low voltage respiratory in origin.

By
A. G. CONRAD
ASSOCIATE A.I.E.E.

H. W. HAGGARD
MEMBER AM. PHYSIOLOGICAL SOC.

Both of Yale University, New Haven, Conn.

RELATIONS between the intensity and duration of electric current eliciting physiological response have been treated extensively in various publications. A critical review of this literature together with a bibliography may be found in *Physiological Reviews*, v. 8, 1928, p. 501–45. La Pique has found that when the current applied is below a certain level of intensity there is no response (i. e., as in the twitch of a muscle to which electrodes are attached) no matter how long the flow is continued. Conversely, a current of high intensity may fail to induce response if applied for a very short time. Experimental determination has shown that the time required for a given current to produce a minimal response, or conversely, the current required to produce this effect in a given time, may be different for different kinds of animals and in fact for different tissues of the same animals; but for any species of animal or any one kind of tissue the relations of time and current intensity vary approximately inversely with each other.

Experiments concerned with the foregoing have dealt with the minimal responses; the magnitudes of the current required to produce these responses are in the order of milliamperes or fractions of milliamperes. On the contrary, in the experiments reported here the authors have studied the relations involved in producing maximal effect which is death. These experiments were conducted with alternating current, and several frequencies were used to determine their comparative effectiveness.

Electric shock may cause the death of animals or man by either cardiac or respiratory failure. The amount of current of definite duration necessary to cause one of these effects in an animal may differ from the amount necessary to produce a similar effect in a human being, but it is reasonable to assume that any information regarding the effect of electric shock in animals will be helpful in the study of these effects on man. The amount of current and the time necessary to produce death by hyperpyrexia (overheating) obviously must be different for small animals than for man because of the difference in the amount of energy necessary to elevate the temperatures of the respective masses. Data presented in this paper were obtained from experiments conducted on rats, to determine the minimum fatal current for durations of $^1/_{10}$ to 30 sec and at frequencies ranging from 25 to 750 cycles per second. The conclusions reached, which of course refer only to the effects of electric shocks on the rats, are briefly as follows:

1. For shocks of equal durations the current required to kill by cardiac or respiratory failure is larger at high frequencies than at low frequencies.

2. For ordinary power frequencies the curve showing the relation between the time and the current required to kill is a composite of 2 intersecting hyperbolas.

3. Explanation of the shape of the curves (Figs. 1 to 3) is to be

Full text of a paper recommended for publication by the A.I.E.E. technical program committee. Manuscript received Sept. 29, 1933; released for publication Jan. 15, 1934. *Not published in pamphlet form.*

found in the variation in susceptibility of different organs to electric shock; in general, shocks fatal in a short time give rise to cardiac failure; those requiring greater duration, to respiratory failure.

4. Currents smaller than those producing fatal cardiac or respiratory effects, if prolonged, may result in death by hyperpyrexia; but within the range of ordinary power frequencies, hyperpyrexia occurs only after cardiac or respiratory failure.

Experimental Procedure

For each experiment the rat first was anaesthetized with ether and then was tied down on a sheet of hard rubber with its legs projecting through holes suitably placed. Spring clips were attached to each leg to prevent withdrawal and to act as contacts. The 2 front legs were attached to 1 lead from the source of power. The 2 rear legs were attached similarly to the other lead. The contacts were wrapped with cotton soaked in a saturated salt solution to reduce the resistance and minimize burning. Shocks were administered only after the effects of the anaesthetic had passed away.

The location of the leads influences the amount of current necessary to cause death, the effects depending on the vital organs situated in the path of the current. Thus when only the front legs (arms) form the 2 contacts, or when the contacts are made on front and rear legs (arm and leg) the fatal current is lower than when the rear legs alone form the contacts. Indeed it is improbable that death can be produced directly from electric shock when the rear legs form the only path of the current, although death may follow from the burns produced. The major resistance in all animals is at the skin surface and may amount to a thousand or more ohms per square centimeter depending upon the moisture of the skin and, in man, also upon the activity of the sweat glands; the resistivity of the moist tissues beneath the skin is low, equaling approximately that of a 1-per cent solution of sodium chloride.

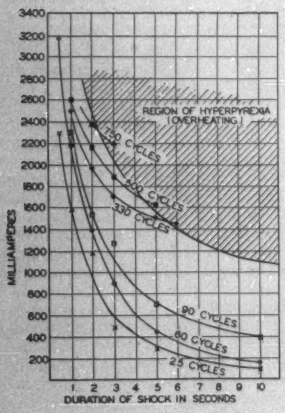


Fig. 1. Minimum currents necessary to cause death from shocks of different durations, for several frequencies

For each time interval studied, and for each frequency, a series of experiments was carried out first to determine approximate values for the fatal amount of current. Shocks with successive increases in voltage were given at intervals of 5 or 10 min until death resulted. In most cases the current and voltage were read from meters properly connected to the circuit leading to the rat. For shocks of short duration it was necessary to determine these quantities by means of an oscillograph. Having limited the field of search by this method, individual rats were exposed to voltages near the fatal value in small steps between successive rats until the minimal fatal current was reached. By repeated experiments for each duration of time and each frequency, the variation of the fatal voltage with duration of the shock could be obtained although at the expense of many rats. A record was kept of the current, voltage, and cause of death for each animal that was killed. If the shock caused the rat's heart to stop beating while its breathing continued for a short period, the cause of death was attributed to cardiac failure. If the shock caused the rat to stop breathing and the heart continued to beat for a short time, the cause of death was recorded as a respiratory failure. Some shocks of long duration caused a pronounced *rigor mortis* which developed even while the current flowed and which was due to overheating. It was found that the fatal voltage for a given time and frequency varied considerably with different rats, but that the current required to cause death was nearly constant. This variation in fatal voltage was due to the differences in the electrical resistances of individual rats. Some variation was found in the time and current required to produce hyperpyrexia. The weight of the animal was of significance in this respect, and to obviate this

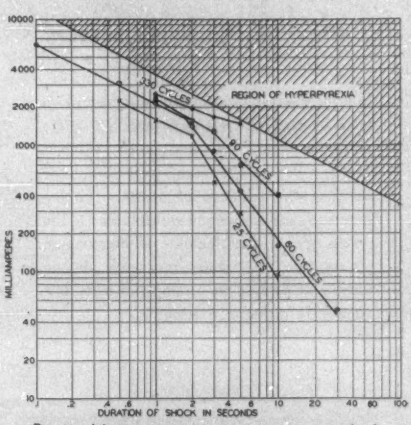


Fig. 2. Minimum currents necessary to cause death from shocks of different durations, for several frequencies (data of Fig. 1 plotted with log scales)

difficulty rats of nearly the same weight were used for all experiments.

The time intervals were controlled by 2 automatic switches. One of these switches was so arranged as to operate synchronously with the voltage supply, closing the circuit when the instantaneous voltage was zero. The second switch, closing at the end of the shock, formed a short circuit around the animal. Oscillograms were taken to check the operation of the switch. The wave form of the current and the time interval of shocks of short duration were determined from the same oscillograms.

Potentials used ranged between 100 and 4,000 volts. The frequencies used in the tests were 25, 60, 90, 330, 500, and 750 cycles per second. Duration of the shocks extended from $^1/_{10}$ to 30 sec. Originally it was intended to employ shorter time intervals, even a single wave; but the amazingly large amount of current necessary to produce death from a shock of less than $^1/_{10}$-sec duration exceeded the capacity

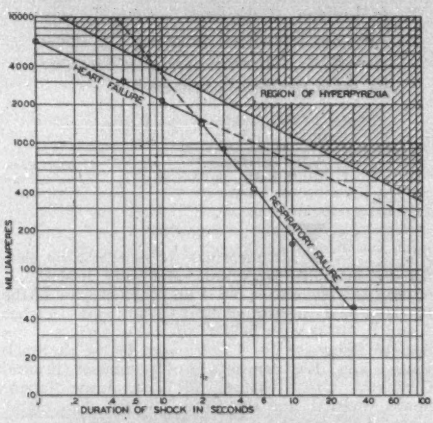


Fig. 3. Minimum currents necessary to cause death from 60-cycle shocks of different durations

of the apparatus used for administering shocks of longer duration. The situation was complicated further by severe burning resulting from the high currents. For the 60-cycle test the current was obtained from a large power supply; for the 25- and 90-cycle tests, from a 15-kva 220-volt alternator; and for those of 330, 500, and 750 cycles, from a 4-kva 220-volt 1000-cycle alternator operating at reduced speed, the desired voltage being obtained by field control on the alternators and by tap changing transformers. In each case the voltage was applied by closing the power circuit on the primary of the transformer and removed by closing a contactor that produced a direct short circuit of the animal before the power circuit was opened. The short circuit prevented any counter or secondary shock that might have been produced during the time of arcking when the main circuit was being opened.

Results

Death from electric shock in a rat is accompanied by a decrease in the electrical resistivity of the animal; a similar effect is not observed during nonlethal shocks. The fall in resistance is of sufficient magnitude, as noted by the sudden increase of current taken

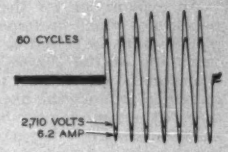


Fig. 4. Oscillographic record of current and voltage during a fatal electric shock

by the animal from the supply, to serve as an indication of the time of death for long shocks. The effect is present also in short shocks as determined from oscillograms; for fatal shocks of $^1/_{10}$-sec duration on 60 cycles the current taken by the rat from a constant potential supply increased approximately 4 per cent. An oscillogram showing the increase in current with time during a fatal shock is shown in Fig. 4.

Results obtained from the final experiments are presented in Fig. 1. Each point shown indicates the magnitude of the minimum sinusoidal alternating current of given frequency necessary to kill an average sized rat from one shock of definite duration indicated by the abscissa.

The curves expressing the relations of time to intensity are influenced by the frequency. Thus for a time interval of 2 sec, 1,000 ma was required to kill when the frequency was 25 cycles; at 60, 90, 330, 500, and 750 cycles the fatal currents for this same time interval were respectively 1,200, 1,300, 1,950, 2,100, and 2,400 ma. The currents required to kill at 750 cycles were so large that hyperpyrexia developed even after shocks of very short duration. Death from cardiac or respiratory failure, which depends upon the maximal response of a vital organ, is affected by the frequency, but death from overheating is not a function of frequency. Hyperpyrexia results when sufficient energy has been supplied to the animal to produce a fatal elevation of body temperature as noted in these experiments by a sensitive thermometer placed in the rectum, and even more clearly indicated by the immediate development of an exaggerated *rigor mortis*. The region of hyperpyrexia is shown by the shaded areas of Figs. 1, 2, and 3. For power frequencies the region of hyperpyrexia is reached only when the duration of the shock exceeds that required to kill by cardiac or respiratory failure.

It may be noted that a few of the points plotted in Fig. 1 do not fall on their respective curves. The experiments showing this divergence were repeated to see if more uniform results could be obtained. These additional tests indicated that the original data were correct. Further analysis of the values given in Fig. 1 is supplied by plotting them with a log scale for both abscissas and ordinates; the re-

sulting curves are shown in Fig. 2. When thus represented the hyperbolic character of the margin of the area of hyperpyrexia is indicated by the resulting straight line bordering the area. The curves for frequencies of 25, 60, and 90 cycles, however, do not appear as straight lines, but show distinct deviation in the region of 2 sec. The curves given in Fig. 1 are therefore the composite of 2 separate intersecting hyperbolas.

An explanation for the double curve, both components of which presumably are hyperbolic if completed, is to be found in a statement made at the beginning of the paper, namely: that the curves showing the relations of the duration of current required to produce the response of different tissues or different organs may not be coincident, but that they are approximately hyperbolic in each case. In the intact animals we are dealing in reality with the response, as death, of the vital organ which is affected by the lowest value of current. Other organs may be able to tolerate a higher value of current before they succumb to the shock, but their activities cease with failure of the organ first affected (death from any occurrence is essentially failure of only one function indispensable to the maintenance of life, rather than to any general disintegration; thus death follows heart failure, although all other organs may be capable of normal operation).

In this series of experiments the rats exposed to shocks of 2 sec or longer, if they escaped hyperpyrexia, almost invariably died of respiratory failure. Those which received shocks of less than 2 sec died of cardiac failure; this fact was emphasized by numerous spontaneous recoveries among rats exposed to presumably fatal currents but of less than 2-sec duration. In a small animal such as the rat, ventricular fibrillation (a common cause of cardiac failure in electric shock) may pass away spontaneously.

The points on the 60-cycle curve shown in Fig. 1 are plotted on log scales in Fig. 3 with the slopes of the 2 component curves extrapolated. It may be seen that for durations of more than 2 sec the curve of cardiac failure falls above that of respiratory failure. Thus when the minimum lethal current is applied, death results from respiratory failure. If, within limits, greater currents are used for the same time duration, cardiac failure may result as well; but since its effects are more rapid than those of respiratory failure, it tends to obscure the effect on the respiratory mechanism.

At time intervals less than 2 sec the conditions are reversed. The curve for respiratory failure falls at a higher current level than that for cardiac failure. Then, in cases of spontaneous recovery from ventricular fibrillation in the rat, currents greater than the minimal fatal amount may cause death by respiratory failure. The complications presented here explain some of the lack of uniformity in the results of experiments to determine the cause of death from electric shock on rats and other animals when precise attention is not given to the minimal fatal currents. The findings of the present tests afford an explanation for the common observation that death from high voltage is usually cardiac in origin, and from low voltage respiratory in origin.

Actions on Electric and Magnetic Units

The following authorized statement of the actions taken at the Paris meeting of the committee on electric and magnetic magnitudes and units of the International Electrotechnical Commission, prepared by Dr. A. E. Kennelly, chairman of the E.M.M.U. committee, is based upon the minutes of the meeting, as circulated among the various I.E.C. national committees. This statement, distributed by the I.E.C. General Secretariat in London, is, however, necessarily subsidiary to the official minutes (I.E.C. document R.M. 105) which should be consulted by those particularly interested.

By
A. E. KENNELLY
FELLOW A.I.E.E.

Harvard Univ.,
Cambridge, Mass.

THE meetings (of section *B* on electric and magnetic magnitudes and units (E.M.M.U.) of advisory committee No. 1 on nomenclature, of the International Electrotechnical Commission, October 5 and 6, 1933) were held at the headquarters of the Société Française des Electriciens, 14 rue de Staël, Paris. The I.E.C. committees of 9 countries (France, Germany, Great Britain, Holland, Italy, Japan, Spain, Sweden, and the United States) were represented by delegates. The national committees of 3 other countries (Norway, Poland, and Roumania) sent in written opinions upon the subjects appearing on the agenda, which had been circulated some months in advance.

There were also in attendance Dr. A. F. Enström, president of the I.E.C., C. le Maistre, general secretary, as well as Prof. H. Abraham, general secretary of the International Union of Pure and Applied Physics, an invitation having been sent to the S.U.N. committee (symbols, units, and nomenclature) of that Union, to attend the meeting.

The minutes of the last preceding E.M.M.U. committee meeting, held in London, September 18, 1931 (I.E.C. document *R.M.* 97), were read and approved.

Name for the Practical Unit of Magnetic Flux

It was unanimously agreed to recommend to the I.E.C. national committees, the name *weber* for the

Prepared especially for Electrical Engineering. *Not published in pamphlet form.*

practical unit of magnetic flux Φ, which is equal to 10^8 *maxwells* or c.g.s. magnetic units. The name *pramaxwell* had provisionally been adopted at Oslo in 1930 for the same quantity; but objection had arisen in some national committees to the name *pramaxwell* while other national committees were content with it, or at least with the prefix *pra* as a means for effecting a transfer from a c.g.s. unit to a corresponding practical unit. The question rose as to whether, in view of the proposed adoption of the *weber*, the use of the *pramaxwell* and also of the *volt-second* should be discontinued. It was agreed to transmit this question to the national committees; but it was suggested that in order to maintain continuity in I.E.C. decisions, it might be desirable to emphasize the recommendation of the *weber*, but to leave the use of the prefix *pra* open to those who might desire for any reason to continue its use. It was also pointed out that as a matter of historical mischance, the name *weber* had been proposed by various international gatherings, in the past, for various practical magnetic units; so that it was very desirable, now that the *weber* had come before the I.E.C., that its attribution to the practical unit of magnetic flux should be definite and final.

Symbol $\mathfrak{F}$ for Magnetomotive Force (mmf)

It was agreed to recommend to section *C* on letter symbols, of I.E.C. advisory committee No. 1, that the list of electrotechnical symbols adopted at the Berlin meeting of 1913, be modified in such a manner as to make $\mathfrak{F}$ the recognized symbol for magnetomotive force and Φ the recognized symbol for magnetic flux, with no alternatives or symbols of second preference in either of these cases.

Modification of the Definition for Magnetic Flux Density B

At the I.E.C. Oslo meeting of 1930, the definition adopted for magnetic flux density *B* was:

"The magnetic flux density *B* is a vector which represents in magnitude and in direction, the state of total polarization due to a magnetic field."

Since this definition involves the attribution of polarization even to a vacuum or free space, it was considered desirable to add the following sentences, for the purpose of clarification:

The value of the flux density at a point may be determined either by the mechanical force exerted on an element of conductor carrying a current and placed at the point; or from a measurement of the electromotive force in an elementary circuit surrounding the point.

These references to the laws of Ampere and Faraday in the definition met with unanimous approval.

Magnitude of the Practical Unit of Magnetomotive Force (mmf)

The question was considered as to whether, in the practical series of magnetic units, the unit of magnetomotive force should be the *ampere-turn* or the ampere-turn/4π (*pragilbert*), the gilbert being equal to the 4πth part of the c.g.s. magnetic unit of current in one turn. The same question had been discussed at the last preceding E.M.M.U. committee meeting of London in 1931; at which meeting, marked differences of opinion had been manifested. Similar divergences of usage appear in modern electrotechnical literature. In view of the differences of opinion over the question, it was unanimously agreed to leave the matter open for further study by the national committees. It is recognized that the question is of considerable importance; because if the *ampere-turn* were definitely adopted as the practical unit of magnetomotive force, the practical series of units would logically become rationalized or at least sub-rationalized; whereas if the 4πth part of one ampere-turn were adopted as the magnitude of the unit, then non-rationalization of the practical magnetic series would be logically involved. It was pointed out that leaving the question undecided, each and every writer is free to use the practical units either in their rationalized or unrationalized form; but it becomes incumbent on writers to indicate clearly which form they employ.

Name for a Unit of Frequency

It was proposed by the Italian committee that the name *hertz* be given to the unit of frequency—one cycle per second. It was brought to mind that the same proposal had been considered twice before by the I.E.C.; but that the majority in favor of the *hertz* had not been held sufficient to justify its adoption. There is, however, an increasing tendency in several countries, toward the use of the *hertz* as name for the frequency unit; so that it seemed desirable to revive the question at this meeting.

The German delegation supported the Italian proposal, indicating that the *hertz* is used almost universally in German technical literature.

The American and British delegations declared themselves unable to support the proposal; not only because the *hertz* was unused in their countries, but also because the name *hertz* was not self explanatory like the phrase *cycle per second*. Moreover frequency of alternation was not discovered by Dr. Hertz and it seemed inconsistent to their national committees that the honored name of *hertz* should be applied to that physical quantity, in which various branches of science and engineering other than electrotechnics were also interested. Nevertheless, if the *hertz* could be transferred from one cycle per second to one million cycles per second, there seemed to be a possibility of overcoming these objections and of introducing it for applications in the high-frequency range, in place of the phrase *megacycles per second*.

The German delegation indicated that their committee considered it would be impracticable to change the *hertz* to one million cycles per second, in view of established usage, and that various pieces of apparatus were in service marked in *hertz* as one cycle per second. A vote being then taken on recommending the adoption of the *hertz* as the name of the unit of frequency (one cycle per second), and submitting the matter to the approval of the national committees, 7 countries voted in favor (France, Germany, Holland, Italy, Poland, Roumania, and Spain), with 3

opposed (America, Great Britain, and Japan), with 1 country abstaining (Sweden).

Name for the Practical Unit of Conductance

It was proposed by the Italian committee that the name *siemens* should be assigned to the practical unit of conductance. It was pointed out that the German committee had first made the proposition in 1911, and had followed it up on various occasions since that date.

Several delegates pointed out that although the name *mho* had never been internationally adopted for the practical unit of conductance, yet it had come into extensive use in technical literature. Other delegates expressed opposition to the *mho*, as being an unsatisfactory name; while yet other delegates considered that there was no need for a name for the practical unit of conductance. A vote was then taken on the question of whether it was desirable to assign an international name to the practical unit of conductance. Six countries voted affirmatively (France, Germany, Holland, Italy, Poland, and Roumania). Three voted negatively (America, Great Britain, and Sweden). One country abstained (Japan). It was agreed to report the result of this vote to the national committees, without making any recommendation.

Table I—Proposed Modifications

Modifications that might advantageously be introduced into certain classical magnetic formulas employing c.g.s. magnetic units, in view of the international conventions recently recommended by E.M.M.U. committee of the I.E.C. in 1930–31.

In Non-Magnetic Media, i. e., free space, a vacuum, or air assumed to be so nearly equivalent to a vacuum that its correction for magnetization may be ignored:

A. *Magnetomechanical Force f*, between 2 like poles, assumed as free point poles, each of strength m c.g.s. units, separated by a distance of r centimeters, in a nonmagnetic medium of space permeability μ_0, the *numerical* value of which is unity in the classical c.g.s. magnetic system:

Revised Formula		Classical Formula	
$f = \frac{m^2}{\mu_0 r^2}$	instead of	$f = \frac{m^2}{r^2}$	(1)

B. *Intensity of Tractive Force f'* or *Tension per Square Centimeter* exerted across an air gap or entrefer, between opposed parallel plane polar surfaces, over which the uniform magnetic flux density is B *gausses:*

$$f' = \frac{B_2}{8\pi\mu_0} \quad \text{instead of} \quad f' = \frac{B^2}{8\pi} \qquad (2)$$

C. *Magnetic Volume Energy w* in free space carrying uniform flux density B *gausses* and magnetizing force H *oersteds:*

$$w = \frac{\mu_0 H^2}{8\pi} = \frac{HB}{8\pi} = \frac{B^2}{8\pi\mu_0} \quad \text{instead of} \quad w = \frac{H^2}{8\pi} = \frac{HB}{8\pi} = \frac{B^2}{8\pi} \qquad (3)$$

In each of the above cases, the numerical results will be the same with the revised formula as with the classical formula, so long as the classical c.g.s. magnetic system is used. With other systems, however, numerical values for μ_0 differing from unity must be used, except with the Maxwell q.e.s. system (quadrant, eleventh-gram, second). In the m.k.s. system (meter, kilogram, second) unrationalized, $\mu_0 = 10^{-7}$, and rationalized $\mu_0 = 4\pi \times 10^{-7}$. In the c.g.s.s. system (centimeter, gram-seven, second) unrationalized, $\mu_0 = 10^{-9}$, and rationalized $\mu_0 = 4\pi \times 10^{-9}$. It seems, therefore, desirable to retain the symbol μ_0 in every instance as generic.

In Magnetic Media:

D. *Formula for Uniform Magnetization:*

$$B = \mu H = \mu_0 H + 4\pi\,\mathcal{I} \quad \text{instead of} \quad B = H + 4\pi\,\mathcal{I} \qquad (4)$$

where $\mathcal{I}$ is the uniform intensity of magnetization of the material.

$$\text{If } \mathcal{I} = 0,\ B = \mu_0 H \text{ instead of } B = H \qquad (4a)$$

E. *Absolute Permeability of the Material* μ (Dividing Eq 4 by H):

$$\mu = \mu_0 + 4\pi\frac{\mathcal{I}}{H} = \mu_0 + 4\pi\kappa \quad \text{instead of} \quad \mu = 1 + 4\pi\kappa \qquad (5)$$

F. *Magnetic Susceptibility of the Material* κ (From Eq 5):

$$\kappa = \frac{\mu - \mu_0}{4\pi} \quad \text{instead of} \quad \kappa = \frac{\mu - 1}{4\pi} \qquad (6)$$

Desirability of Introducing the Symbol μ_0 Into Various Working Formulas

In view of the I.E.C. convention adopted at Oslo in 1930; namely that space permeability μ_0 is not a mere numeric, but has physical dimensions, it was unanimously agreed that in the list of working formulas appearing in Table I, it is desirable to insert the symbol μ_0 for space permeability, even when, as in the c.g.s. magnetic system, the numerical value of μ_0 is taken as unity.

Several delegates favored the recommendation to section C, that the symbols for absolute permeability should be changed from μ_0 to some other letter, for the reason that it was desirable to have a different symbol for absolute permeability (including permeability of a vacuum), from that for relative permeability, which is universally admitted to be a mere numeric. On putting this proposal to a vote, it was found that 7 countries favored making no change, while 2 favored a change, with 2 countries abstaining. Consequently, it was agreed to keep μ for absolute permeability, and μ/μ_0 for relative permeability, with μ_0 for the absolute permeability of vacuum or free space, as at present.

Use of the Gauss and of the Oersted

The following propositions were presented for consideration by President Janet of advisory committee No. 1, with the object of seeking an agreement with physicists:

1. In order to respect the decisions of the International Electrical Congress of 1900, and also to recognize the general usage of physicists, the *gauss* should continue to be available as the unit of magnetic field.

2. Having given that in the classical electromagnetic system, magnetic field and magnetic induction are quantities of the same dimensions, and also that both among physicists and among electrotechnicians, the usage has extended of giving the name *gauss* to the unit of induction, the use of the name *gauss* for the unit of induction is definitely authorized.

3. Electrotechnicians having found it useful and convenient, for

practical purposes, to give different names, even in the c.g.s. magnetic system to the units of magnetizing field and of induction, the name *oersted* is authorized for the name of the unit of magnetizing field.

It was recognized that the adoption of these proposals would mean annulling the Oslo conventions of 1930, and all of the international agreement concerning magnetic unitology that has been attained since that date.

Several delegates expressed the opinion that the Oslo decisions on this question should be upheld, as otherwise, if H and B were accepted as identical physical quantities, it would be illogical to assign different names to their units, and the confusion which existed prior to the Oslo convention would only be increased. While it was regrettable that no solution could be found that would satisfy all parties, yet various physicists who had been accustomed to express H in *gauss* had already adopted the *oersted* or the *gilbert per centimeter* for H and there were indications that this tendency was increasing. Moreover, much misunderstanding accompanied the use of the magnetic term field (*champ*). This term in its general sense, was susceptible of meaning either field of magnetizing force H or field of induction B. On the continent of Europe, it was generally taken as H, but in the English-speaking countries it was generally understood as B. It was therefore important to avoid using the general term *magnetic field* without specification.

Professor Janet having stated that he was personally in favor of the Oslo conventions, it was finally unanimously agreed that in view of the importance of maintaining the Oslo conventions, no action should be taken on the 3 proposals, concerning the *gauss* and *oersted*.

Inductively Reactive Power in Triangular Vector Power Diagrams

The proposition to adopt a standard method of interpreting unspecified right-angled triangle power diagrams had been considered at the E.M.M.U. committee meeting of London, but had been laid on the table until further proposals were offered by the American committee. These having been submitted, the following resolution was unanimously agreed to:

The committee recommends that in vector power diagrams, inductively reactive power should be indicated as $-j$ *vars* plotted vertically downward, and condensively reactive power as $+j$ *vars* plotted vertically upward, it being understood that generated active power (watts) is indicated by a horizontal line drawn to the right.

This recommendation was directed to be sent to the national committees.

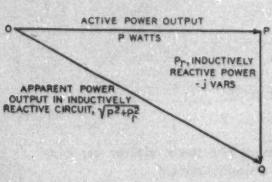


Fig. 1. Interpretation of unspecified power diagrams

Name for the Associated Practical Unit of Resistance for 1,000 Ohms

The proposition of the British committee to adopt the name *kilohm* as an abbreviation for the term *kiloohm*, representing 1,000 ohms, was unanimously approved.

Extension of the Existing Practical Units Into a Complete Practical Absolute System

Attention was called to the resolution adopted at the Chicago meeting (June 24, 1933) of the American section of the International Union of Pure and Applied Physics:

The existing series of practical electrical units (*ohm*, *volt*, *ampere*, *coulomb*, *farad*, *henry*, *joule*, and *watt*) may advantageously be extended into a complete absolute practical system, either through the medium of the meter-kilogram-second (m.k.s.) or through the centimeter-gram-seven (10 Tonnes) and second (c.g.s.s.). Of these, the m.k.s. system is preferred for consideration.

The m.k.s. system here referred to is the system advocated by Prof. G. Giorgi since 1901.

Prof. Giorgi, who was present, gave by invitation a short explanation of the m.k.s. system and answered various questions asked by delegates. He also accepted an invitation to send to the Central Office in London a memorandum summarizing the general principles of the m.k.s. system, and of its applications to electrotechnics, for distribution to the various national committees.

Mr. Brylinski, the president of the French committee, made a short exposition of the comparative merits of the c.g.s.s. and m.k.s. systems, pointing out the superiority of the m.k.s.

Prof. Abraham drew attention to the fact that although the m.k.s. system is independent of the c.g.s. system, yet they are definitely connected, and the fundamental units of the m.k.s. system, in regard to length and mass, are identical with those whose standards are maintained by the International Bureau of Weights and Measures at Sèvres, namely, the *meter* and the *kilogram*. He advocated the importance of keeping the unit of resistance in the m.k.s. system (the *ohm*) at the definite value of 10^9 c.g.s. absolute units of resistance.

The following resolution was then unanimously adopted:

Section *B* of advisory committee No. 1 on nomenclature, having heard with interest Mr. Giorgi's communication on the m.k.s. system, and supporting the resolution adopted by the American section of the International Physical Union at Chicago, in June 1933, decides to invite the national committees to express their views on the extension of the existing series of practical units used in electrotechnics into a complete coherent system having for its fundamental units of length, mass, and time, the meter, kilogram and second, and as fourth unit, either that of resistance defined as 10^9 c.g.s. magnetic units, of the corresponding value of the magnetic permeability of free space.

It may be observed that while the general introduction of the m.k.s. system would in no way affect the operation of the classical c.g.s. system of Maxwell in the general field of physical science, it would enable electrotechnicians to carry on their work independently through their own absolute system in which their practical units were constituent elements.

Steam Ejector System For Car Conditioning

Steam ejector refrigeration for railroad passenger car air conditioning has been proved to be practicable. Equipment of this type which has been developed and thoroughly tested is described in this article.

By
C. M. ASHLEY

Carrier Engineering Corp., Newark, N. J.

AIR CONDITIONING, that new art whereby comfortable conditions in stores, offices, and theatres are maintained during the summer as well as in winter, has definitely entered the field of the railroads. During 1930 to 1932 an increasing number of semiexperimental installations of air conditioning equipment were made on passenger cars. These brought forth an unmistakable public response to the controlled temperature and humidity, good ventilation, and freedom from dust and noise thus made possible. Not only was it shown that more people used air conditioned trains than had used the unconditioned ones, but that there was a net increase in the number of people using rail transportation. With the imminent prospect of equipping thousands of cars, a number of equipment manufacturers, as well as the railroads themselves, began to take stock of the peculiar problems inherent in railroad air conditioning, many of which had been ignored in the earlier designs. These problems are:

First, and most serious of these problems, is that of motive force to drive the equipment. It has been found that the temperature in a car may rise as rapidly as $^3/_4$ deg per minute when the air conditioning apparatus is stopped. This quickly creates an intolerable condition. To assure continuous cooling, the motive force must be available continuously and regardless of train speed.

Second, and a natural outgrowth of the first, is that the demands upon the existing power sources, steam and locomotive power, must be moderate both from a standpoint of economy and in order to prevent an unfortunate reaction on the train performance.

Third, new hazards must be avoided. It was early recognized that no system using such common but noxious refrigerants as ammonia or sulphur dioxide would be tolerable, nor would a gasoline engine drive be acceptable.

Fourth, the new air conditioning system must be on a car-unit basis. This demand results from the operation of cars, both Pullman and railroad owned, on more than one line and together with various other types of cars. Where trains do operate as a unit they may some day use a centrally located refrigeration system for the whole train.

Fifth, the system must be reliable in its operation. It should likewise be accessible for repair as well as for routine servicing. The railroads find equipment requiring extensive maintenance is expensive regardless of first cost.

Besides these major considerations there are a number of others which will be apparent, such as a reasonable first cost, adaptability to available space, light weight, flexibility as to altitude, climate, etc.

Two Types of Installations

During the summer of 1933, several types and a number of makes of air conditioning equipment were tried out by different roads, some of the roads going so far as to try out several types while others equipped whole trains with air conditioning. Of these equipments the air conditioning apparatus as distinguished from the refrigeration apparatus, is identical in principle for all. Air from the car, and from outdoors, is mixed and drawn over coils chilled by some refrigeration process. The air passes through a fan and is then discharged either directly or through ducts into the upper part of the car. In passing over the coils, not only is the air cooled but moisture is condensed out as well. The windows are kept closed at all times, thus excluding dirt and noise, while ventilation and usually cleaning of the outside air is accomplished by the air conditioning unit. Those systems which did not draw in some outside air were not successful and have since been replaced.

The approach to the problem of providing refrigeration for chilling the coils for cooling the air has been along diverse paths. In general, we may group these into 3 types. First, there is refrigeration using ice as a cooling means. A variety of systems of this type, designed largely by the railroads themselves, have in common a bin and tank into which ice is loaded at the beginning of the run and possibly during the run if it is long. Cooled water passes from a pump through the cooling coils of the air conditioner. It is then sprayed over the ice, chilled, and returned to the pump.

The low first cost and simplicity of this equipment would have precluded all others had it not been for the operating expense, and, even more, the trouble of maintenance. As it is, this type of system has a useful but limited field.

The second line of attack was through the applica-

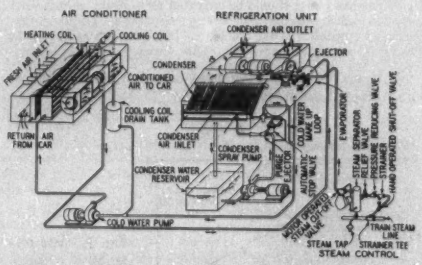


Fig. 1. Diagram of the steam ejector car conditioning system

Prepared especially for ELECTRICAL ENGINEERING. *Not published in pamphlet form.*

tion of mechanical refrigeration. In the various systems of this type the power and drive problems received various treatments. Representative of the more workable solutions is the use of a belt or gear driven axle generator, a storage battery, a motor driven reciprocating compressor with a forced air-cooled finned coil type of condenser. The refrigerant used is freon, relatively harmless when compared with ammonia or sulphur dioxide. The cooling of the air is by the direct evaporation of the refrigerant in the coil located in the air stream. Such a system designed to produce 6 tons of refrigeration, requires 11 kw for its full operation with moderately high outdoor temperatures. A storage battery to supply the air conditioning system and lights for 6 hr without recharging must have 2,000-amp-hr capacity. The generator should be of 20-kw capacity in order to meet a wide variety of road conditions. The designer of such a system must solve the problem of transmitting as much power as this at relatively low train speeds; the refrigeration compressor must require negligible mechanical maintenance even when working under the heavy load imposed by extremely hot weather, and the refrigeration system must be and must remain tight.

Steam Ejector Refrigeration

Mindful of these problems, one company offered a third solution for the refrigeration: the steam ejector refrigeration machine. This is one of nature's modern paradoxes, cooling by the direct application of steam.

Cold water, circulating through the cooling coil of the air conditioning unit (Fig. 1) receives heat from the air, flows thence to a chamber or evaporator into which it is sprayed. This evaporator is maintained at a vacuum so high that it permits the boiling of the water, cold as it is, 40 deg to 50 deg F. The evaporation of a portion of this water cools the rest which is then recirculated by a pump to cool the air further.

The steam ejector maintains the vacuum which permits this evaporation. To do this, steam from the train steam line is admitted through a nozzle to

Fig. 2. Refrigeration unit of the steam ejector type, containing evaporator, ejector, condenser, fans, and purge system, located in the upper deck of the car

Fig. 3. Alternative location of the refrigeration unit under the car

the end of the venturi shaped tube forming the ejector. In expanding from its fixed positive pressure to the high vacuum, it attains an enormous velocity, which permits it to entrain vapor from the evaporator. This vapor enters the ejector near the nozzle. It is first accelerated and mixed with the high velocity steam, then due to the shape of the venturi the mixture is compressed, changing its velocity energy to pressure. The compressed mixture is delivered to a special type of air condenser in which it is condensed. It is apparent that the function of the ejector is like that of the mechanical compressor, to draw refrigerant from the evaporator and compress it so that it can be condensed by giving up heat to the outside air.

A part of the condensate thus formed is automatically returned to the evaporator to make up for the evaporation which has occurred. The rest, together with any air leakage into the system, flows into a water jet ejector which discharges to atmosphere at low pressure through spray nozzles.

The nozzles are so arranged that the spray wets the outside of the finned surface condenser while at the same time, air from outside the car is forced over it by means of a fan. The resultant evaporation cools the condenser surface and condenses vapor within the condenser. The air which passes over the condenser is discharged upward and the unevaporated water flows to a reservoir from which it is repumped as needed.

As can be seen, the system consists of a number of more or less closed circuits: the cold water circuit, the refrigeration circuit, the air-condensate removal circuit, and the condenser heat removal circuit. These are so interrelated that it is necessary only to supply steam for compression, a small amount of water for condensation and power for air and water circulation, to obtain refrigeration.

Electrical Equipment

The fact that the motive force for the refrigeration compressor is steam, does not exclude electrical equipment from the steam ejector system. It rather reduces the electrical problems to those which have already been successfully solved. Four small motors

are required to operate fans and pumps, which are of the centrifugal type; one fan is required to circulate the air in the car, another to circulate outside air over the condenser; one pump is required to circulate cold water through the air conditioning unit while another provides water for the purge and condenser of the refrigeration machine. The total power of these 4 is 2.25 kw under normal voltage (32 volts). To supply a continuous source of power for the air conditioning system regardless of train speed, a 5-kw axle driven generator together with a 1,000-amp-hr storage battery is more than ample, the battery being able to serve the other electrical demands of the car as well. This equipment is of a size already accepted for lighting service and involves no new design problems. The motors are started by across the line type starting switches. The operation of the cooling system is controlled through relays by a car temperature switch, a steam pressure switch, and a vacuum switch of conventional design. These operate the motor switches and an electrical valve on the steam line. By means of these switches the system is not only operated automatically but started automatically as well. In the winter time, the air conditioning unit introduces warmed air into the car controlled in the same manner as is the present car heating system, through a system of electrical thermostats and valves.

Besides the electrical control elements the steam pressure to the ejector is controlled and the quality is maintained close to saturation.

Arrangement of Refrigerating Equipment

For convenience of handling and installation, the refrigeration equipment has been grouped into several units. Largest of these is the refrigeration unit which contains the evaporator, ejector, condenser, fans, and purge system. Originally the car had this unit located in the upper deck (Fig. 2). However, to make installation easier on existing cars, an alternative location under the car is now employed (Fig. 3). The 2 pumps are mounted separately under the car or inside. The steam control equipment is grouped in an enclosure under the car and the condenser make-up tank is located adjacent to the condenser pump under the car. All of these elements have great flexibility as to their relative locations. The air conditioning unit (Fig. 4) has been located, like the refrigeration unit, in the upper deck of the car and is arranged to draw outside air through filters in both sides of the deck. This unit is now available in an alternate location (Fig. 5) as a vertical unit within the car.

Fig. 4. Rear top view of the air conditioning unit for location in the upper deck. The cover is removed, showing the cold water circulating coils and fan housings

Fig. 5. Air conditioning unit arranged for vertical mounting inside the car

Comparison of Characteristics

Steam ejector refrigeration has some interesting differences in characteristics from other types of refrigeration. These are illustrated in Figs. 6 and 7. In Fig. 6 is shown how the temperature of the condenser affects the performance of the steam ejector refrigeration, and for purposes of comparison, the effect on a mechanical refrigeration system. The part of each curve which would be used in practice under usual summer weather conditions is shown in solid lines and the projection to higher temperatures in dotted lines. It is apparent that within the limits of normal operation the condenser temperature has no effect whatever on the capacity of the steam ejector system.

In Fig. 7 is shown the variation of refrigeration capacity with cold water temperature. It is apparent when comparing the steam ejector performance with that for a mechanical compressor that the variation in capacity is much more rapid in the former. As the result of this characteristic, the steam ejector machine is less affected than is the mechanical

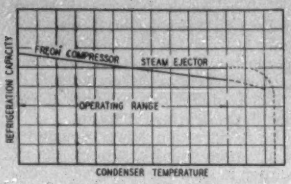
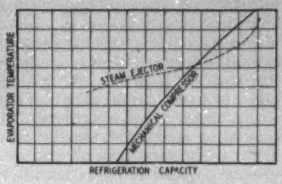


Fig. 6. Effect of the temperature of the condenser on refrigeration capacity for 2 types of refrigeration

Fig. 7. Variation of refrigeration capacity with cold water temperature for 2 types of refrigeration



refrigeration machine by changes in load and is better able to carry an overload.

Refinements in Condenser Design

The main elements of the steam ejector system were well proved in other fields or uses. The steam ejector itself has a history of 30 years or more as a refrigeration compressor but has only recently gained favor due to its special adaptability to air conditioning refrigeration. However, there were some very interesting problems to be solved in the development of this system. Perhaps the most important of these was that of the condenser design. The finned evaporative type air condenser is in principle old but by taking advantage of new highly effective forms of surface and by the use of forced circulation, the space occupied and the power required for condensation of the steam has been greatly reduced over conventional types of equipment. An essential part of the design is the use of an all closed system in which a vacuum is maintained continuously in distinction to earlier types using a jet condenser and a spray air conditioner. By the use of a closed system, it is possible to start refrigeration almost instantly after a short shutdown instead of having to wait until the purge equipment has been able to draw the required vacuum. It is also possible to reduce the size of the purge, as the entrained air which is brought into an open system must no longer be removed. The smaller purge system makes possible another combination of function by the use of a water ejector which acts as both purge and condensate pump and which makes use of the same stream of water with which the condenser surface is flooded. Another elimination of equipment is accomplished in the evaporator feed which returns water from the condenser to the evaporator by balancing the pressure difference with a gravity head, removing the necessity of a valve to control the feed.

Problem of Air Leakage Overcome

One of the bugaboos often raised against vacuum refrigeration is that of air leakage into the system. A very common assumption is that a vacuum refrigeration system must be tighter than one operating under a pressure. This is not so. A leak which would permit the full continuous operation of the steam ejector system would cause a mechanical refrigeration system to begin to lose in refrigeration capacity in 15 hr and be inoperative in 27 hr, due to loss of refrigerant charge. Moreover, such a leak would cost in refrigerant at the rate of $16 per day. Obviously, such a situation would be intolerable for the mechanical system while not materially affecting the steam ejector system. This leakage rate, corresponding to the air removal capacity of the purge of the steam ejector system, is many times the acceptable test leakage. The excess purge capacity is provided to permit the system to be put into operation quickly in the event the vacuum should be lost completely and also to provide against contingencies which may be encountered in railroad service.

The steam ejector system is designed and constructed with great care to obtain tightness. One of the most common sources of leakage is a stuffing box. There is, however, but one stuffing box in the vacuum system and this is continuously liquid sealed. The joints in piping and apparatus are in large measure either fused or gasketed. The automatic valves which connect the steam supply and purge discharge to the vacuum are closed at all times that the system is not in operation and in addition they are liquid sealed. While tightness of these valves is desirable it is in no way essential to the successful operation of the system.

Freezing Guarded Against

Freezing is avoided either by draining the system or where winter cooling does not allow this, the same precautions are taken which prevent freezing of existing water storage tanks on cars. A steam line, turned on seasonally or thermostatically, parallels the heat insulated, water containing equipment, thus maintaining it above freezing. To provide against the possibility of freezing those parts which are exposed to the outside air, an internal drainage system is provided which insures their freedom from water at all times when the system is not in operation.

Steam Requirements

No matter how effective a system may be for cooling one car of a train, its ultimate value depends upon its usability for an entire train. The mechanical system is faced with a large power demand; the steam ejector system must keep its steam requirements within the capacity of existing lines if success is to be attained. At the start of the development the criterion was set up that it should be possible to cool as many cars as can be heated with the steam lines. This criterion has been fulfilled in the existing equipment providing 6 tons of refrigeration per car. Early in the development an actual train was tested. Using the 2-in. metallic couplers now becoming standard equipment, it was possible to supply steam

for 15 cars at one time with this equipment.

A problem akin to that of getting steam to the end of a long train is that of getting steam at all on electrified lines. Steam must be available for heating, however, even on electrified lines, because of the cars which come from other lines and are unequipped to be heated by electricity. This same steam generating equipment, usually an oil boiler located in the locomotive, may be used for supplying steam to steam ejector refrigeration machines in the summer. Furthermore, if electricity is to be used directly for heating or for operation of refrigeration machines, additional equipment must be provided over and above that which supplies steam or power on unelectrified lines. Thus, the presence of a direct source of electricity is not as helpful as might seem to be the case at first thought.

Effect on Train Operation

The question of the effect of the refrigeration systems upon the train operation and cost is one of paramount concern, both with mechanical and steam ejector refrigeration. Considering first the question of operation some figures may be of interest.

Train lighting systems are commonly designed with a generator capacity nearly twice the expected load, to provide additional current to charge a storage battery for use during slow speed operation and during stops when the generator is not delivering current. There seems to be good reason to maintain the proportion for the cooling load. Even where charging and operation in terminals are from an outside power source, it is still necessary to provide sufficient generator and battery capacity to balance the load in order to assure continuous operation under adverse conditions.

On this basis, the generator capacity required for refrigeration, for battery charging, and for one kilowatt of continuous lighting load will be 20.5 kw for a 6-ton mechanical system and 5.9-kw for the 6-ton steam ejector system. The load imposed upon the power supply by the mechanical refrigeration system varies with the outside air temperature; that imposed by the steam ejector system remains constant. In picking the load of the mechanical system, moderately warm weather, not the extreme of summer heat, has been used. After taking into account the efficiencies of drives and generators, the figures of capacity given above become 43 indicated horsepower at the locomotive for the mechanical system and 13 indicated horsepower for the steam ejector system. Battery capacity to operate the air conditioning system and lights for 6 hr without recharging would have to be 2,070 and 610 amp-hr, respectively. The car which has no refrigeration but has some disc fans for air circulation in the car would have a generator capacity of 2.3 kw equivalent to 5 indicated horsepower at the locomotive.

Now, let us assume that a train consisting of one locomotive and 12 passenger cars is moving at 30 miles per hour up a grade such that the locomotive is just able to maintain the speed. Let us assume that the train is equipped with axle generator train lighting equipment which is fully on the line at 30 miles per hour. If, then, steam ejector refrigeration is added with its drag on the locomotive, the locomotive can pull only 11.5 cars, or half a car less than with the lighting generator only. If, on the other hand, the train is equipped with mechanical refrigeration, then the locomotive can pull only 10 cars or 2 cars less than with the lighting generator.

The effect of the refrigeration power demand is either to decrease the train speed or require the use of a second locomotive in such cases as given above. At lower and at higher speeds and on level tracks where the train has ample power, the effect of the refrigeration is not so marked although it must be recognized as a factor in slowing down acceleration. Obviously, all of these effects are greater in magnitude for the systems having the greater power demand on the locomotive.

Fuel Cost

One of the most important elements of the operating cost is the cost of fuel and of the services which go into the generating of steam. For a 6-ton refrigerating and air conditioning system of the steam ejector type, the steam required to drive the generator is 223 lb per hour per car, the steam for the ejector is 200 lb, and the line loss about 35 lb, making a total of 458 lb per hour. With steam costing 25 cents per 1,000 lb this makes an hourly cost with the refrigeration in operation of 11.4 cents. Of this, however, 2 cents would have been spent to pull the lighting generator without refrigeration, making a net addition due to refrigeration of 9.3 cents per hour. In the case of the mechanical refrigeration the amount of steam required to drive the generator would be 725 lb per hour on a similar basis and the gross cost would be 18.1 cents per hour. The net cost of steam for refrigeration after deducting the cost of steam for driving the lighting generator would be 16 cents per hour.

Conclusions

It is apparent that the steam ejector refrigeration system conforms to every criterion laid down at the beginning of this article. The principal motive force is the readily available steam of the train line, the electrical power requirements being moderate. The steam ejector system is not excessive in its demand for either steam or locomotive power. The use of water as a refrigerant presents a hazard about as nearly zero as it is possible to attain. The system is on a car unit basis independent of other train equipment and requiring but the normal supply of steam and the occasional motion of the train to maintain refrigeration. The steam ejector principle is by nature reliable for refrigeration, and the operating records of a season attest to the low maintenance costs of the system in practice. Considerations of first cost, suitability to available spaces, weight, flexibility, and a number of other practical factors are satisfactory with the use of the steam ejector refrigeration for railroad passenger cars. It is thus apparent that this system is a contender of promise for the railroad air conditioning business.

Shunt Resistors for Reactors—II

Shunt resistors applied to current limiting reactors used on large electric power systems function to reduce voltages caused by reflections and oscillations, to provide an avenue of escape for bus disturbances, and to reduce the voltages across the reactors. To be suitable for this purpose, a resistor must have an inverse characteristic such that its resistance during short circuits is many times that during transient conditions. The material known to the trade as "thyrite" fulfills these requirements admirably. A method of calculating the effects of such a resistor, with results given in convenient curve form, is presented in this paper.

By
F. H. KIERSTEAD
MEMBER A.I.E.E.

L. V. BEWLEY
ASSOCIATE A.I.E.E.

Both of the Gen. Elec Co., Pittsfield, Mass.

CURRENT LIMITING reactors are used universally on large metropolitan systems to limit the short-circuit currents caused by faults. Usual practice is to place a current limiting reactor in series with each feeder or tie, as well as in the generator leads and for bus sectionalizing purposes, as indicated in Fig. 1. Unfortunately, however, as has long been recognized, a reactance in series with a line or cable acts as a reflection point to traveling waves such as are initiated by lightning, arcing grounds, or switching surges; and furthermore it enters into oscillation with the capacitance of the bus and connected apparatus, thereby causing dangerous transient voltages to appear on the bus. Moreover, transient disturbances originating on the bus are trapped there temporarily, and are unable to find immediate relief by dissipation in the outgoing feeders. These difficulties, inherent in the simple reactor may be circumvented by equipping each reactor with a simple shunt resistor of proper characteristics. Such a resistor functions to reduce substantially the voltages caused by reflection and oscillations, to provide an avenue of escape for bus disturbances, and to reduce the voltage across the reactor as well as its internal transient.

Full text of a paper recommended for publication by the A.I.E.E. committee on protective devices. Manuscript submitted Oct. 26, 1933; released for publication Jan. 1, 1934. *Not published in pamphlet form.*

In a previous paper these advantages were pointed out and illustrated by calculations and tests (see "Shunt Resistors for Reactors" by F. H. Kierstead, H. L. Rorden, and L. V. Bewley, A.I.E.E. TRANS., v. 49, 1930, p. 1161–77). It is the object of the present paper to extend both the calculations and tests, and to show how the effects of a thyrite shunt resistor may be calculated with precision. The method is based upon rigid mathematical solutions given in the Appendix. By fortunate circumstances, however, the relative values of the circuit constants are such that a complicated circuit can be solved very simply numerically and the calculation reduced to a set of curves (see Fig. 6). From these curves it is possible either to determine the thyrite constant necessary to limit the voltage at the reflection point to a given value, or conversely to determine what the voltage would be for a given thyrite resistor. The curves consider only the reduction of reflections, for the reason that a thyrite resistor capable of reducing reflections also will reduce the amplitude of oscillations to negligible values, and provide an immediate avenue of escape into the outgoing feeders for any transient disturbance originating on the bus.

From the curves given in this paper it is clearly evident as to what extent a thyrite shunt resistor is beneficial. Although the virtues of a suitable shunt resistor long have been recognized by those familiar with the problem, this is believed to be the first occasion where specific cases can be demonstrated quickly by inspection of a set of curves. In brief, the thyrite shunt resistor is a simple, inexpensive and reliable device for reducing in the order of 20 to 40 per cent transient voltages that can appear at reactors in service.

CIRCUIT CONSTANTS

A typical system, such as indicated in Fig. 1 reacts to an incoming traveling wave like the simplified circuit of Fig. 2A in which are $(N + 1)$ feeders of surge impedance Z, each with a series reactor L and shunt resistor R. The bus itself has a capacitance C; if transformers or other apparatus are connected thereto, they contribute a certain amount of capacitance, representative values of which are given in the following table:

Apparatus	Capacitance in μf		
	Max.	Min.	Avg.
Generators (salient poles)	0.001	0.0002	0.0006
Generators (turbine)	0.001	0.0001	0.0005
Transformers (distribution)	0.002	0.0004	0.0010
Transformers (power)	0.001	0.0002	0.0005
Transformers (nonresonating)	0.003	0.0010	0.0020
Bus systems	0.015	0.0020	0.0050

For traveling wave calculations this capacitance may be regarded as lumped.

The surge impedance of cables varies from 30 to 100 ohms, depending upon the construction of the cable, but an average value of 50 ohms will fit most cases. If the cable sheath is not well grounded, the

effective surge impedance will be higher; in fact, a cable with insulated sheath has a surge impedance of several hundred ohms. In this paper the cable sheaths are assumed to be thoroughly grounded, and numerical calculations are based on a cable surge impedance, Z, of 50 ohms. The surge impedance of overhead lines is approximately 500 ohms.

The inductance of current limiting reactors is given by

$$L = \frac{1.59\ (\%\ \mathrm{IX})\ (\mathrm{kv})^2}{f\ (\mathrm{kva})} \tag{1}$$

Thus on a 13.8-kv 7,150-kva circuit with 3 per cent reactance, the inductance is 0.0021h. For traveling wave calculations this inductance may be regarded as lumped. A reactor also possesses distributed capacitances to ground and between turns; but while

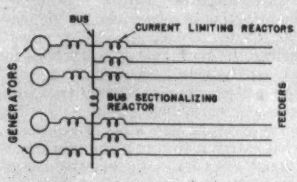


Fig. 1. Typical system layout employing current limiting reactors

these capacitances are vitally important as far as internal oscillations in the windings of the reactor are concerned (see previous paper) they exercise no particular influence on the reflected and transmitted waves, and therefore may be ignored for purposes of the present paper. The normal series resistance of a

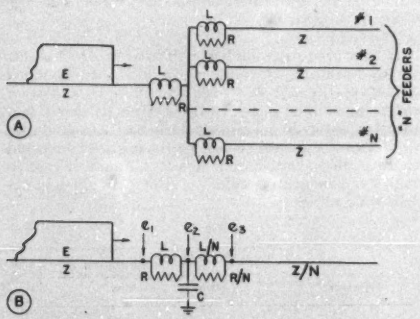


Fig. 2. Equivalent circuits to traveling waves

A. Actual bus and feeders B. Equivalent circuit

reactor is quite small, but the transient skin effect (see previous paper) becomes of some importance in determining the rate of decay of the transient oscillations across the reactor. However, the decrement due to this cause does not change materially the crest voltages obtained. For this reason the reactor will be considered free of losses in this discussion.

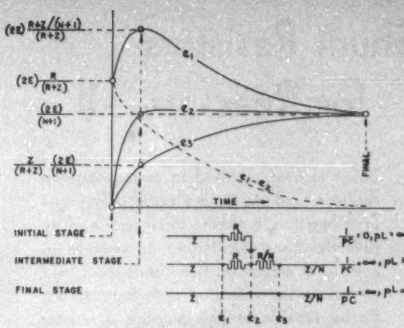


Fig. 3. Calculation of the limiting points of the transient

A *constant* shunt resistor is of little use, since its resistance must be so high, in order to stand short circuit conditions, that it will not pass enough current upon the impact of a traveling wave to provide any relief to the system. Thus, as has been pointed out before (see previous paper) a constant shunt resistor capable of substantially reducing transient voltages would have to absorb energy on a 13.8-kv circuit, under short-circuit conditions, at the rate of 1,274 kw. A resistor capable of absorbing so much energy without overheating would be prohibitive in size and cost. For this reason a suitable shunt resistor must have an inverse characteristic such that its resistance is of the order of 10 times as high under short-circuit conditions as under transient conditions.

This requirement is fulfilled admirably by thyrite (see "Thyrite—A New Material for Lightning Arrestors," by K. B. McEachron, A.I.E.E. TRANS., v.50, 1930, p. 410–17) the characteristic equations of which are

$$\left.\begin{aligned} E &= KI^{1-n} \quad \text{or } \log E = \log K + (1-n)\log I \\ R &= KI^{-n} \quad \text{or } \log R = \log K - n\log I \end{aligned}\right\} \tag{2}$$

in which I is the current, E the voltage, R the resistance, n a constant depending upon the ingredients, and K a constant depending upon the dimensions as well as the mixture. The exponent n varies in different mixtures, but for these reactor applications a value of 0.72 is used. From eqs 2 it is evident that K is the voltage drop across a given piece of thyrite when one ampere is flowing through it. It varies directly with the length L, and inversely with the 0.56 power of the diameter D and the 0.28 power of the cross section A of the piece; thus for a standard mixture

$$K = \frac{2{,}100\ L}{D^{0.56}} = \frac{1{,}960\ L}{A^{0.28}} \tag{3}$$

The heating of thyrite under short time short-circuit conditions is based upon the assumption that all the heat is stored in the material. It is, for any time t,

$$Q = \alpha EIt = \alpha KI^{1.28}\,t = \frac{\alpha\, E^{4.57}\, t}{K^{3.57}} \tag{4}$$

where α is the ratio of average to crest power during the cycle. Herefrom, if a voltage E_1 for time t_1 causes a temperature rise T (from test) then the voltage E that will cause the same temperature rise in time t is

$$E = \left(\frac{t_1}{t}\right)^{0.219} E_1 = \frac{1.884\ L}{t^{0.219}} \tag{5}$$

from which a family of curves may be plotted for design purposes, as in Fig. 7.

Choice of a suitable thyrite shunt consists of: (1) determining the value of K that will give adequate impulse protection to the system; and (2) selecting a length and cross section for the thyrite unit that will have the desired value of K and at the same time be long enough to prevent overheating under short-circuit conditions. The possibilities are considered in detail in the next section of this paper.

Calculations

From the foregoing discussion of the circuit constants of the various units comprising a typical system employing reactors, it is evident that the equivalent circuit of such a system, with respect to impulses, is that of Fig. 2B. The feeder on which the incident wave approaches the bus hereafter is designated as the "incoming" line, while the other feeders are called "outgoing" lines. If the reactances in different feeders have different inductances, or other dissimilarity exists, then the solution to the circuit becomes very involved. However, if all feeders with their reactors and shunt resistors are alike, the solutions are relatively simple, the differential equations not exceeding the second order. In the Appendix these solutions are carried out in detail. Now the principal points of interest in these calculations are the maxima encountered. It so happens that the circuit constants in practical cases are of such magnitude that the capacitance becomes fully charged through the shunt resistor before any appreciable current flows through the reactor. On this account the maximum voltages, as well as the initial and final conditions, may be calculated ignoring the inductance. Referring to Fig. 3 it is seen that initially the voltages e_1, e_2, and e_3 are determined from the consideration that the bus capacitance acts like a short circuit and the inductances like open circuits. A little later the capacitance becomes fully charged, but the inductances still behave as open circuits; under this condition the voltage e_1 reaches its maximum. Then the inductances begin to take appreciable current, causing all 3 voltages eventually to reach the same final voltages, as determined by the conditions that the capacitance behaves as an open circuit while the inductances act as short circuits. That these limiting points as thus determined are essentially correct, may be verified by the complete solutions given in the Appendix and by the cathode ray oscillograms reproduced in this paper.

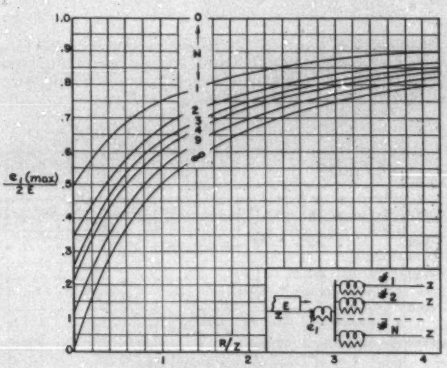
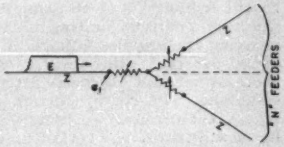


Fig. 4. Maximum voltage at reflection point, infinite rectangular applied wave

Figure 4 comprises a set of curves, based upon Fig. 3, giving the maximum value of e_1 as a function of the ratio of the shunt resistance of each reactor to the surge impedance of the line, and the number of outgoing feeders. These curves show that the greater the number of feeders, the lower the voltage at the reflection point, although the gain is not great for more than 6 feeders. The curves also show that the smaller R or the greater Z, the smaller the voltages at the reflection point. Therefore, a given shunt resistor will prove more effective for overhead line construction than for underground cables; or conversely, to realize the same advantages in either case, the resistance must be less for cable networks than for overhead lines. There is, however, another important point in this connection: Underground cable systems cannot be subjected to voltages greater than those caused by arcing grounds or switching surges, whereas overhead lines are exposed to much higher voltages due to lightning.

If thyrite resistors are used—and as already pointed out they are necessary—the circuit governing the conditions of maximum voltage is shown in Fig. 5; this circuit is solved in detail by the curves of Fig. 6.

Fig. 5. Circuit for calculating maximum voltages with thyrite



By means of these curves (for derivation of which see the Appendix) it is possible either to find the thyrite constant necessary to hold the voltage at the reflection point to any desired value; or conversely, to find what this voltage would be for a given thyrite constant. As an example, suppose that a certain 13.8-kv system is susceptible to impulse voltages of $E = 50$ kv, and that a thyrite shunt is to be found

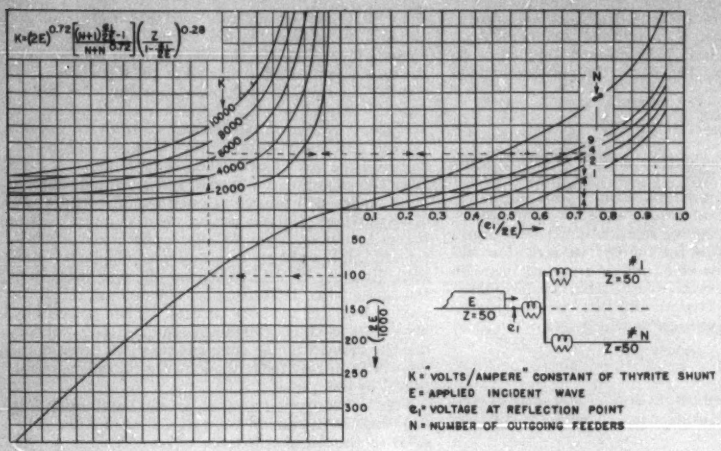


Fig. 6. Chart for calculating constants of thyrite shunt, or voltage at reflection point for a given shunt

such that the voltage at the reflection point will not exceed the insulation strength there of $e_1 = 70$ kv with 4 outgoing lines. Then entering the third quadrant of Fig. 6 at $2E = 100$ kv and the first quadrant at $e_1/2E = 0.70$ thence horizontally from the curve marked $N = 4$, it is seen that the 2 lines entering the second quadrant intersect on the $K = 6{,}600$ curve. This is the thyrite constant necessary to effect the specified requirements. So far as the impulse conditions are concerned, there are no restrictions on the dimensions of the thyrite piece having this constant; but the fact that the thyrite must stand a system short circuit for a fixed time decides the minimum length of the thyrite unit. In Fig. 7, the lower set of curves gives the necessary length of thyrite corresponding to the system voltage and the duration of short circuit. For a 13.8-kv system and a 10-sec short circuit, the minimum length is 7 in. Entering the upper set of curves at this length and at $K = 6{,}600$ shows that the nearest standard thyrite is (2) 3 in. in diameter. Thus the addition of 2 thyrite cylinders 3 in. in diameter by 7 in. long as a shunt for a current limiting reactor is instrumental in reducing the impulse voltage at the reflection point by 30 per cent; this resistor will not overheat on short circuit, nor otherwise interfere with operating conditions. In routine design of these shunt resistors, the necessity of using standard sizes of thyrite usually involves a certain amount of compromise; but in any event, reductions of impulse voltages of the order of 20 to 40 per cent are usually obtainable. From an engineering point of view the reduction should be enough to prevent a flashover at the reflection point, but if the insulation levels of the system and the impulse voltages to which they are subjected are not known definitely (which is usually the case) then the reduction, based upon switching surges, should be at least 25 per cent.

The equations of the Appendix enable one to calculate the effect of exponential incident waves, and hence, by superposition, waves compounded of exponential components, such as typical lightning waves with finite fronts and tails.

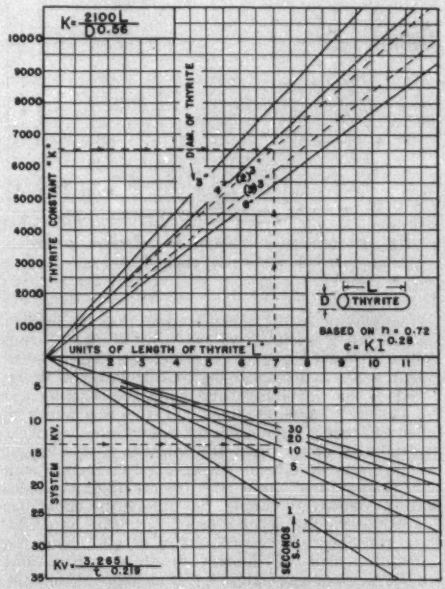
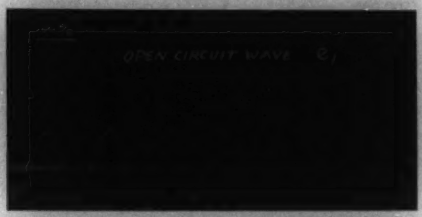


Fig. 7. Calculations of dimensions of thyrite shunt

Impulse Tests

In order to verify calculations pertaining to the circuit shown in Fig. 2A, impulse tests were made on the equivalent circuit shown in Fig. 2B. It has been shown mathematically, and by test, that the effect of an impulse upon a circuit is the same if it enters the circuit through a resistor as it would have been had it entered through a line or a cable, providing that the resistance of the resistor is the same as the surge impedance of the line or cable. It was permissible, therefore, to simplify the test circuit by replacing the incoming line with a resistor. Since reactors are used largely with underground cables having surge impedances of approximately 50 ohms, a resistor of 52 ohms was selected as the equivalent of the incoming cable. It is equally equivalent to replace the outgoing lines with a resistor, providing that the resistance of the resistor is made equal to the surge impedance of all the outgoing lines in parallel; therefore, the outgoing lines were replaced by resistors. Typical current limiting reactors were



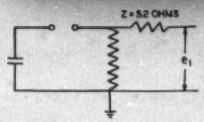


Fig. 8. Diagram of connections of impulse generator and wave form of open circuit voltage used in these tests (500,000-cycle timing wave)

used for the reactors. Capacitors were used to obtain the effect of the capacitance of the bus. The test circuits were as shown on Figs. 9, 10, 11, and 12.

Figure 8 shows the type of impulse employed in these tests. It may be noted that at the front of the wave there is an oscillation of very high frequency; this was inherent in the impulse generator circuit used and could not be eliminated. In order to make the comparisons between tests more definite, the axis of the oscillation is taken as the height of the wave.

On the oscillogram of Fig. 8, e_1 labelled 100% corresponds to a totally reflected incident wave of voltage E (in other words $e_1 = 2E$). That this is so is evident from the fact that if a surge impedance equal to Z_1 (52 ohms) be connected from Z_1 to the other terminal of the generator (which is the condition for no reflection) the value of e_1 would drop to E.

Tests were made on circuits corresponding to the following conditions:

Case I. An impulse entering a station having no other outgoing lines connected.

Case II. An impulse entering a station having 1 other outgoing line connected.

Case III. An impulse entering a station having 2 other outgoing lines connected.

Case IV. An impulse entering a station having 4 other outgoing lines connected.

In each case the tests were made (1) with no resistor shunting the reactor, (2) with a constant resistance of 52 ohms shunting the reactors, and (3)

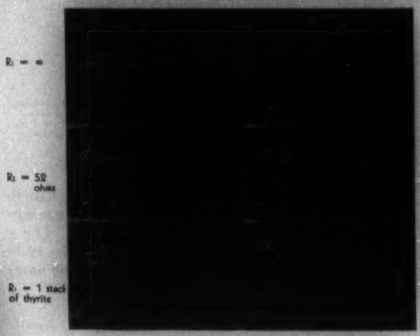
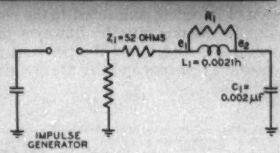
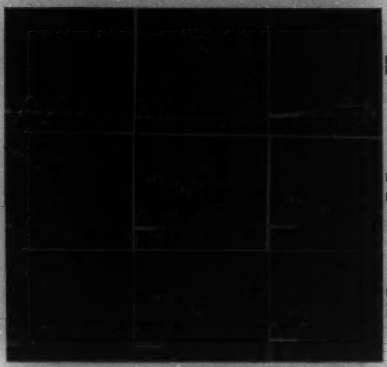


Fig. 9. Case I: test with no outgoing lines (500,000 - cycle timing wave)

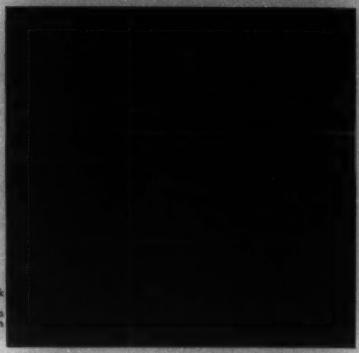


with a stack of thyrite shunting the reactor. Voltages were measured at e_1, e_2, and e_3 (Fig. 2B) by a cathode ray oscillograph. A comparison of these tests shows in each case the effect of a constant shunt resistor on the impulse voltages and also the effect of thyrite.

Case I (Fig. 9). These tests correspond to an impulse entering a station that has no other outgoing feeders. The voltages at the reflection point and at the bus are higher than for any of the other cases, as should be expected. Thus when there was no shunt resistor the voltage e_1 was 0.99 $(2E)$, which indicates almost complete reflection ($e_1 = 2E$ corresponds to complete reflection). The oscillation due to the passage of the impulse through the inductance L_1 into the capacitance C_1 causes the voltage e_2 to build up to 1.77 $(2E)$. The addition of a constant shunt resistor of 52 ohms had no effect on the voltage e_1, but critically damped out the oscillation in the voltage e_2 reducing e_2 to 0.99 $(2E)$, a reduction of 44 per cent. When the reactor was shunted by the thyrite resistor, the voltage e_1 again was unchanged. The oscillation in e_2 was almost entirely damped out, e_2 being 1.05 $(2E)$, a reduction in voltage due to the thyrite of 41 per cent. This case does not represent practical operation because a bus seldom, if ever, would be operated with only one feeder connected. It is included for the sake of completeness.



$R_1 = 52$ ohms
$R_2 = 52$ ohms
R_1 = 1 stack of thyrite
R_2 = 1 stack of thyrite



$R_1 = 52$ ohms
$R_2 = 26$ ohms
R_1 = 1 stack of thyrite
R_2 = 2 stacks of thyrite in parallel

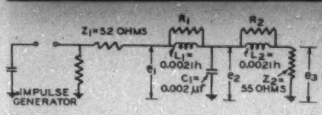


Fig. 10. Case II: test with one outgoing line (500,000 - cycle timing wave)

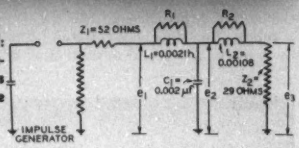


Fig. 11. Case III: test with 2 outgoing lines (500,000 - cycle timing wave)

Case II (*Fig. 10*). This test represents the condition of 2 feeders connected to the station bus with an impulse coming into the bus over one of them. The voltages e_1 and e_2 and the per cent reductions due to constant resistors and thyrite are given in the following table:

Resistors R_1	Resistors R_2	$\frac{e_1}{2E}$	Per Cent Reduction	$\frac{e_2}{2E}$	Per Cent Reduction
None	None	0.97		0.87	
52 ohms	52 ohms	0.72	26	0.48	45
1 Thyrite	1 Thyrite	0.72	26	0.48	45

Case III (*Fig. 11*). In these tests the circuit is equivalent to a bus with 3 connected feeders and an impulse coming in on one of them. The voltages e_1 and e_2 together with the per cent reduction due to constant resistors and thyrite are given in the following table:

Resistors R_1	Resistors R_2	$\frac{e_1}{2E}$	Per Cent Reduction	$\frac{e_2}{2E}$	Per Cent Reduction
None	None	0.95		0.55	
52	26	0.62	35	0.33	40
1 Thyrite	2 Thyrite	0.59	38	0.39	29

Case IV (*Fig. 12*). In these tests the circuit is approximately equivalent to a bus with 5 connected feeders. It is believed that this circuit more nearly represents operating conditions than the preceding ones. Occasions where a station would operate with less than 5 feeders connected to a bus are believed to be rare. The voltages e_1 and e_2 together with per cent reductions due to resistors and thyrite, are given in the following table:

Resistors R_1	Resistors R_2	$\frac{e_1}{2E}$	Per Cent Reduction	$\frac{e_2}{2E}$	Per Cent Reduction
None	None	0.96		0.39	
52	12	0.54	44	0.18	54
1 Thyrite	5 Thyrite	0.49	49	0.26	33

Comparison Between Calculations and Tests

In Table I is given a comparison between the tested and calculated voltages for all 4 cases. The agreement between the tests and calculations is well within the limits of testing accuracy. This close agreement demonstrates that the effect of thyrite shunt resistors on voltages caused by impulses can be calculated accurately by use of the formulas and curves given in this paper, and thus lends confidence to their use.

Appendix

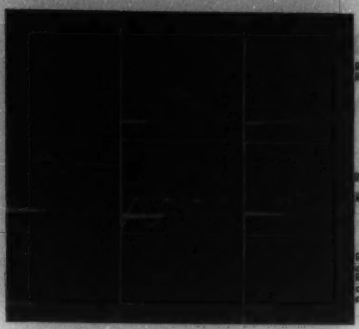
Referring to Fig. 2B, the operational equations for the 3 voltages e_1, e_2, and e_3 easily are verified to be:

$$e_2 = \frac{2E}{N+1}\frac{\omega_n^2}{\alpha}\left(\frac{p+\alpha}{p^2+2\beta p+\omega_n^2}\right)\epsilon^{-\alpha t} \tag{6}$$

$$e_3 = \frac{\gamma}{\alpha}\left(\frac{p+\alpha}{p+\gamma}\right)e_2 \tag{7}$$

$$e_1 = 2E\epsilon^{-\alpha t} - \frac{\gamma}{\alpha}\left(\frac{p+\alpha}{p+\gamma}\right)(2E\epsilon^{-\alpha t} - e_2)$$

$$= (2E\epsilon^{-\alpha t} + e_2) - \frac{\gamma}{\alpha}\left(\frac{p+\alpha}{p+\gamma}\right)2E\epsilon^{-\alpha t} \tag{8}$$



$R_1 = =$
$R_2 = =$

$Z_1 = 52$ ohms
$Z_2 = 12$ ohms

$R_1 = 1$ stack of thyrite
$R_2 = 5$ stacks of thyrite in parallel

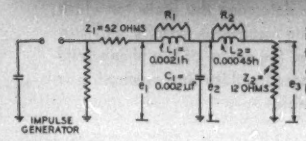


Fig. 12. Case IV: test with 4 outgoing lines (500,000 - cycle timing wave)

where

$$\left.\begin{aligned}
\alpha &= \frac{R}{L} \\
\beta &= \frac{(N+1)L + CRZ}{2LC(R+Z)} \\
\gamma &= \frac{RZ}{(R+Z)L} \\
\omega_o^2 &= \frac{(N+1)R}{LC(R+Z)} \\
E\epsilon^{-\alpha t} &= \text{applied incident wave}
\end{aligned}\right\} \quad (9)$$

Also let

$$\left.\begin{aligned}
\omega &= \sqrt{\omega_o^2 - \beta^2} \\
\sigma &= \beta + j\omega \\
\rho &= \beta - j\omega \\
A &= \frac{2E}{(N+1)}\frac{\omega_o^2}{\alpha}\left[\frac{\alpha - a}{\omega^2 + (\beta - a)^2}\right] \\
B &= \frac{\omega^2 + (\beta - \alpha)(\beta - a)}{\omega(\alpha - a)} \\
D &= \frac{\gamma}{\alpha}\left[\frac{\gamma - \alpha}{\gamma - a} - \frac{B\omega(\gamma - \alpha) + (\gamma - \beta)(\gamma - \alpha)}{(\gamma - \beta)^2 + \omega^2}\right] \\
G &= \frac{\gamma}{\alpha}\left[\frac{B\omega(\gamma - \alpha) - \omega^2 - (\alpha - \beta)(\gamma - \beta)}{(\gamma - \beta)^2 + \omega^2}\right] \\
H &= \frac{\gamma}{\alpha}\left[\frac{\omega(\gamma - \alpha) + \omega^2 B + (\alpha - \beta)(\gamma - \beta)B}{(\gamma - \beta)^2 + \omega^2}\right]
\end{aligned}\right\} \quad (10)$$

The solutions to eqs 6, 7, and 8 then are:

$$e_1 = e_3 + 2E\left(\frac{\gamma - \alpha}{\gamma - a}\right)\left(\frac{a\epsilon^{-\alpha t} - \gamma\epsilon^{-\gamma t}}{\alpha}\right) \quad (11)$$

$$e_3 = A\ \{\epsilon^{-\alpha t} + \epsilon^{-\beta t}\ [B \sin \omega t - \cos \omega t]\} \quad (12a)$$

$$= A\left\{\epsilon^{-\alpha t} - (1 + jB)\frac{\epsilon^{-\rho t}}{2} - (1 - jB)\frac{\epsilon^{-\sigma t}}{2}\right\} \quad (12b)$$

$$= A\ \{\epsilon^{-\alpha t} + \epsilon^{-\beta t}\ [\omega B t - 1]\}\ \text{if } \omega = 0 \quad (12c)$$

Table I—Comparison of Calculated and Tested Voltages

Equivalent Number of Outgoing Lines	Shunt Resistor R_1	$\frac{e_1}{2E}$ Test	$\frac{e_1}{2E}$ Calc.	$\frac{e_3}{2E}$ Test	$\frac{e_3}{2E}$ Calc.
0	None	0.99		1.77	1.93
	52 ohms	0.99	1.00	0.99	1.00
	Thyrite	0.98	1.00	1.05	
1	None	0.97	1.00	0.87	0.97
	52 ohms	0.72	0.75	0.48	0.50
	Thyrite	0.72	0.70	0.48	0.51
1.8	None	0.95	1.00	0.55	
	52 ohms	0.62	0.68	0.33	0.35
	Thyrite	0.59	0.61	0.39	0.40
4.3	None	0.96	1.00	0.39	
	52 ohms	0.54	0.60	0.18	0.18
	Thyrite	0.49	0.48	0.26	0.26

$$e_3 = A\left\{\frac{\gamma}{\alpha}\left(\frac{\alpha - a}{\gamma - a}\right)\epsilon^{-\alpha t} + D\epsilon^{-\gamma t} + \epsilon^{-\beta t}(G\cos\omega + H\sin\omega t)\right\} \quad (13a)$$

$$= A\left\{\frac{\gamma}{\alpha}\left(\frac{\alpha - a}{\gamma - a}\right)\epsilon^{-\alpha t} + D\epsilon^{-\gamma t} + (G - jH)\frac{\epsilon^{-\rho t}}{2} + (G + jH)\frac{\epsilon^{-\sigma t}}{2}\right\} \quad (13b)$$

$$= A\left\{\frac{\gamma}{\alpha}\left(\frac{\alpha - a}{\gamma - a}\right)\epsilon^{-\alpha t} + D\epsilon^{-\gamma t} + \epsilon^{-\beta t}(G + \omega H t)\right\}$$

$$\text{if } \omega = 0 \quad (13c)$$

In the foregoing solutions, eqs 12a and 13a are for the oscillatory case; 12b and 13b for the nonoscillatory case; and 12c and 13c for the critically damped case. In the critically damped case $\omega = 0$, and therefore:

$$\left.\begin{aligned}
\omega B &= \frac{(\beta - \alpha)(\beta - a)}{(\alpha - a)} \\
D &= \frac{\gamma}{\alpha}\left[\frac{\gamma - \alpha}{\gamma - a} - \frac{(\beta - \alpha)(\beta - a)(\gamma - \alpha) + (\gamma - \beta)(\gamma - \alpha)(\alpha - a)}{(\alpha - a)(\gamma - \beta)^2}\right] \\
G &= \frac{\gamma}{\alpha}\left[\frac{(\beta - \alpha)(\beta - a)(\gamma - \alpha) - (\alpha - \beta)(\gamma - \beta)(\alpha - a)}{(\alpha - a)(\gamma - \beta)^2}\right] \\
\omega H &= \frac{\gamma}{\alpha}\left[\frac{-(\alpha - \beta)^2(\gamma - \beta)(\beta - a)}{(\alpha - a)(\gamma - \beta)^2}\right]
\end{aligned}\right\} \quad (14)$$

Criterion for Suppression of Oscillations

All oscillations will be suppressed if

$$\beta^2 > \omega_o^2 \quad (15)$$

Substituting from eq 9 there results

$$R < \left[\frac{(N+1)L}{ZC + 2\sqrt{(N+1)LC}}\right] < \frac{1}{2}\sqrt{(N+1)\frac{L}{C}} \quad (16)$$

In order to insure that the circuit will not oscillate under the most susceptible conditions, i. e., no outgoing feeders and zero surge impedance, the shunt resistor should be not more than

$$R_o = \frac{1}{2}\sqrt{\frac{L}{C}} \quad (17)$$

If this value of shunt resistance be used, then all possibility of oscillation vanishes, even in case of a line-to-ground sparkover at the line end terminal of the reactor.

Limiting Points

These equations give the characteristics of the transient, and serve to show why it is permissible, when shunt resistors are used, to determine the upper boundary of the transients from the following 3 limiting conditions:

(a). Initially the capacitance acts like a short circuit and the inductances like an open circuit. so that

$$e_1 = (2E)\left(\frac{R}{R + Z}\right) \qquad e_2 = 0 \qquad e_3 = 0$$

(b). The capacitance quickly charges in a few microseconds and then acts like an open circuit, but the inductances do not yet draw

an appreciable current, so that at this intermediate period

$$e_1 = (2E)\left\{\frac{(N+1)R+Z}{(N+1)(R+Z)}\right\}$$

$$e_2 = \frac{(2E)}{(N+1)} \qquad e_3 = \frac{(Z)}{(R+Z)}\,\frac{(2E)}{(N+1)}$$

(c). Finally the inductances act like short circuits, and the fully charged capacitance like an open circuit, so that all 3 voltages approach equality

$$e_1 = e_2 = e_3 = \left(\frac{2E}{N+1}\right)$$

Determination of the Thyrite Shunt

A suitable thyrite shunt resistor must fulfill 3 requirements:

1. Under transient conditions the effective resistance must be low enough to render the circuit essentially nonoscillatory.

2. Under transient conditions the effective resistance must be low enough to limit the reflection to a safe value.

3. Under normal frequency conditions the effective resistance must be high enough to prohibit overheating of the resistor during a system short circuit.

It is evident from the oscillograms and from Fig. 3 that the maximum voltages occur when the capacitance first becomes fully charged, but before the inductances are carrying an appreciable current. The circuit then acts like a resistance circuit, in which the elements are the surge impedances of the lines (or cables) and the thyrite shunts. The voltage consumed by a thyrite resistor is $e = KI^{1-n}$ where the constants K and n are characteristic properties of the material; the constant K varies directly with the length of the thyrite stack, but the exponent n is independent of the dimensions and depends only on the material. An average value for the exponent is $n = 0.72$.

Rational design procedure for the thyrite shunt resistor consists in finding K such that the above transient conditions are met. The length and cross section of the thyrite stack then is selected so that for the required value of K the heating condition will not be violated.

Figure 5 represents the circuit at the period when the maximum reflection occurs. At the bus the current divides, each outgoing feeder carrying (I/N) amperes. Therefore

$$2E - ZI = KI^{1-n} + K\left(\frac{I}{N}\right)^{1-n} + Z\left(\frac{I}{N}\right) = e_1 \tag{18}$$

This equation may be solved either graphically or by a step by step method to determine the current I and hence e_1. Solving eq 18 for K there results

$$K = \left\{\frac{(N+1)e_1 - 2E}{(N+N^n)}\right\}\left(\frac{Z}{2E - e_1}\right)^{1-n} \tag{19}$$

where E is the maximum possible incident wave that can occur on the system and e_1 is the limit permitted at the reflection point. If E is fixed by the line insulation, then it is essential to prevent any positive reflection, for if a positive reflection occurs the insulation at the reflection point will break down. Therefore substituting $e_1 = E$ in eq 19 as the condition for no reflection there is

$$K = \frac{(N-1)E}{N+N^n}\left(\frac{Z}{E}\right)^{1-n} \quad \text{for no reflection} \tag{20}$$

The voltage at the bus is, in general,

$$e_2 = e_1 - KI^{1-n} = \frac{2E - (N^n - 1)e_1}{N + N^n} \tag{21}$$

The fewer the number of feeders the smaller must K be. Of course if there are no outgoing feeders the voltage at the reflection point will double, but the resistor will still be effective in preventing excessive oscillations to still higher values at the bus. One defect of a thyrite resistor is the fact that some oscillation always will occur if there are no outgoing feeders, because the final value of e_2 which comprises its axis of oscillation, is the same as e_1, and therefore each time that e_1 and e_2 approach equality, the voltage across the resistor approaches zero. However, the thyrite characteristic is such that its resistance is infinite when the voltage across it is zero. Hence it is helpless to exercise influence on the oscillation as e_2 passes through the critical value $e_2 = e_1$. Nevertheless, as soon as e_1 and e_2 part company the thyrite resistor becomes active in limiting the amplitude of oscillation.

Transients in Magnetic Systems

In the past, the solution of the transients in magnetic systems with solid cores has been carried out by assuming that the radial distribution of flux in other portions of the magnetic circuit is the same as in the solid portion. This paper presents a more precise mathematical analysis, the purpose of which is to determine the limits for which the foregoing assumption applies, and also to determine the nature of the phenomena for other cases in which that assumption is not permissible.

By
C. F. WAGNER
MEMBER A.I.E.E.

Westinghouse Elec. and Mfg. Co.
East Pittsburgh, Pa.

THE MAGNETIC CIRCUIT in different types of equipment frequently consists of an air gap, a laminated iron part, and a solid iron part. When the field winding associated with a magnetic circuit of this character is energized by the application of a constant voltage, the eddy currents in the solid part of the core hinder the building up of the magnetic field. In the past, the treatment of this problem was carried out by assuming that the radial distribution of magnetic flux is the same in the air gap and laminated portion as in the solid portion. While for most cases this approximation is sufficiently accurate, it is desirable to obtain a more precise method to determine the limits for which this approximation applies and also to determine the nature of the phenomenon for the other cases in which this approximation is not permissible. In Fig. 1 the rectangle bounded by the heavy lines represents the solid part of the magnetic core. During the transient the eddy currents in the solid part of the core force most of the flux toward the outer edge. As the ends of the solid part are approached the flux lines curve tending to produce uniform distribution across the air gap and laminated portion. This is particularly true if the reluctance of the radial path of the flux be small compared with the reluctance of the air gap and laminated part. For the purpose of the present analysis the definite assumption will be made that the flux lines in the solid part are straight and that at the bound-

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery. Manuscript submitted Jan. 24, 1933; released for publication Aug. 28, 1933. *Not published in pamphlet form.*

ary ends of the solid part the flux lines can redistribute themselves without an radial drop in magnetomotive force. Thus the flux density in the air gap and laminated part is uniform, but in the solid part it is dependent upon the distribution of the eddy currents. This assumption is equivalent to inserting 2 disks of infinite permeability into the magnetic circuit at either end of the solid part as shown by the shaded areas of Fig. 2. This assumption implies that the radial component of magnetomotive force is small with respect to the component parallel to the axis. The analysis will follow along the general lines developed in an earlier paper (see "Field Transients in Magnetic Systems" by Ernst Weber, A.I.E.E. TRANS., v. 50, 1931, p. 1234–46).

PROBLEM AND RESULTS

With the foregoing fundamental assumption the flux and exciting current are determined as a constant voltage V is applied to the exciting winding shown in Fig. 2. The full development is given in the appendix; only sufficient data are given in the forepart of the paper to enable one to use and understand the results which are given in curve form.

The solid part of the core is assumed to be of circular cross section. The remainder of the magnetic circuit also is assumed to be of circular cross section of the same diameter; however, this is not essential as the remainder of the circuit always can be reduced to an equivalent one of the same reluctance, but having the diameter of the solid part.

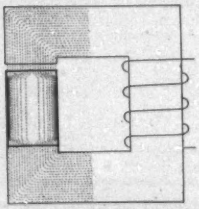


Fig. 1. Flux distribution in core as constant voltage is applied to exciting winding

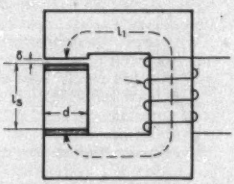


Fig. 2. Representation of magnetic circuit. Shaded portions represent disks of infinite permeability

The symbols indicated in Fig. 2 have the following significance:

d = diameter of solid part in centimeters
l_s = length of solid part in centimeters
δ = length of air gap in centimeters
l_i = length of laminated part in centimeters
ρ = resistivity of the solid part in ohms per cubic centimeter
N = number of turns in exciting winding
R = resistance of exciting winding in ohms
μ_l = permeability of laminated part
μ_s = permeability of solid part

For simplicity other auxiliary constants also are used. Since the flux distribution in both the air gap and the laminated portion is uniform, it is evident that an equivalent air gap can be used to represent both the actual air gap and the laminated portion. This equivalent air gap will be designated by a; its length will be

$$a = \delta + \frac{l_i}{\mu_l} \text{ centimeter} \tag{1}$$

A similar air gap can be used to represent the solid part of the iron for its magnetic properties, so that

$$b = \frac{l_s}{\mu_s} \text{ centimeter} \tag{2}$$

A convenient parameter for use in connection with the results is the fractional part, n, of the total magnetomotive force consumed in the solid part of the iron, thus

$$n = \frac{b}{a + b} \tag{3}$$

The self inductance of the exciting winding, neglecting leakage flux and eddy currents, is

$$L_o = \frac{(\pi d N)^2 \, 10^{-8}}{a + b} \text{ henries} \tag{4}$$

The time constant of the exciting winding for the same conditions is designated

$$T_o = \frac{L_o}{R} \text{ seconds} \tag{5}$$

An additional parameter will appear in the development which, because it has a dimension of time and involves constants of the solid part of the core, will be called the core time constant and will be designated by T_s.

$$T_s = \frac{\pi}{10} \frac{\mu_s}{\rho} d^2 \text{ seconds} \tag{6}$$

Results of the mathematical analysis are plotted in curve form in Fig. 3. These curves show the instantaneous values of flux and exciting current as a fraction of their final or sustained values as a function of t/T_o for different values of n and T_s/T_o. An arbitrary value of leakage inductance associated with the exciting winding equal to 25 per cent of L_o was assumed in computing the curves.

Since the ordinates of the foregoing curves are expressed as a fraction of the final or sustained value, the actual values can be obtained from a knowledge of the sustained values which for the current is equal to V/R and for the flux $(VL_o/RN)10^8$.

DISCUSSION OF RESULTS

From Fig. 3 it may be observed that for any value of n the flux lags more the larger T_s/T_o. The physical significance of this relation is evident from the fact that increasing T_s means decreasing ρ or increasing d^2, either one of which results in larger values of eddy currents.

The curves also show that for any given value of T_s/T_o the lag of the flux increases as n increases. From eqs 4, 5, and 6 it may be seen that

$$\frac{T_s}{T_o} = \frac{\mu_s R(a + b)}{10 \pi \rho N^2} \tag{7}$$

Everything else remaining constant, as n increases, b must increase and a must decrease; thus the resistance of the eddy current path is decreased.

On the other hand the inductance of the eddy current path is not greatly affected by changing n so long as $(a + b)$ is constant. The net effect is that the eddy currents are larger and have a larger time constant, which delays the building up of the flux.

When n is equal to 1, the magnetic circuit consists of solid iron only. There being no radial component of flux, the assumptions upon which the analysis is based apply rigorously for this case. As n is decreased, the actual phenomenon departs more and more from the assumptions; but, as may be observed from the curves, more latitude is permissible in the fundamental data for a given accuracy in the results. The case in which $n = 1$, is also the only one for which the assumptions made by previous investigators apply. The results for this case are identical with those of Weber's (*loc. cit.*).

In his analysis Weber designates the individual curves by the symbol θ/T_e in which T_e is the same as in this paper, but θ is equal to nT_e. Thus for values of n differing from unity, it is only necessary to use the curve corresponding to the appropriate value of θ/T_e. The difference involved may be determined by comparing, for example, the curve for $n = 0.5$ and $T_s/T_e = 40$, which gives the results for the assumptions made in this paper, with the curve for $n = 1.0$ and $T_s/T_e = 20$, which gives the results for the assumptions made by Weber, namely, that the flux distribution in the air is the same as that in the iron. This comparison is as follows:

Time in Terms of $\frac{t}{T_e}$	A: $\frac{T_s}{T_e} = 40$, $n = 0.5$	B: $\frac{T_s}{T_e} = 20$, $n = 1.0$	$\frac{B}{A}$
1	0.320	0.280	0.875
2	0.503	0.450	0.895
3	0.615	0.575	0.935
4	0.694	0.665	0.958
5	0.753	0.737	0.979

It may be observed that the correspondence is quite close and will be still better for smaller values

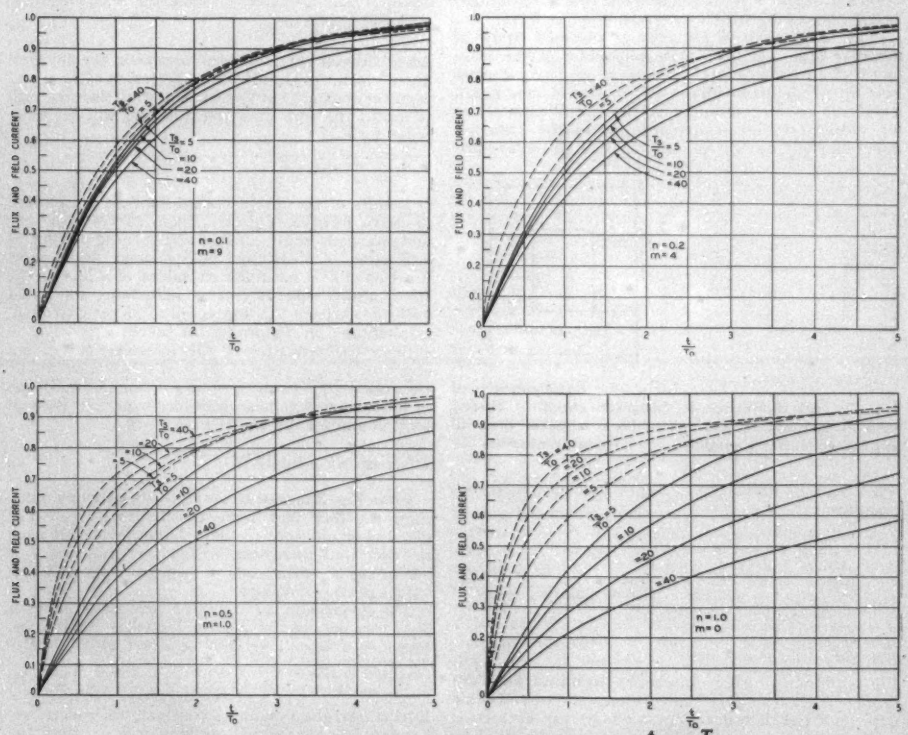


Fig. 3. Variation of total flux and field current as a function of $\frac{t}{T_e}$ and $\frac{T_s}{T_e}$

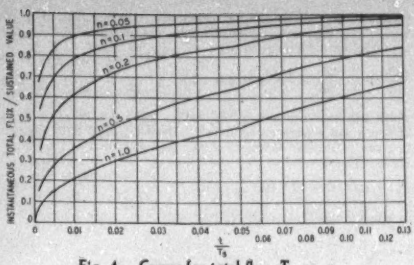


Fig. 4. Curves for total flux, $T_o = \infty$

of n and T_s/T_o, but will be worse for larger values of n and T_s/T_o.

Special Case for $T_o = \infty$

A particularly interesting case arises when $T_o = \infty$. Thus one might wish to know the character of the voltage of an alternator having a partially solid core for which the field current suddenly is interrupted. Because of the eddy currents in the solid part, the voltage cannot fall to zero instantly. The results for this case were obtained by letting $R = 0$, thus $T_o = 0$ and $T_s/T_o = \infty$. The transient components will be the same for suddenly removing and suddenly applying the voltage. The results for the case in which a voltage suddenly is applied to such a circuit are plotted in Fig. 4. For suddenly opening the field current the curves should be inverted, starting from unity instead of zero.

In this connection it is interesting to compare the results of this investigation with those obtained by R. Rudenberg (see "Elektrische Schaltvorgange," Julius Springer, Berlin, 1923, p. 70, 73, and 75). For the particular case for which Rudenberg's analysis is rigorous, *viz.*, when in the notation of this paper $n = 1$, he finds that when the core is of square cross section of d on a side the time constant of the fundamental component of the transient is $0.637\ (\mu s/\rho)d^2$ and the amplitude is 0.66. The results for the circular cross section of diameter d given in this paper for $n = 1$ give a time constant for the fundamental component equal to $0.543\ (\mu s/\rho)d^2$ and an amplitude equal to 0.69. Considering the greater volume of the core for the square cross section, the results agree quite closely.

Appendix

As stated previously, the analysis will follow quite closely that of Weber (*loc. cit.*), the fundamental difference being with regard to the assumption of uniform flux density in the air gap and laminated part. The practical system of units will be used, for example, centimeters, ohms, henries, and (magnetic) lines.

Fundamental Equations

The flux in the core can be resolved into 2 components: (1) that due to the exciting or field winding, and (2) that due to the induced eddy currents in the solid part of the core.

Flux Due to Exciting Winding. This flux circulates through the entire magnetic circuit and has a uniform density, B_1, across the section; it is a function of time only. The line integral of flux density is related to the exciting current of the field by the following equation:

$$\left(\frac{l_s}{\mu_s} + \frac{l_l}{\mu_l} + \delta\right) B_1 = \frac{4\pi}{10} Ni$$

or

$$B_1 = K_1 i \quad \text{gausses} \tag{8}$$

in which

i = instantaneous value of field current
N = number of turns in field current

$$K_1 = \frac{4\pi 10^{-1} N}{\frac{l_s}{\mu_s} + \frac{l_l}{\mu_l} + \delta} \tag{9}$$

Flux Due to Eddy Currents. The flux density due to the eddy currents is designated B_2 and is a function of both time and radius. Let G be the current density at any point in the solid part of the iron as shown in Fig. 5. The total current enclosed in the incremental area shown is $l_s G dr$. The current enclosed by this area times 0.4π must be equal to the line integral of the magnetomotive force about it. On the inner side the contribution to the line integral is $\frac{l_s}{\mu_s} B_2$ and on the outer side $\frac{l_s}{\mu_s}\left(B_2 + \frac{\partial B_2}{\partial r} dr\right)$. The ends contribute nothing because the integral passes through material which by assumption has infinite permeability. Then

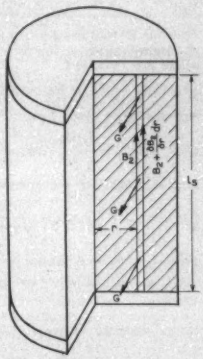


Fig. 5. Solid part of core

$$\frac{l_s}{\mu_s} B_2 - \frac{l_s}{\mu_s}\left(B_2 + \frac{\partial B_2}{\partial r} dr\right) = 0.4\pi l_s G dr$$

or

$$\frac{\partial B_2}{\partial r} = -0.4\pi\mu_s G \quad \text{gausses per centimeter} \tag{10}$$

The eddy currents are produced by the time rate of change of the flux encircling any point, thus

$$\int \rho G d_s = -10^{-8} \frac{\partial}{\partial t} \iint (B_1 + B_2) dA$$

$$2\pi r \rho G = -10^{-8} \frac{\partial}{\partial t} \int 2\pi r (B_1 + B_2) dr$$

$$r\rho G = -10^{-8} \frac{\partial}{\partial t} \int r (B_1 + B_2) dr$$

Differentiating with respect to r

$$r \frac{\partial G}{\partial r} + G = -10^{-8} \frac{r}{\rho} \frac{\partial}{\partial t} (B_1 + B_2) \tag{11}$$

The total flux, ϕ_t, flows through both the solid part and the air gap, but with different radial distribution in the 2 parts. This flux is

$$\phi_t = \iint (B_1 + B_2) dA$$

and since B_1 is uniform over the section

$$\phi_t = \frac{\pi d^2}{4} B_1 + 2\pi \int_0^{\frac{d}{2}} r B_2 \, dr \tag{12}$$

The following voltage equation may be written for the exciting winding

$$Ri + S\frac{di}{dt} + 10^{-9} N \frac{d\phi_1}{dt} = V \text{ in volts} \tag{13}$$

where S is the leakage inductance of the exciting winding.

Equations 8, 10, 11, 12, and 13 constitute the mathematical statement of the problem.

From eq 10

$$\frac{\partial G}{\partial r} = -\frac{1}{0.4\pi\mu_s}\frac{\partial^3 B_1}{\partial r^3} \tag{14}$$

After substituting $\frac{\partial G}{\partial r}$ from eq 14 and G from eq 10 into eq 11, there results

$$\frac{\partial^2 B_2}{\partial r^2} + \frac{1}{r}\frac{\partial B_2}{\partial r} = \frac{4\pi 10^{-9}\mu_s}{\rho}\frac{\partial}{\partial t}(B_1 + B_2) \tag{15}$$

Equation 13 may be rewritten using the notation of the Heaviside operational calculus. Heaviside's unit function will be denoted by a bold face numeral **1**.

$$(R + pS)i + p\,10^{-8} N\phi_1 = V\cdot\mathbf{1} \tag{16}$$

Substituting eq 12

$$(R + pS)i + p\frac{\pi d^2 10^{-8}}{4} NB_1 = V\cdot\mathbf{1} - 2\pi 10^{-8} Np\int_0^{\frac{d}{2}} rB_2 dr \tag{17}$$

Replacing B_1 by its value from eq 8

$$\left(R + pS + p\frac{\pi}{4}k_1 N d^2 10^{-8}\right) i = V\cdot\mathbf{1} - 2\pi 10^{-8} Np\int_0^{\frac{d}{2}} rB_2 dr \tag{18}$$

From eq 8, the total flux due to i is $\frac{\pi d^2}{4}B_1$ or $\frac{\pi d^2}{4}k_1 i$, so that defining L_o as the self inductance of the exciting winding, neglecting leakage,

$$L_o = \frac{\pi}{4}k_1 N d^2 10^{-8} \text{ henries} \tag{19}$$

After substituting eq 19, eq 18 becomes

$$(R + pS + pL_o)i = V\cdot\mathbf{1} - 2\pi 10^{-8} Np\int_0^{\frac{d}{2}} rB_2\, dr \tag{20}$$

from which

$$i = \frac{V\cdot\mathbf{1} - 2\pi 10^{-8} Np\int_0^{\frac{d}{2}} rB_2 dr}{R + pS + pL_o} \tag{21}$$

The denominator may be designated conveniently by P so that

$$P = R + pS + pL_o \tag{22}$$

and eq 20 becomes

$$i = \frac{V}{P}\cdot\mathbf{1} - \frac{2\pi 10^{-8} Np}{P}\int_0^{\frac{d}{2}} rB_2 dr \tag{23}$$

From eqs 8 and 23

$$B_1 = \frac{k_1 V}{P}\cdot\mathbf{1} - \frac{2\pi 10^{-8} k_1 Np}{P}\int_0^{\frac{d}{2}} rB_2 dr \tag{24}$$

Now returning to eq 15, by converting to the Heaviside notation

$$\frac{\partial^2 B_2}{\partial r^2} + \frac{1}{r}\frac{\partial B_2}{\partial r} - \frac{4\pi 10^{-9}\mu_s}{\rho}pB_2 = \frac{4\pi 10^{-9}\mu_s}{\rho}pB_1 \tag{25}$$

and after substituting eq 24

$$\frac{\partial^2 B_2}{\partial r^2} + \frac{1}{r}\frac{\partial B_2}{\partial r} - \frac{4\pi 10^{-9}\mu_s}{\rho}pB_2 = \frac{4\pi 10^{-9}\mu_s}{\rho}p\left[\frac{k_1}{P}V\cdot\mathbf{1} - \frac{2\pi 10^{-8} k_1 N}{P}p\int_0^{\frac{d}{2}} rB_2 dr\right] \tag{26}$$

It may be observed that the left hand side of eq 26 is a differential equation in r and that the right hand side is independent of r. It follows that the solution consists of the sum of the solution for the homogeneous differential equation

$$\frac{\partial^2 B_2}{\partial r^2} + \frac{1}{r}\frac{\partial B_2}{\partial r} - \frac{4\pi 10^{-9}\mu_s}{\rho}pB_2 = 0 \tag{27}$$

which will be designated by B_2' and a particular integral of eq 25 which will be designated by B_2''. The solution for eq 27 is given in terms of Bessel's functions of the first order and of the first 2 kinds. Thus

$$B_2' = CJ_o(kr) + DN_o(kr) \tag{28}$$

in which C and D are arbitrary constants of integration, in which

$$k = \sqrt{-\frac{4\pi 10^{-9}\mu_s}{\rho}p} \tag{29}$$

The particular integral may be assumed to be

$$B_2'' = F(p) \tag{30}$$

Therefore

$$B_2 = B_2' + B_2'' = CJ_o(kr) + DK_o(kr) + F(p) \tag{31}$$

The integration constants will be determined next. At $r = 0$ the density of the eddy currents is zero, so that placing $G = 0$ in eq 10,

$$\frac{\partial B_2}{\partial r} = 0 \tag{32}$$

Differentiating eq 31 with respect to r

$$\frac{dB_2}{dr} = -C(kr)J_1(kr) - D(kr)N_1(kr) \tag{33}$$

The $F(p)$ drops out because its differential with respect to r is zero. Now letting $kr = 0$ in eq 33

$$J_1(kr) = 0$$

$$(kr)N_1(kr) = -1$$

so that, since $\frac{dB_2}{dr} = 0$,

$$D = 0 \tag{34}$$

Therefore,

$$B_2 = CJ_o(kr) + F(p) \tag{35}$$

To determine the constant C, the value of B_2 will be determined for $r = d/2$. Taking the line integral of magnetomotive force along a path for $r = d/2$ in the solid part, and continuing through the air gap and laminated part to form a closed loop, since no current is enclosed, the integrals must be equal to zero. There results then that

$$\frac{l_s}{\mu_s}B_s\Big|_{r=\frac{d}{2}} + \left(\delta + \frac{l_i}{\mu_i}\right)B_a = 0 \tag{36}$$

in which B_a is the flux density in the air gap and laminated iron. B_s is also equal to the average flux density in the solid part of the iron, that is

$$B_s = \frac{4}{\pi d^3}\int\int B_2\, dA$$

$$= \frac{4}{\pi d^3}2\pi\int_0^{\frac{d}{2}} B_2 r dr$$

and substituting eq 35

$$B_s = \frac{8}{d^3}\int_0^{\frac{d}{2}}\left[CJ_o(kr) + F(p)\right]rdr$$

$$= \frac{8}{d^3}C\int_0^{\frac{d}{2}} J_o(kr)rdr + \frac{8}{d^3}F(p)\int_0^{\frac{d}{2}} rdr$$

$$= \frac{8}{d^3}C\int_0^{\frac{d}{2}} J_o(kr)r\, dr + F(p) \tag{37}$$

But

$$\int_0^{\frac{d}{2}} J_o(kr)r\,dr = \frac{d}{2k}\,J_1\left(\frac{kd}{2}\right) \tag{38}$$

After substituting eq 38 in eq 37

$$B_o = \frac{4}{kd}\,CJ_1\left(\frac{kd}{2}\right) + F(p) \tag{39}$$

After inserting $d/2$ for r in eq 35 and then substituting this value of eq 35 and also 39 in 36

$$\frac{l_s}{\mu_s}\left[CJ_o\left(\frac{kd}{2}\right) + F(p)\right] + \left(\delta + \frac{l_l}{\mu_l}\right)\left[\frac{4}{kd}\,CJ_1\left(\frac{kd}{2}\right) + F(p)\right] = 0 \tag{40}$$

Solving for C

$$C = -\frac{\left(\delta + \frac{l_l}{\mu_l} + \frac{l_s}{\mu_s}\right)}{\frac{l_s}{\mu_s}\,J_o\left(\frac{kd}{2}\right) + \left(\delta + \frac{l_l}{\mu_l}\right)\frac{4}{kd}\,J_1\left(\frac{kd}{2}\right)}\,F(p) \tag{41}$$

The notation may be simplified by inserting the a and b quantities defined in the body of the paper.

$$C = -\frac{a+b}{bJ_o\left(\frac{kd}{2}\right) + a\,\frac{4}{kd}\,J_1\left(\frac{kd}{2}\right)}\,F(p) \tag{42}$$

Substitute eq 42 in eq 35

$$B_2 = F(p) - \frac{(a+b)J_o(kr)}{bJ_o\left(\frac{kd}{2}\right) + a\left(\frac{4}{kd}\right)J_1\left(\frac{kd}{2}\right)}\,F(p) \tag{43}$$

Taking stock, a solution of B_2 has been found in operational form which must satisfy the fundamental equation (26). It may be recalled from eqs 30 and 31 that

$$B_2 = F(p) + B_2'$$

in which B_2' now represents the second part of eq 43. Since B_2' was obtained by solving eq 27, on substituting it back into the left hand member of eq 26 it will be equal to zero and, therefore, may be neglected. It remains only necessary, therefore, to substitute $F(p)$ into the left hand member and B_2 into the right hand member. When differentiated with respect to r, $F(p)$ is zero and the left hand member becomes $-\frac{4\pi\,10^{-9}\,\mu_s}{\rho}\,p\,F(p)$.

Substitution into the right hand member involves the determination of $\int_0^{\frac{d}{2}} r\,B_2\,dr$

$$\int_0^{\frac{d}{2}} rB_2dr = F(p)\int_0^{\frac{d}{2}} rdr - F(p)\,\frac{a+b}{bJ_o\left(\frac{kd}{2}\right) + a\,\frac{4}{kd}\,J_1\left(\frac{kd}{2}\right)}\int_0^{\frac{d}{2}} rJ_o(kr)dr$$

The expression for the second integral of the right hand member is given by eq 38, so that

$$\int_0^{\frac{d}{2}} rB_2dr = \frac{d^2}{8}\,F(p) - \frac{\frac{d}{2k}\,(a+b)\,J_1\left(\frac{kd}{2}\right)}{bJ_o\left(\frac{kd}{2}\right) + a\,\frac{4}{kd}\,J_1\left(\frac{kd}{2}\right)}\,F(p)$$

$$= F(p)\,\frac{d^2}{8}\left[1 - \frac{2\,(a+b)J_1\left(\frac{kd}{2}\right)}{\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)}\right] \tag{44}$$

Equation 26 then becomes, after substituting eq 44,

$$-\frac{4\pi10^{-9}\mu_s}{\rho}\,pF(p) = \frac{4\pi10^{-9}\mu_s}{\rho}\,p\left\{\frac{K_1}{P}\,V\cdot 1 - \frac{2\pi10^{-9}K_1N}{P}\,\frac{d^2}{8}\,F(p)p\left[1 - \frac{2(a+b)J_1\left(\frac{kd}{2}\right)}{\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)}\right]\right\}$$

or

$$F(p) = \frac{V}{\frac{P}{K_1}\left[\frac{\pi10^{-9}NK_1d^2}{4P}\,p\left\{1 - \frac{2(a+b)J_1\left(\frac{kd}{2}\right)}{\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)}\right\} - 1\right]}\cdot 1$$

and substituting L_o from eq 19

$$F(p) = \frac{K_1V}{L_op\left\{1 - \frac{2(a+b)J_1\left(\frac{kd}{2}\right)}{\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)}\right\} - P}\cdot 1 \tag{45}$$

Now substituting eq 45 in eq 43

$$B_2 = \frac{\left[1 - \frac{(a+b)J_o(kr)}{bJ_o\left(\frac{kd}{2}\right) + 2a\left(\frac{2}{kd}\right)J_1\left(\frac{kd}{2}\right)}\right]K_1V}{L_op\left[1 - \frac{2\,(a+b)J_1\left(\frac{kd}{2}\right)}{\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)}\right] - P}\cdot 1$$

But $P = R + P(S + L_o)$, so that

$$B_2 = \frac{\left[\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right) - (a+b)\left(\frac{kd}{2}\right)J_o(kr)\right]K_1V}{L_op\left[\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) - 2bJ_1\left(\frac{kd}{2}\right)\right] - \left[R + p(S+L_o)\right]\left[\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)\right]}\cdot 1 \tag{46}$$

Equation 46 provides a solution of B_2 in operational form. A corresponding solution for i and ϕ_1 will be obtained next. Equation 23 will be used to obtain i, but it will be necessary to obtain first the integral that appears in that expression. Substituting eq 45 in eq 44

$$\int_0^{\frac{d}{2}} rB_2dr = \frac{\frac{d^2}{8}\left[1 - \frac{2(a+b)J_1\left(\frac{kd}{2}\right)}{\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)}\right]K_1V}{L_op\left[1 - \frac{2(a+b)J\left(\frac{kd}{2}\right)}{\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)}\right] - P}\cdot 1$$

$$= \frac{d^2}{8}\,\frac{\left[\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) - 2bJ_1\left(\frac{kd}{2}\right)\right]K_1V}{L_op\left[\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) - 2bJ_1\left(\frac{kd}{2}\right)\right] - P\left[\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)\right]}\cdot 1 \tag{47}$$

Substituting eq 47 in eq 23

$$i = \frac{V}{P}\left\{1 - \frac{2\pi10^{-9}NPd^2K_1}{8}\,\frac{\left[\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) - 2bJ_1\left(\frac{kd}{2}\right)\right]}{L_op\left[\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) - 2bJ_1\left(\frac{kd}{2}\right)\right] - P\left[\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)\right]}\cdot 1\right.$$

But since $\frac{\pi10^{-9}Nd^2K_1}{4} = L_o$ from eq 19, then

$$i = -\frac{\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)}{L_op\left[\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) - 2bJ_1\left(\frac{kd}{2}\right)\right] - P\left[\left(\frac{kd}{2}\right)bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)\right]}\,V\cdot 1 \tag{48}$$

The operational form for ϕ_1 can be obtained by substituting B_1 from eq 8, i from eq 48, and $\int_0^{\frac{d}{2}} r\, B_2\, dr$ from eq 47 into eq 12 giving

$$\phi_1 = \frac{\begin{aligned} &-\frac{\pi d^2}{4} K_1\left[\left(\frac{kd}{2}\right) bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)\right] \\ &+\frac{\pi d^2 K_1}{4}\left[\left(\frac{kd}{2}\right) bJ_o\left(\frac{kd}{2}\right) - 2bJ_1\left(\frac{kd}{2}\right)\right] \end{aligned}}{\begin{aligned} &L_o p\left[\left(\frac{kd}{2}\right) bJ_o\left(\frac{kd}{2}\right) - 2bJ_1\left(\frac{kd}{2}\right)\right] \\ &- P\left[\left(\frac{kd}{2}\right) bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)\right] \end{aligned}} V \cdot 1$$

and since $\frac{\pi d^2}{4} K_1 = \frac{L_o}{N} 10^8$

$$\phi_1 = -\frac{2 \times 10^8 \frac{L_o}{N}(a+b) J_1\left(\frac{kd}{2}\right) V}{\begin{aligned} &L_o p\left[\left(\frac{kd}{2}\right) bJ_o\left(\frac{kd}{2}\right) - 2bJ_1\left(\frac{kd}{2}\right)\right] \\ &- P\left[\left(\frac{kd}{2}\right) bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)\right] \end{aligned}} \cdot 1 \tag{49}$$

The solutions for B_2, i, and ϕ_1 now are expressed in operational form and may be written

$$B_2 = \frac{Y_2(p)}{Z(p)} V \cdot 1 \tag{50}$$

$$i = \frac{Y_i(p)}{Z(p)} V \cdot 1 \tag{51}$$

$$\phi_1 = \frac{Y_\phi(p)}{Z(p)} V \cdot 1 \tag{52}$$

in which

$$\begin{aligned} Y_2(p) = K_1 &\left[b\left(\frac{kd}{2}\right) J_o\left(\frac{kd}{2}\right)\right. \\ &\left. + 2aJ_1\left(\frac{kd}{2}\right) - (a+b)\left(\frac{kd}{2}\right) J_o(kr)\right] \end{aligned} \tag{53}$$

$$Y_i(p) = -\left(\frac{kd}{2}\right) bJ_o\left(\frac{kd}{2}\right) - 2aJ_1\left(\frac{kd}{2}\right) \tag{54}$$

$$Y_\phi(p) = -2 \times 10^8 \frac{L_o}{N}(a+b) J_1\left(\frac{kd}{2}\right) \tag{55}$$

$$\begin{aligned} Z(p) = L_o p &\left[\left(\frac{kd}{2}\right) bJ_o\left(\frac{kd}{2}\right) - 2bJ_1\left(\frac{kd}{2}\right)\right] \\ &- [R + p(S + L_o)]\left[\left(\frac{kd}{2}\right) bJ_o\left(\frac{kd}{2}\right) + 2aJ_1\left(\frac{kd}{2}\right)\right] \end{aligned} \tag{56}$$

By the application of the Heaviside expansion theorem

$$B_2 = \frac{Y_2(o)}{Z(o)} V + V \sum_1^\infty \left[\frac{Y_2(p)}{p \frac{d}{dp}(Zp)}\right]_{p=p_r} \epsilon^{p_r t} \tag{57}$$

where the values of p_r are the roots of $Z(p)$. Similarly

$$i = \frac{Y_i(o)}{Z(o)} V + V \sum_1^\infty \left[\frac{Y_i(p)}{p \frac{d}{dp} Z(p)}\right]_{p=p_r} \epsilon^{p_r t} \tag{58}$$

and

$$\phi_1 = \frac{Y_\phi(o)}{Z(o)} V + V \sum_1^\infty \left[\frac{Y_\phi(p)}{p \frac{d}{dp} Z(p)}\right]_{p=p_r} \epsilon^{p_r t} \tag{59}$$

The next step involves the determination of the roots of $Z(p)$ which may be rewritten, collecting terms,

$$\begin{aligned} Z(p) = &-(R + pS)\left(\frac{kd}{2}\right) bJ_o\left(\frac{kd}{2}\right) \\ &- 2(bL_o p + Ra + paS + paL_o) J_1\left(\frac{kd}{2}\right) \end{aligned} \tag{60}$$

Letting $\frac{kd}{2} = q$, from eq 29

$$q = \frac{kd}{2} = \sqrt{-\frac{\pi 10^{-9} \mu_o d^2}{\rho} p} \tag{61}$$

or

$$q^2 = -\frac{\pi 10^{-9} \mu_o d^2}{\rho} p = T_o p \tag{62}$$

in which

$$T_o = \frac{\pi 10^{-9} \mu_o d^2}{\rho} \text{ seconds} \tag{63}$$

This quantity has the dimension of time and determines the lag of the phenomenon due to the eddy currents. Also

$$p = -\frac{q^2}{T_o} \tag{64}$$

After substituting eqs 61 and 64 in eq 56, $Z(p)$ becomes

$$\begin{aligned} Z(p) = &-\left(R - \frac{q^2}{T_o} S\right) qbJ_o(q) \\ &- 2\left[aR - \frac{q^2}{T_o}(bL_o + aL_o + aS)\right] J_1(q) \end{aligned}$$

Now let

$$\sigma = \frac{S}{L_o} \tag{65}$$

This is a fraction which expresses the leakage associated with the exciting winding in terms of the self-inductance of the exciting winding.

Also let

$$T_o = \frac{L_o}{R} \text{ seconds} \tag{66}$$

which is defined in the body of the paper, and

$$m = \frac{a}{b} \tag{67}$$

Then substituting these quantities in the expression for $Z(p)$,

$$\begin{aligned} Z(p) = -\frac{L_o b}{T_o} &\left\{\left(\frac{T_o}{T_o} - \sigma q^2\right) qJ_o(q)\right. \\ &\left. + 2\left[m\frac{T_o}{T_o} - q^2(1 + m + m\sigma)\right] J_1(q)\right\} \end{aligned} \tag{68}$$

To obtain the roots, q_1, q_2, q_3, etc., transform to

$$\frac{J_o(q)}{J_1(q)} = -\frac{2\left[m\frac{T_o}{T_o} - q^2(1 + m + m\sigma)\right]}{\left[\frac{T_o}{T_o} - \sigma q^2\right] q} \tag{69}$$

This is most readily solved by a graphical method, plotting the left hand and right hand members and determining the intersections of the resulting curves.

The denominator of eqs 57 to 59, $p\frac{d}{dp} Z(p)$, being a function of p must be evaluated and expressed as a function of q.

$$p\frac{d}{dp} Z(p) = -\frac{q^2}{T_o}\frac{dq}{dp}\frac{d}{dq} Z(p) \tag{70}$$

Differentiating eq 68

$$\begin{aligned} \frac{d}{dq} Z(p) = -\frac{L_o b}{T_o} &\left\{\left(\frac{T_o}{T_o} - 3\sigma q^2\right) J_o(q) - \left(\frac{T_o}{T_o} - \sigma q^2\right) qJ_1(q)\right. \\ &- 4q(1 + m + m\sigma) J_1(q) + 2\left[\frac{T_o}{T_o} m - q^2(1 + m + m\sigma)\right] \\ &\left.\left[J_o(q) - \frac{1}{q} J_1(q)\right]\right\} \\ = -\frac{L_o b}{T_o} &\left\{\left[\frac{T_o}{T_o}(1 + 2m) - 2(1 + m + m\sigma) q^2 - 3\sigma q^2\right] J_o(q)\right. \\ &\left. - \left[\frac{T_o}{T_o}\left(q + \frac{2m}{q}\right) - \sigma q^3 + 2(1 + m + m\sigma) q\right] J_1(q)\right\} \end{aligned} \tag{71}$$

From eq 64

$$\frac{dq}{dp} = -\frac{T_s}{2q} \tag{72}$$

so that inserting eqs 71 and 72, eq 70 becomes

$$p\frac{d}{dp}Z(p) = -q\frac{L_o b}{2T_s}\left\{\left[\frac{T_s}{T_o}(1+2m) - 2(1+m+m\sigma)q^2 - 3\sigma q^3\right]J_o(q) - \left[\frac{T_s}{T_o}\left(q+\frac{2m}{q}\right) - \sigma q^3 + 2(1+m+m\sigma)q\right]J_1(q)\right\} \tag{73}$$

The numerators of eqs 57 to 59 may be obtained in terms of q by inserting eqs 65, 66, and 67 in eqs 53 to 55, giving

$$Y_2(p) = bK_1\left[qJ_o(q) + 2mJ_1(q) - (1+m)qJ_o\left(\frac{2qr}{d}\right)\right] \tag{74}$$

$$Y_1(p) = -b[qJ_o(q) + 2mJ_1(q)] \tag{75}$$

$$Y\phi(p) = -\frac{2\times 10^8 bL_o(1+m)}{N}J_1(q) \tag{76}$$

There remains yet to determine the first terms of eqs 57 to 59. Since $q = 0$ when $p = 0$, $\frac{Y_2(o)}{Z(o)}$ can be determined by letting $q = 0$ in eqs 74 and 68. As q approaches zero $J_o(q)$ approaches unity and $J_1(q)$ approaches $q/2$, so that

$$\frac{Y_2(o)}{Z(o)} = \frac{bK_1\left[q + \frac{2mq}{2} - (1+m)q\right]}{-\frac{L_o b}{T_s}\left\{\frac{T_s}{T_o}q + m\frac{T_s}{T_o}q\right\}} = \frac{K_1(1+m-1-m)}{-\frac{L_o}{T_s}\frac{T_s}{T_o}(1+m)} = 0 \tag{77}$$

which means that the sustained value of flux density due to the eddy currents is zero.

For eq 58, $\frac{Y_1(o)}{Z(o)}$ can be determined in a similar manner.

$$\frac{Y_1(o)}{Z(o)} = \frac{-b\left(q + \frac{2mq}{2}\right)}{-\frac{L_o b}{T_s}\left(\frac{T_s}{T_o} + 2\frac{m}{T_o}\frac{q}{2}\right)} = \frac{1}{R} \tag{78}$$

This result checks Ohm's law in that the steady state value of the exciting current must be equal to the applied voltage divided by the resistance.

Similarly $\frac{Y\phi(o)}{Z(o)}$ for eq 59, becomes

$$\frac{Y\phi(o)}{Z(o)} = \frac{-\frac{2bL_o}{N}(1+m)\frac{q}{2}}{-\frac{L_o bq}{T_o}(1+m)} = \frac{T_o}{N} = \frac{L_o}{RN} \tag{79}$$

Therefore on substituting eqs 73 to 76 in eqs 57 to 59 the solutions for B_2, i, and ϕ_t, become as shown in eqs 80 to 85, inclusive.

The foregoing equations use the quantity m as a parameter; this quantity is the ratio of the equivalent air gaps, a/b. It is more convenient to express the relation between these equivalent gaps by introducing a term which expresses the fraction of the total magnetomotive force consumed by the solid iron part under steady state conditions. This fraction will be designated by n. The relations between m and n are then

$$m = \frac{1-n}{n} \tag{86}$$

$$n = \frac{1}{1+m} \tag{87}$$

Equations 80 to 85

$$B_2 = V\,b\,K_1\sum_1^{\infty}\left[\frac{q\,J_o(q) + 2mJ_1(q) - (1+m)q\,J_o\left(\frac{2qr}{d}\right)}{-\frac{qL_o b}{2T_s}\left\{\left[\frac{T_s}{T_o}(1+2m) - 2(1+m+m\sigma)q^2 - 3\sigma q^3\right]J_o(q) - \left[\frac{T_s}{T_o}\left(q+\frac{2m}{q}\right) - \sigma q^3 + 2(1+m+m\sigma)q\right]J_1(q)\right\}}\right]_{q=q_p}\epsilon^{-\frac{q_p^2}{T_s}} \tag{80}$$

$$i = \frac{V}{R} + V\sum_1^{\infty}\left[\frac{-b[qJ_o(q) + 2mJ_1(q)]}{-\frac{qL_o b}{2T_s}\left\{\left[\frac{T_s}{T_o}(1+2m) - 2(1+m+m\sigma)q^2 - 3\sigma q^3\right]J_o(q) - \left[\frac{T_s}{T_o}\left(q+\frac{2m}{q}\right) - \sigma q^3 + 2(1+m+m\sigma)q\right]J_1(q)\right\}}\right]_{q=q_p}\epsilon^{-\frac{q_p^2}{T_s}t} \tag{81}$$

$$\phi_t = \frac{VL_o}{RN} + V\sum_1^{\infty}\left[\frac{-\frac{2\times 10^8 b\,L_o(1+m)}{N}J_1(q)}{-\frac{qL_o b}{2T_s}\left\{\left[\frac{T_s}{T_o}(1+2m) - 2(1+m+m\sigma)q^2 - 3\sigma q^3\right]J_o(q) - \left[\frac{T_s}{T_o}\left(q+\frac{2m}{q}\right) - \sigma q^3 + 2(1+m+m\sigma)q\right]J_1(q)\right\}}\right]_{q=q_p}\epsilon^{-\frac{q_p^2}{T_s}t} \tag{82}$$

Equations 80, 81, and 82 may be simplified as follows:

$$B_2 = -\frac{V}{R}\frac{T_s}{T_o}2K_1\sum_1^{\infty}\left[\frac{2m + q\frac{J_o(q)}{J_1(q)} - (1+m)q\frac{J_o\left(\frac{2qr}{d}\right)}{J_1(q)}}{q\left\{\left[\frac{T_s}{T_o}(1+2m) - q^2(2[1+m+m\sigma] + 3\sigma)\right]\frac{J_o(q)}{J_1(q)} - \frac{T_s}{T_o}\left(q - \frac{2m}{q}\right) + \sigma q^2 - 2q(1+m+m\sigma)\right\}}\right]_{q=q_p}\epsilon^{-\left(\frac{q_p^2T_o}{T_s}\right)\frac{t}{T_o}} \tag{83}$$

$$i = \frac{V}{R}\left\{1 + 2\frac{T_s}{T_o}\sum_1^{\infty}\left[\frac{2m + q\frac{J_o(q)}{J_1(q)}}{q\left\{\left[\frac{T_s}{T_o}(1+2m) - q^2(2[1+m+m\sigma] + 3\sigma)\right]\frac{J_o(q)}{J_1(q)} - \frac{T_s}{T_o}\left(q - \frac{2m}{q}\right) + \sigma q^2 - 2q(1+m+m\sigma)\right\}}\right]_{q=q_p}\epsilon^{-\left(\frac{q_p^2T_o}{T_s}\right)\frac{t}{T_o}}\right. \tag{84}$$

$$\phi_t = \frac{VT_s}{N}\left\{1 + 4\frac{T_s}{T_o}\sum_1^{\infty}\left[\frac{1+m}{q\left\{\left[\frac{T_s}{T_o}(1+2m) - q^2(2[1+m+m\sigma] + 3\sigma)\right]\frac{J_o(q)}{J_1(q)} - \frac{T_s}{T_o}\left(q - \frac{2m}{q}\right) + \sigma q^2 - 2q(1+m+m\sigma)\right\}}\right]_{q=q_p}\epsilon^{-\left(\frac{q_p^2T_o}{T_s}\right)\frac{t}{T_o}}\right. \tag{85}$$

Theory of Primary Networks—Part II

This paper, Part II of a group on theory of primary electric power distribution networks, deals with short-circuit and relay problems. Data showing the distribution of fault currents for both 3-phase and ground faults is presented, and a rational method of relaying based upon that data is discussed and analyzed.

By
F. M. STARR
ASSOCIATE A.I.E.E.

General Elec. Co.,
Schenectady, N. Y.

IN ORDER that primary electric power distribution networks may be designed to give optimum service reliability, and in order that circuit breakers having adequate interrupting capacities may be provided, the maximum possible fault currents that can exist must be known. This paper, Part II of a group on theory of primary networks (for Part I, which dealt primarily with voltage regulation and load distribution problems, see ELECTRICAL ENGINEERING, v. 53, Feb. 1934, p. 310–18) presents results of calculating board studies showing maximum possible faults on typical primary networks having a variety of characteristics, with tie line impedance, load density, and kilovoltampere capacity of the networks as parameters. Data showing the distribution of fault current for both 3-phase and ground faults is given.

Upon the basis of the fault data presented, methods of relaying that are best fitted to give reliable operation and service continuity are described and analyzed. An example is given demonstrating the method of calculating relay settings for a typical network. Special network operating conditions also are discussed briefly; however, no operating difficulty has been found that cannot be remedied satisfactorily in a fairly simple and inexpensive manner.

Magnitude of Faults on Primary Networks

MAXIMUM POSSIBLE FAULTS

It is of considerable importance to know the magnitude of faults in primary networks having various characteristics in order that the networks may be designed to give optimum service reliability, and in order that circuit breakers having adequate interrupting capacities may be provided. A section of a typical primary network is shown in Fig. 1. The maximum possible fault that can occur on the 4-kv network will be located either on the unit substation bus or immediately outside the feeder circuit breaker.

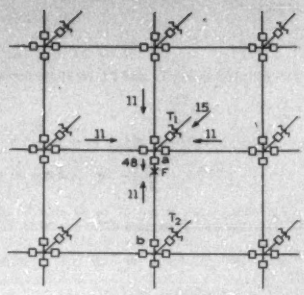


Fig. 1. Section of a typical primary network

This figure shows the distribution of fault currents for the maximum possible fault that can occur on a large network. Network ties having an impedance of 6 per cent and transformers having a reactance of 6 per cent (1500-kva base) are assumed. Currents are in "times-normal" current of the network transformer rating

Consider such a fault at point F, for example, on the network unit fed by transformer T_1. Since the maximum fault exists when the impedances of the generating system and transmission lines feeding the network are minimum, such a condition will be assumed (actually about 0.4 per cent in this case). It will be assumed further that the network is very large (i. e., it is infinite so far as faults at any internal point are concerned), that the network ties are overhead lines having impedances of 6 per cent, and that the transformer reactances are 6 per cent. (All per cent impedances are on a 1,500-kva base, the rating of the unit. The tie impedance of 6 per cent in this case corresponds to a load density of about 1,400 kva per square mile.) With these conditions the maximum possible 3-phase fault at point F will be 59 times normal (normal being 1,500 kva). The maximum current through a feeder breaker for this particular fault is 48 times normal or 72,000 kva. If transformer T_1 were out of service, a likely condition, the fault current through breaker A would be reduced to 33 times normal.

A fault at point F results in breaker A opening first, after which the current through breaker B increases from 11 times normal to 12.4 times normal. Of this current, approximately 23 per cent will come from each of the other 3 network ties and 31 per cent will flow from transformer T_2. If transformer T_2 should be out of service, the current fed to the fault through breaker B would be less by the 31 per cent which T_2 otherwise would carry. (This condition exists only in networks having 5 or more network units; the network considered here is assumed to be infinite.)

In the foregoing example, the maximum fault in a network having 6 per cent impedance mains was found to be 59 times normal. The curve in Fig. 2 gives similar values of maximum faults plotted against network tie impedance. A curve showing the distribution of this fault into each of the adjacent ties also is given. The curves in Fig. 2, as in the previous example, presume a very large network,

Full text of a paper recommended for publication by the A.I.E.E. committee on transmission and distribution. Manuscript submitted Oct. 23, 1933; released for publication Feb. 5, 1934. *Not published in pamphlet form.*

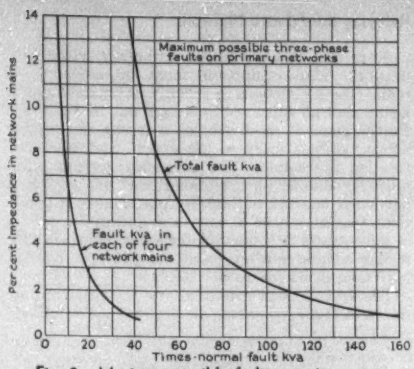


Fig. 2. Maximum possible faults on primary networks

These curves show the maximum possible 3-phase fault that can occur on a very large primary network, as a function of tie line impedance. Currents are in "times-normal" rating of the network transformer, and the impedance base is the kilovoltampere rating of the network transformer

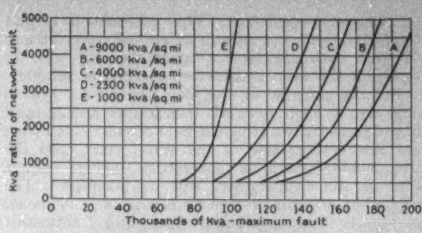


Fig. 3. Variation of fault kilovoltamperes with load density and network unit rating

These curves show the maximum possible 3-phase faults that can occur on a very large primary network, as a function of load density and kilovoltampere rating of the network unit. Network transformers having 6-per cent reactance are assumed in each case

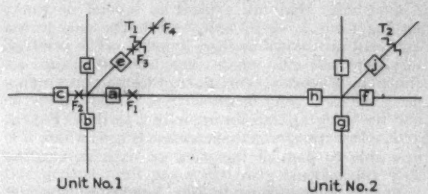


Fig. 4. Equivalent impedance diagram of the primary network unit and connected system

For the purpose of studying fault conditions in the average primary network having from 5 to 10 units, the above impedance elements are sufficient. Refer to Table I

a low impedance transmission system, 6 per cent reactance transformers, etc.

The size of network unit that has been found most economical for most applications is 1,500 kva; and unless otherwise stated, this is the rating of unit considered throughout this paper. However, it is of interest to note how the maximum possible fault currents vary with the size of network unit. For a given load density, the larger the unit, the farther apart they are and the greater the impedance of the ties. The greater tie impedance tends to reduce fault currents, but the increased transformer capacity of the larger units tends to increase fault currents. For a given size of unit an increase in load density results in shorter ties, more units, and increased magnitude of faults. These relations are shown quantitatively in the curves of Fig. 3.

From economic considerations, primary networks in most cases will not be applied to load densities greater than 10,000 kva per square mile. It appears, therefore, from the curves of Fig. 3, that a primary network having 1,500-kva units and overhead ties (the curves of Figs. 2 and 3 are based upon overhead ties) is subject to a maximum 3-phase fault of about 180,000 kva. If cable ties are used this maximum will approach 225,000 kva.

Usually the most severe fault on a system is a 3-phase fault, but in some cases the most severe network fault is a ground fault. A ground fault may be 5 or 10 per cent greater than a 3-phase fault. However, 3-phase faults are the best standards for comparative purposes since ground faults vary between wide limits depending on system conditions.

In some cases, the transmission lines feeding a network receive their power not directly from a generating station, but rather from a long transmission line with high-reactance transformer banks at either end. A system of this type materially reduces the maximum possible faults on a network. The maximum fault on a network fed in this manner may be approximated closely by considering the transmission system as a lumped impedance and applying the following simple formula

$$I = \frac{100\,I'}{100 + ZI'}$$

where Z is the lumped impedance of the transmission system (1,500-kva base), I' is the apparent maximum fault current as read from the curves of Fig. 2 or 3, and I is the true maximum fault current.

The preceding data has been found extremely useful in determining circuit breaker interrupting duties on a rational and economic basis. In networks having underground cable ties, 250,000-kva breakers have been adopted; networks having overhead ties have been equipped with breakers having ratings of 100,000 and 150,000 kva. In one case, a network having underground cable ties, but a high impedance transmission system, was equipped with 100,000-kva breakers; however, in this case a 50,000-kva breaker would have been adequate for load densities up to 5,000 kva per square mile.

Faults in Typical Networks

The foregoing material has considered the maximum possible faults on a primary network. In addition to this information it was necessary to know the actual faults, both 3-phase and ground, that are likely to be encountered in a typical network

of relatively small size. This information is particularly useful, not only to determine relay settings to give optimum service reliability, but also to establish the most satisfactory method of relaying.

For the purpose of studying faults on a typical network, a single network transformer and lumped impedances representing the network as viewed from the low voltage side of the transformer, and the transmission system as viewed from the high voltage side of the transformer, will be adequate. The single-line diagram of such an arrangement is shown in Fig. 4. The impedances H, L, and T represent the equivalent "Y" of the network transformer; impedance S represents the transmission system and impedance N represents the network. The faults in which we are interested are F_H on the high voltage side of the transformer and F_L on the low voltage side.

Constants that are typical of several networks having from 5 to 10 units which the author has analyzed are shown in Figs. 5 and 6. The positive, negative, and zero phase impedance diagrams are shown for 2 types of network transformers in common use: the Y-Y transformer with Δ tertiary (Fig. 5); and the Y-zigzag transformer with Δ tertiary (Fig. 6). This latter transformer connection is used where it is desirable to parallel the network with an existing Δ-Y substation.

For the 2 cases shown in Figs. 5 and 6, 3-phase and ground faults at points F_H and F_L have been calculated. The results of these calculations are given in Table I. It is interesting to note in this case that ground faults on the low-voltage side are somewhat greater than are the 3-phase faults. The maximum faults possible in this network are seen to be about 50 times normal or 75,000 kva. The difference in distribution of ground fault currents between the Y-Y and the Y-zigzag transformers should be noted. The data in Table I will be considered more fully later in the paper in connection with relay settings.

Relaying the Primary Network

As in any well designed distribution system, the network relay equipment must be adequate to remove faulty sections as quickly as possible and to insure that all other sections shall not be disturbed. Furthermore, it must provide a means of restoring service automatically to the extent that such restoration is feasible. The network relay equipment must be suitable for fault conditions not only on a particular network but also for potential fault conditions that may exist at any time during the growth of the network. It must be sufficiently flexible to be readily adaptable to any particular form the network may take in its future development.

The several fault conditions to be considered are shown in Fig. 7; they may be summarized as follows:

1. Faults on the 4-kv network tie, as at F_1 (or faults on any lateral extension from the tie).
2. Faults on the network unit bus, as at F_2.
3. Faults on the low voltage side of the transformer, as at F_3.
4. Transmission line faults, as at F_4.
5. Internal transformer faults.

Because of the general limitations of network installations, relays for this service must be relatively inexpensive, must occupy a minimum of space, and must require infrequent inspection.

Recommended Network Relays

Before analyzing the various network fault conditions upon which the choice of suitable relays has been based, it seems pertinent to describe briefly the general relay scheme that has been adopted in practice and found to be satisfactory.

All factors being considered, the inverse-time overcurrent relay has been found most desirable for primary tie line and bus protection, i. e., for faults F_1 and F_2 shown in Fig. 7. Common practice is to

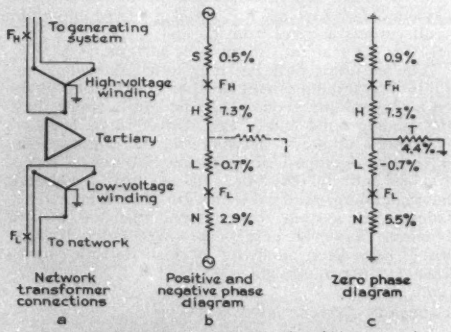


Fig. 5. Impedance constants for Y-Y network transformer and connected system

The above positive, negative, and zero phase reactances may be used in studying fault conditions in a typical primary network having from 5 to 10 units, each having a Y-Y transformer with grounded neutrals. Refer to Table I

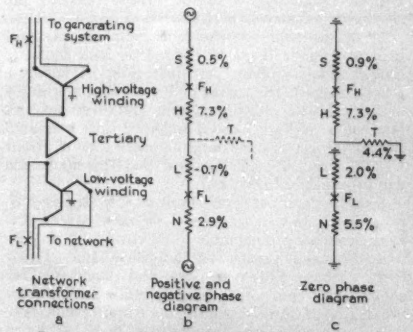


Fig. 6. Impedance constants for Y-zigzag network transformer and connected system

The above positive, negative and zero phase reactances may be used in studying fault conditions in a typical primary network having from 5 to 10 units, each having a Y-zigzag transformer with grounded neutrals. Refer to Table I

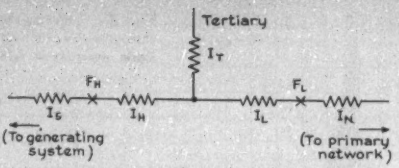


Fig. 7. Elements of a primary network and typical faults

provide a set of inverse-time overcurrent relays to trip each feeder breaker (i. e., breakers *a*, *b*, *c*, or *d* in unit No. 1) in the event of feeder faults. Another set of inverse-time overcurrent relays excited by the transformer current is provided to trip the transformer breaker *e* and all feeder breakers in case of a bus fault, and also to trip all breakers in the event of a failure of feeder protective equipment.

In addition to the time overcurrent relays for feeder faults, instantaneous relays are provided the tripping contacts of which are in parallel with those of the time overcurrent relays. These instantaneous elements are set with a relatively high pick-up and are intended to clear all faults on the network tie line having a magnitude greater than the maximum current that any fault external to the tie lines in question may impose upon it. Since the time overcurrent relays have an extremely inverse characteristic, the combination with the instantaneous element insures unusually rapid isolation of all feeder faults.

In at least one installation bus differential protection has been provided in addition to the overcurrent protection for bus faults. The addition of differential protection is an added factor of safety insuring the rapid removal of bus faults, but it is not considered necessary for reliable network operation.

Transformer and transmission line faults, i. e., all faults such as F_3 and F_4 outside of transformer breaker *e*, are isolated by means of a reverse power relay in conjunction with an overcurrent relay, the tripping contacts of the 2 relays being in series. With this arrangement a reverse power flow of sufficient magnitude through the transformer breaker *e* will trip breaker *e* to isolate any transformer or transmission line fault. In some cases it may be desirable to trip transformer breaker *e* instantaneously for certain faults above a certain magnitude. For this purpose an instantaneous element with adjustable pick-up may be connected to operate in parallel with the time overcurrent relay in the same manner as outlined for the tie line relays.

It should be noted here that the foregoing relay devices are intended to function for ground faults as well as phase faults. If both sides of the network transformer are grounded, which is usually the case, ground fault currents always will be of sufficient magnitude to operate the overcurrent relays. This fact is borne out by actual experience on networks in operation, and also by several network short-circuit studies which the author has made. In some networks it may not be permissible to ground the neutral of the high voltage winding of the transformer. In

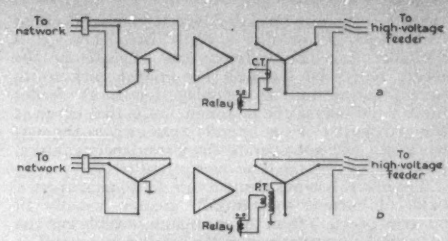


Fig. 8. Selective relaying of high voltage ground faults

a. This scheme is applicable only to transformers having zigzag windings

b. This is the conventional method of obtaining selective ground protection

such cases a potential transformer may be inserted between the neutral and ground to provide excitation for a voltage relay as shown in Fig. 8b. The potential transformer, normally unexcited, will be impressed with "leg" voltage in the event of a ground fault.

If the network transformer happens to have a zigzag winding, which some of them do have, selective ground fault protection may be provided in a very simple manner. In a transformer of this type, ground faults on the high voltage side cannot initiate zero-phase currents in the low voltage winding; and, similarly, ground faults on the low voltage side cannot initiate zero-phase currents in the high voltage winding. Because of this characteristic of transformers having zigzag windings, very selective and sensitive ground fault protection for transmission line faults may be obtained by simply inserting an overcurrent relay in the neutral of the high voltage winding as shown in Fig. 8a. This relay may be instantaneous and may be given an extremely low pick-up. A similar relay might be inserted in the neutral of the low voltage winding for selective relaying of 4-kv ground faults, but this refinement never is necessary.

In order to demonstrate the adequacy of the relay methods outlined, it seems pertinent to consider the details of relaying an actual network. For this purpose the data applying to a typical network and tabulated in Table I will be used. The analysis for both high voltage and low voltage faults is given in the following paragraphs.

Isolating Faults on Network Tie Lines

From the standpoint of selectivity and speed of operation, the tie line faults (or primary feeder faults as they sometimes are called) are of considerable importance and perhaps require more study than all other network faults. Refer again to the network elements shown in Fig. 7. Reliable fault protection requires that a feeder fault such as F_1 must open breakers *a* and *h* as quickly as possible and must fail to open all other breakers. The cycle of operation for fault F_1 is as follows: Circuit breaker *a* opens first, probably instantaneously; this allows the

current to rise in breaker h which is tripped either instantaneously or after a slight time delay. It is desirable that the instantaneous elements of the feeder relays be set with low enough pick-up to permit instantaneous tripping for most feeder faults. Of course the minimum faults that occur at the extremities of the laterals connected to the network ties will not operate the instantaneous relays, but must rely on the time overcurrent relays.

The instantaneous elements are set to pick up on a value of current substantially greater (usually 10 per cent greater) than the maximum possible current that can be drawn through the breaker as a result of any external fault under any probable operating condition. (Note that one probable operating condition is that of a transformer at either end of the faulty section being out of service.) It will be found that this criterion permits practically all faults on the tie line itself to be cleared instantaneously.

For any fault less than the pick-up setting of the instantaneous element, the inverse-time overcurrent element must operate. The time overcurrent relay should have a minimum pick-up corresponding to the minimum fault that can occur on any long lateral tied to the feeder. The time lever setting of this relay must be such that the time required for it to close its contacts when its feeder is faulted must always be at least 0.4 to 0.5 sec less than the corresponding time for any relay on an adjacent feeder under the same fault condition. Since the minimum time differentials occur for the maximum faults, and since the maximum fault for which the time overcurrent element is required to operate is the pick-up current of the instantaneous element, a good conservative criterion for setting the time lever of the time overcurrent relay is that the tripping time for a fault corresponding to the pick-up of the instantaneous element should be at least 0.5 sec faster than the tripping time for a fault of half this value. It is a rare condition in a well designed network for a sound feeder to carry more than 50 per cent of the current in an adjacent faulty feeder.

With the foregoing criteria as a basis, the fault data given in Table I, which is representative of a typical network, may be used in determining typical relay settings. The network elements of Fig. 7 may be used again for reference. Table II has been prepared to show the distribution of currents in the various breakers of Fig. 7 for fault F_1 under several probable operating conditions. The data here is taken directly from Table I, a Y-Y transformer being assumed.

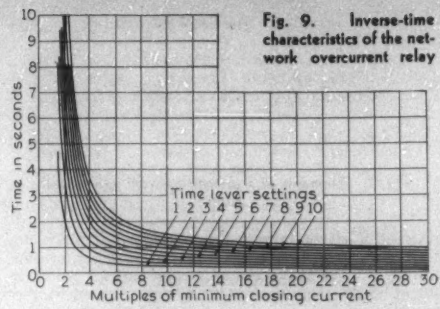


Fig. 9. Inverse-time characteristics of the network overcurrent relay

Fault F_1 draws 39.9 times normal current through breaker a and 8.6 times normal through breaker h (assuming a 3-phase fault with T_1 and T_2 in service); after breaker a opens the current in h increases to 13.4 times normal. These currents are somewhat different for ground faults and for the condition of T_1 or T_2 being out of service. The maximum current that can flow in a sound feeder owing to any external fault condition is 8.7 times normal; therefore, on the basis of the foregoing criterion, the instantaneous elements should be set to pick up on 1.10×8.7 or 9.6 times normal current. With this setting all faults on the feeder itself will be cleared instantaneously except a fault at F_1 with T_2 out of service.

All faults of less than 9.6 times normal must be cleared by means of the time overcurrent relay. It will be assumed here that the minimum possible fault is 4 times normal. The pick-up of the time overcurrent relay should be set somewhat less than this value, say 3 times normal. Refer now to Fig. 9 which shows the very inverse time characteristic of the recommended network relay. Note that a current of 9.6 times normal (which is 3.2 times minimum pick-up) will close the tripping contacts in 0.9 sec (No. 1 time lever setting) whereas half this current requires 3 sec for tripping. Since the differential is much greater than the required 0.5 sec, No. 1 time lever setting may be used with safety.

Isolating Bus Faults

As pointed out previously in this paper, bus faults are isolated by means of an inverse-time overcurrent relay that has exactly the same time characteristics as the feeder relays (but no instantaneous

Table I—Maximum Fault Currents in Average Small-Sized Primary Networks

Type of Faults	Transformer Connection	High-Voltage Faults—F_H						Low-Voltage Faults—F_L					
		I_f	I_s	I_h	I_l	I_n	I_t	I_f	I_s	I_h	I_l	I_n	I_t
3-Phase	Y-Y	210	199.5	10.5	10.5	10.5	0	48.5	14.1	14.1	14.1	34.4	0
	Y-zigzag	210	199.5	10.5	10.5	10.5	0	48.5	14.1	14.1	14.1	34.4	0
Ground	Y-Y	169	158.7	10.5	7.95	7.95	2.52	52.9	14.7	14.7	22.9	30.0	8.24
	Y-zigzag	168	158.4	9.6	5.6	5.6	4.0	53.7	10.4	10.4	23.5	30.2	0

This data applies to an average small-sized network (4 to 10 units) and an average transmission system. All fault currents are given in "times-normal" values (normal current corresponds to 1,500 3-phase kva in this case). For the following symbols, refer to Fig. 4:

I_f = fault current
I_s = transmission line current
I_h = transformer current on high voltage side
I_l = transformer current on low voltage side
I_n = net work current
I_t = transformer tertiary current

element is provided) and that operates to trip the transformer breaker when the transformer current exceeds a predetermined value. In addition to bus protection this relay provides "back-up" for the feeder relays.

Since the bus relay serves as a "back-up" device, it should have the same minimum pick-up setting as the feeder relays. Continuing the foregoing example in reference to Fig. 7 and the fault data in Tables I and II, then, the minimum pick-up of the transformer relay should be set at 3 times normal current.

Inasmuch as the bus relay will operate only on rare occasions, its speed may be sacrificed to a certain degree to insure that false operation will not result in the event of a heavy feeder fault. Furthermore, the bus relay should be set on the basis that the instantaneous elements of the feeder relays may fail to function. It will be stipulated therefore that the transformer relay shall be at least 0.6 sec slower than any feeder relay for the worst possible feeder fault. Refer now to Table II and note that the worst feeder fault is a ground fault that imposes a current on breaker *a* of 45.4 times normal and a current on breaker *e* of 22.9 times normal. For these values of fault currents it may be noted from Fig. 9 that the transformer relay must have a time lever setting of 5 in order to obtain a time differential of 0.6 sec.

Transformer and Transmission Line Faults

As already noted the transformer or transmission line faults are isolated by virtue of the operation of a polyphase power-directional relay and an overcurrent relay to trip the transformer breaker. The tripping contacts of the 2 relays are in series. The overcurrent relay should be set to pick up on all fault currents likely to flow in the transformer or on the high voltage feeder. However, it should be set high enough to insure that false operation will not result from circulating currents.

Refer again to Fig. 7. For a fault such as F_4 the current in transformer breaker *e* may be almost zero before the station breaker opens. After the station breaker opens however, this current will rise to a value varying from 8 to 14 times normal depending on various circuit conditions. The pick-up setting selected for the overcurrent relay will be determined largely by the nature of the transmission line. For the typical network considered in Table I, however, a pick-up setting of 4 times normal would appear to be entirely adequate to clear all high voltage faults. The time lever setting of this relay should be very fast to insure that the feeder breakers shall not be tripped for high voltage faults. An instantaneous element is recommended to be used in parallel with the overcurrent relay to clear heavy faults, such as those occurring at point F_3, as rapidly as possible. Such a relay might be set to pick up at currents of 8 times normal.

Restoration of Service

Closely associated with the protective devices of the primary network equipment are the reclosing features. The recommended reclosing characteristics will be described briefly. Each feeder breaker is equipped with a reclosing and timing relay that may be adjusted to provide 1, 2, or 3 reclosures at predetermined intervals. Automatic reclosure of a feeder breaker is effected only after automatic tripping due to a feeder fault. A circuit interruption for any other cause requires manual resetting of the breaker.

Automatic reclosure of the transformer breaker is effected by means of a voltage reclosing relay. This relay operates to reclose the transformer breaker only after it has been tripped by the action of the reverse power relay and provided 3-phase voltage of the correct phase rotation exists on the transmission feeder.

When the transformer overcurrent relay operates from any cause whatever, all 5 network breakers are tripped and locked out and must be reset manually.

Special Operating Conditions

Occasionally some one presents a special operating condition that appears to offer some difficulty to the satisfactory relaying of a network. For example, the question of relaying an isolated transmission feeder or of relaying high voltage ground faults of extremely low magnitude frequently is brought up. Again, the question of relaying transmission feeders when rapid breaker reclosures are required is debated. The author has studied these and several other special operating problems, and in no case has he been able to find any difficulty that cannot be remedied satisfactorily in a fairly simple and inexpensive manner.

Table II—Distribution of Fault Currents in the Various Breakers Shown in Fig. 7, for a Fault at F_1

Types of Faults	Breakers	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*
3-Phase		39.9	8.6	8.6	8.6	14.1	1.9	1.9	8.6	1.9	3.0
	a open	0					2.9	2.9	13.4	2.9	4.7
	e open	26.1	8.7	8.7	8.7	0	1.9	1.9	8.7	1.9	3.1
	e and *a* open	0				0	2.8	2.8	13.1	2.8	4.7
	f open	39.9	8.6	8.6	8.6	14.1	2.0	2.0	8.0	2.0	0
	f and *a* open	0					3.0	3.0	9.0	3.0	0
Ground		45.4	7.5	7.5	7.5	22.9	1.2	1.2	7.5	1.2	3.8
	a open	0					2.3	2.3	13.9	2.3	7.0
	e open	23.4	7.8	7.8	7.8		1.3	1.3	7.8	1.3	3.9
	e and *a* open	0				0	2.2	2.2	13.6	2.2	7.0
	f open	45.4	7.5	7.5	7.5	22.9	1.3	1.3	3.9	1.3	0
	a and *f* open	0					2.4	2.4	7.2	2.4	0

Network constants and fault conditions corresponding to the fault data on a typical network as shown in Table I were assumed in preparing this table (this case being for a Y-Y transformer). The above currents are given in "times-normal" values for various operating conditions.

The Theory of Incremental Rates and Their Practical Application to Load Division—Part I

By
M. J. STEINBERG
MEMBER A.I.E.E.

THEODORE H. SMITH
NONMEMBER

Both of the Brooklyn Edison Co., Brooklyn, N. Y

The calculation of the most economical division of load between generating units and power plants is of considerable importance on large inter-connected systems. The most complete analysis of the subject of load division published to date is contained in the present paper, which shows that the method of incremental rates gives the division of load which is the most economical. Both the basic theory and the practical application of the method are contained in this paper. An outline is given in the accompanying table of contents.

Table of Contents—Part I

	Page
Introduction	432
Theoretical Background	433
Incremental Rates	433
Conditions for Maximum Efficiency	434
Effect of Decreasing Incremental Rates	434
Characteristics of Input-Output Curves	435
Discontinuous Input-Output Curves	436
Use of Approximate Input-Output Curves	436
Application to the Boiler Room	436
Methods of Load Division	436
Boiler Performance Data	437
Boiler Efficiency Curve	437
Maximum and Minimum Steaming Rates	438
Banked Boilers	438
Boiler Room Incremental Rates With All Boilers Steaming	440
Incremental Rate in Banked Region	440
Effect of Coal Cost	441
Application to the Turbine Room	441
Methods of Turbine Load Division	442
Turbine Performance Data	442
Turbine Heat Rate and Incremental Rate Curves	443
Sequence of Adding Turbine-Generators	444
Appendix A	
Derivation of Conditions for Maximum Efficiency	445
Part II (Scheduled for publication in the April issue)	
Application to the Generating Station	
Corrections to Station Performance	
Steam Auxiliaries	
Electric Auxiliaries	
House Transformers	
House Generators	
House Turbine-Generators, Noncondensing Type	
House Turbine-Generators, Condensing Type	
Superheat and Feedwater Temperature	
Superheat Correction, Feedwater Temperature Constant	
Superheat Correction, Feedwater Temperature Variable	
Boilers Without Economizers	
Economizers on All Boilers	
Some Boilers With Economizers, Some Without	
Seasonal Variation in Vacuum	
Heating and Process Steam	
Maintenance	
Computation of Station Performance	
Approximate Method of Calculating Station Performance	
Load Division Between Generating Stations	
Conclusion	
Appendix B	
Proof That Independent Loading of Boilers and Turbines Incrementally Will Result in Maximum Station Efficiency	
Effect of Steam Tie Line of Limited Capacity on Above	
Appendix C	
Derivation of Equation for Station Incremental Rate in Terms of Incremental Rates of Boilers, Turbine-Generators and Auxiliaries	
Appendix D	
Derivation of Equation for Load Division Between Stations Joined by a Transmission Line	
References	

Part I of a paper recommended for publication by the A.I.E.E. committee on power generation. Manuscript submitted July 11, 1933; released for publication Sept. 7, 1933. *Not published in pamphlet form.*

Introduction

THE INCREASING number of interconnections between large generating stations in recent years has necessitated the discarding of methods of calculating load division which do not result in the most economical generation, and the acceptance of the incremental rate method instead. Although much has been written on the subject of load division, a review of the literature shows that there is a need for a comprehensive discussion on the theory and nature of incremental rates and their practical application. It is hoped that this paper will supply that need.

The failure to understand fundamentals often results in the incorrect application of incremental rates. Two specific cases will suffice to illustrate. *First*, the failure to recognize the conditions under which equal loading of identical turbine-generators will not result in maximum combined economy. *Second*, the failure to realize that for machines with mathematically discontinuous performance curves, incremental rates alone may not be sufficient to determine the proper load division.

In addition to the theoretical aspects of the subject, there is the practical side to be considered. The calculation of the performance curves which constitute the basis of incremental loading, may be too laborious or even impossible for a complete, academically correct solution. Approximate methods which must therefore be resorted to, are suggested in this paper and should be helpful to

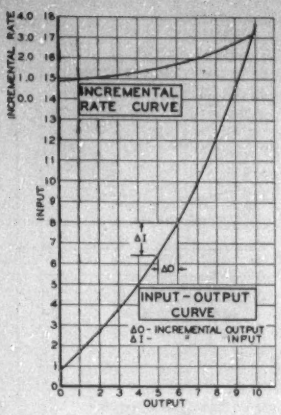


Fig. 1 Derivation of incremental rate curve from input-output curve

those engaged in such calculations. The factors which require consideration and methods of correlating them are discussed in detail.

Although the wide scope of the subject has made it necessary to limit the discussion of some phases, an effort has nevertheless been made to present a complete picture of the problem by always indicating at least the principles involved.

Theoretical Background

When 2 or more machines or groups of machines are operated in parallel, the combined efficiency of operation is affected by the division of the total output among the machines. It will subsequently be shown that the maximum combined efficiency is usually obtained when the machines are operated at outputs corresponding to equal incremental rates. This establishes a definite relation between the total output and the outputs of the individual machines. In order to determine this relation, it is necessary to know, for each machine, the relation between the output and the corresponding input. This is defined by the conventional efficiency curve or by the more fundamental input-output curve. For expediency in computing incremental rates, the use of the latter is preferable.

Incremental Rates

The incremental rate at any given output is the slope of the input-output curve at the point corresponding to that output. The slope of the input-output curve, and hence the incremental rate, measures the *rate of increase* of the input and should not be confused with the absolute value of the input.

The incremental rate may be derived by one of the following methods:

1. When the input-output curve can be expressed by an algebraic equation, the incremental rate can be derived by differentiation, since it is the first derivative of the equation for the input-output curve.

2. A tangent may be drawn to the input-output curve at the point corresponding to the output. The slope of the tangent is the incremental rate at the given output.

3. In actual practice the slope is usually determined graphically by an approximate method. The input-output curve is drawn, a series of output values are chosen and the corresponding input values are read. The differences between successive values of the output are usually made constant and are made small enough to insure that the characteristic of the incremental rate is accurately determined. The latter is merely the ratio of the input difference to the output difference, and is assumed to be a function of the mid-point. The output and input differences are termed respectively, incremental output and incremental input. This method is illustrated in Fig. 1 and Table I.

The physical significance of the incremental rate can best be illustrated by the following example. Consider 2 boilers supplying a common load and operating at equal outputs with incremental rates and efficiencies as shown below.

	Boiler A	Boiler B
Boiler output, million Btu per hour	10	10
Incremental rate	1.42	1.33
Boiler efficiency, per cent	80	70

If it were necessary to increase the total output by one million Btu per hour, then the additional output should be supplied by boiler B, notwithstanding the fact that boiler A is more efficient. The criterion is not the relative boiler efficiencies but the relative efficiencies of generating the *additional* or *incremental outputs*. Thus the incremental inputs for the additional output would be 1.42 and 1.33 million Btu per hour, respectively, for boilers A and B. The efficiency of generating the additional output would be $\frac{1 \times 100}{1.42} = 70.42$ per cent for boiler A and $\frac{1 \times 100}{1.33} = 75.19$ per cent for boiler B.

Thus it is the *efficiencies of generation* of the *incremental outputs* or the *incremental efficiencies* which should determine the division of load be-

Table I—Calculation of Incremental Rate Curve From Input-Output Curve

Output	Incremental Output	Input	Incremental Input	Incremental Rate	Output Against Which Incremental Rate Is Plotted
0		0.8			
	1.0		0.9	0.9	0.5
1		1.7			
	1.0		1.0	1.0	1.5
2		2.7			
	1.0		1.1	1.1	2.5
3		3.8			
	1.0		1.2	1.2	3.5
4		5.0			
	1.0		1.4	1.4	4.5
5		6.4			
	1.0		1.6	1.6	5.5
6		8.0			
	1.0		1.9	1.9	6.5
7		9.9			
	1.0		2.2	2.2	7.5
8		12.1			
	1.0		2.5	2.5	8.5
9		14.6			
	1.0		3.0	3.0	9.5
10		17.6			

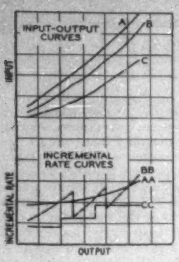


Fig. 2. Types of input-output and corresponding incremental rate curves

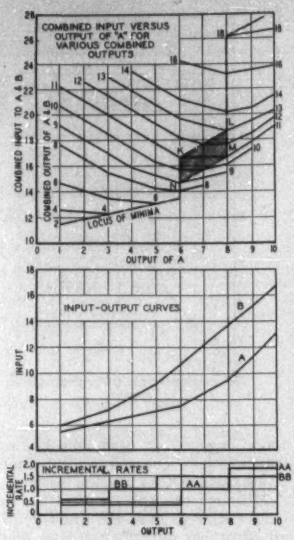


Fig. 3. Load division between 2 units having discontinuous incremental rates but no decreasing values

tween machines, and not their respective absolute efficiencies.

Since the incremental rate was defined as the ratio of incremental input to incremental output, the incremental efficiency expressed as a decimal becomes the reciprocal of the incremental rate.

Conditions for Maximum Efficiency

In Appendix A is a mathematical analysis establishing the conditions for maximum overall efficiency when 2 units of different characteristics are operating in parallel to supply a common load.

The minimum input (subject to the conditions laid down in the subsequent section) for the given combined output is obtained when the incremental rates of the 2 units are equal. Furthermore, there is only one pair of loads for any given output at which the incremental rates will be equal.

Many input-output curves are found to be continuous, but to have discontinuous incremental rate curves. If it happens that, as in the case of curve *C* Fig. 2, the slope or incremental rate of the curve changes suddenly at certain points, yet *never decreases as the output increases*, the incremental rate may be used as simply as if it were everywhere continuous. It is only necessary to consider that *at the point of discontinuity* (where the incremental rate has a step-like increase), the incremental rate takes all the values between the lower and upper limits. There will be only one pair of loads at any given total output for which the input will be a minimum, excepting the case where units have ranges in which the incremental rates are equal as well as constant. For such a condition there will be many combinations for any total output within the given range, for which the input will be constant. This will be the lowest obtainable combined input.

An illustration of the effect of varying load division on the combined input of 2 machines is shown in Fig. 3. Machines *A* and *B* have continuous input-output curves consisting of portions of intersecting straight lines. Their incremental rate curves, *AA* and *BB* are discontinuous and consist of successive horizontal straight lines; the incremental rates have ranges in which they are equal and constant. The curve net shows, for various constant values of the combined output, the combined input plotted as a function of the load on machine *A*. The locus of the minimum points is shown. It is an inclined or vertical straight line everywhere except for combined loads between the values of 9 and 13, for which it becomes a plane area included in the parallelogram *K-L-M-N*. For any combined load in that range, there is an indefinite number of pairs of loads which will give the same minimum total input. This can be seen by examining the curve for a total of 11. Any load on *A* between 6 and 8 will give 16.7 for the combined input.

The incremental rates of 2 units of different type or capacity will often be unequal at minimum loads, in which case there will be a range of total output during which the incremental rates cannot be kept the same. If 2 units are at minimum output it is naturally best to take additional load on the one with the lower incremental rate until the point is reached at which the incremental rates are equal. From then on, the 2 units should be loaded to keep the incremental rates equal until the maximum output of one unit is reached.

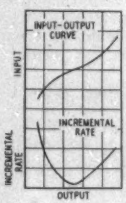
Effect of Decreasing Incremental Rates

It has been assumed heretofore that the incremental rate is always constant or increasing as the load on a unit increases. When this is true, the point at which the incremental rates of 2 units are equal always corresponds to a minimum input; and for any total output there can be only one pair of unit loads for which the incremental rates are equal, with the exception discussed above.

If one unit has a range through which the incremental rate decreases as load increases, for any total load there may be 2 or more pairs of unit loads

at which the incremental rates are equal. Any of these may correspond to a minimum, a maximum, or a point of inflection according to whether the sum of the *slopes* of the *incremental rates* (hence the sum of the second derivatives of the input-output curves) is respectively positive, negative, or zero. Thus there may be no mathematical minimum in the range of possible operation, or there may be more than one, in which case computation of both may be necessary to pick the correct one. Furthermore, when there are one or more mathematical minima there may yet be a pair of loads—the minimum or maximum load on one machine will be one of them—for which the total input is less than at the mathematical minimum.

There are several classes of curves which have this ambiguity. A curve may be smooth and have a point of inflection of curvature, such as is illustrated in Fig. 4. Its incremental rate curve is continuous and has a mathematical minimum. In Fig. 5 is shown a curve which is continuous but has a discontinuous incremental rate. Over any region in which the incremental rate is continuous, it is also increasing with the output. In passing through the points of discontinuity, the incremental rate decreases greatly resulting in a saw-tooth appearance.



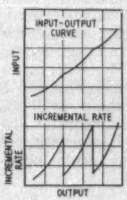


Fig. 4 (left). Input-output curve having point of inflection, and corresponding incremental rate curve

Fig. 5 (right). A continuous input-output curve having a discontinuous incremental rate curve

The problems encountered in determining the correct load division when one of the input-output curves has the characteristics as shown in Fig. 4, are illustrated in Fig. 6. Input-output curve A is continuous and has a continuous incremental rate (curve AA) which always increases. Input-output curve B is continuous but has a point of inflection of curvature. Its incremental rate (curve BB) is continuous, decreasing to a mathematical minimum and then increasing. The family of curves show the combined input for all possible load divisions for various values of combined output. Each curve of this family represents a constant value of combined output and shows the combined input plotted against the output of machine A. It is evident from inspection that some of these curves have mathematical minima, some have minima and maxima and some have neither. The loci of *mathematical* minima and maxima are shown, as well as the locus of the *actual* minima. It will be noted that the loci of actual and mathematical minima coincide only for combined outputs exceeding 69. For combined outputs below that value, the actual minima are obtained when machine B is operated at minimum output even though by so doing the machines are not operating at equal incremental rates.

Characteristics of Input-Output Curves

It is well to note at this time that the analysis of Appendix A is based on 3 assumptions, namely:

1. **That the input-output curves are continuous.**
2. **That the derivative or incremental rate curves are continuous.**
3. **That the value of incremental rate always increases as the output increases.**

In many cases the input-output curves representative of power plant equipment do not fulfill the above conditions, and hence it is important to study the types of curves that may occur in actual practice and their effect on load division. The input-output curves which are important in power plant computation can be divided into 2 classes, namely, continuous curves and discontinuous curves. The distinguishing characteristic is the fact that at certain parts of the discontinuous curve there is a sudden increase or decrease in the input with no change in output.

Continuous curves may be further subdivided into those which consist of *one* smooth curve (see curve A, Fig. 2) and those which are formed from 2 or more *intersecting* smooth curves. (See curves B and C, Fig. 2.) The input-output curve for a single boiler is an example of the former, while those of most turbines are of the latter class. It can be seen that

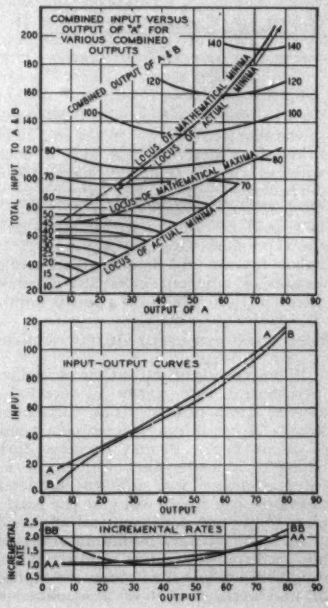


Fig. 6. Load division between 2 units having continuous incremental rates, one with and the other without decreasing values

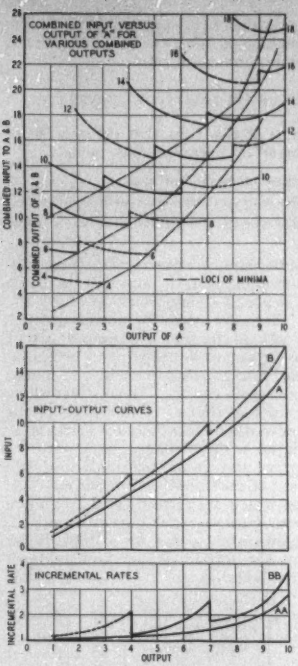


Fig. 7. Load division between 2 units, one having a continuous incremental rate curve with no decreasing values, the other having a discontinuous incremental rate curve with decreasing values

the distinguishing feature of these curves is the shape of the first derivative. In the case of curve A of Fig. 2 the first derivative is also a continuous curve whereas curves B and C have discontinuous first derivatives. Curves AA, BB, and CC of Fig. 2 show the first derivatives of curves A, B, and C, respectively. It should be noted that for input-output curves of the type shown by curves B and C, there will be 2 values for the first derivative, at any point of intersection of adjacent intervals, depending upon the direction from which the point is approached.

Discontinuous Input-Output Curves

When the input-output curve is discontinuous, its incremental rate curve is usually discontinuous at the same points. The incremental rate may always increase, may decrease in passing the points of discontinuity, or may decrease during a range in which it is continuous. In any case, incremental rates alone are not sufficient to determine the division of load which will give the least input. There may be several mathematical minima to be investigated. The actual minimum combined input may not correspond to a pair of loads having equal incremental rates, but it will then correspond to minimum or maximum output of a machine, or to a point of discontinuity in one of the input-output curves.

In Fig. 7 is shown 2 input-output curves, one of which is discontinuous and has an incremental rate curve which is discontinuous at the same points. The other input-output curve and its incremental rate are continuous. The curve net is similar to those of Figs. 3 and 6. Loci of the points of minimum input corresponding to operation in each of the 3 continuous ranges of curve B, are shown. The actual minimum combined input may be on any of the 3 loci.

Use of Approximate Input-Output Curves

As is evident from the discussion thus far, the general rule that the total input will be a minimum when 2 or more machines in parallel operate at outputs corresponding to equal incremental rate values, is invariably true only for those types of input-output curves which are continuous and whose respective incremental rates have no decreasing values with increase in output. If these conditions do not exist, incremental rates alone are not sufficient to determine the load division for most efficient operation. Hence, in order to simplify computations wherever it is possible to do so without introducing serious deviation from the actual operating characteristics of the equipment, input-output curves which are discontinuous or whose incremental rates decrease with increasing load, should be replaced by continuous curves with never-decreasing incremental rates.

The manner by which this can be done without introducing more than a negligible error will be indicated in the subsequent discussion relating to the application of incremental rates to the equipment of the boiler and turbine rooms.

Application to the Boiler Room

Methods of Load Division

There are 3 methods commonly used in dividing load among boilers. These are:

1. Division of load among the boilers such that each one is steaming at the same percentage of its rated boiler horsepower even though they may have radically different maximum capacities and performance characteristics.

2. Division of load among the boilers such that their efficiencies are equal.

3. Division of load among the boilers such that they operate at equal incremental rates.

It has been shown above that the fundamentally correct method of load division is the one based upon equal incremental rates.

In Fig. 8 are shown the combined efficiencies, and in Fig. 9 the loading curves, resulting from the division of load by each of the 3 methods, between 2 boilers of different size and performance characteristics.

The performance curves for these boilers are shown in Fig. 10 and Fig. 11. Under the method of loading by equal per cent ratings, both boilers are loaded simultaneously until boiler A reaches maxi-

mum output. This range corresponds to the portion of the curve marked 1–2 in Fig. 8 and Fig. 9; between points 2 and 3 boiler *A* operates at maximum capacity while boiler *B* supplies the remainder of the load. By the equal efficiency method, boiler *A* is held at minimum output while boiler *B* picks up the additional load until its efficiency is reduced to that of boiler *A*. This is represented by the portion of the curve between points 1 and 5. From point 5 the boilers are loaded simultaneously until boiler *B* reaches its maximum output at point 6. From 6 to 3 boiler *A* takes the additional load. By the incremental rate method, boiler *A* remains at minimum output while boiler *B* picks up the additional load until at point 4 its incremental rate is equal to that of boiler *A*. In the range from point 4 to point 7 the boilers have equal incremental rates; from point 7, at which boiler *A* reaches maximum, to point 3, boiler *B* takes all the additional load.

The curves in Fig. 8 show that at no time is the combined efficiency based upon incremental rate loading exceeded by the efficiency obtained by either of the other methods. In the range of output indicated between points 1 and 4 the boilers cannot be operated at outputs corresponding either to equal incremental rates or equal efficiencies. Similarly, in the range between points 7 and 3 neither the per cent ratings nor the incremental rates corresponding to the respective outputs can be equal. This explains the coincidence of the curves in those ranges.

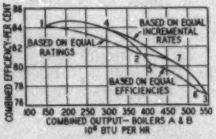


Fig. 8 (left). The combined efficiency of 2 boilers for 3 methods of load division

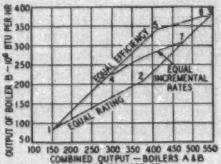


Fig. 9 (right). Effect of method of load division on the loading of a boiler

In Fig. 8 it is shown that considerable economy is obtained by using the incremental rate method in preference to either of the others.

Boiler Performance Data

In order to apply incremental rates to the operation of a boiler room it is necessary to have performance data for each type of boiler. The efficiency, steam temperature, and feedwater temperature curves, and the maximum and minimum steaming rates should be determined. In addition, whenever it is possible, the consumption curves of steam and electric auxiliaries for each type of boiler should be obtained.

Boiler Efficiency Curve

Boiler efficiency curves are usually obtained from tests. It is desirable, however, that the boiler efficiency used in load division shall represent normal operating conditions, and since tests are generally conducted under conditions most favorable to the boiler, some adjustment is usually necessary. Under normal operating conditions the boiler will become dirty, settings will become leaky, fuel bed conditions will not be watched so closely as on a test because an attendant will usually have to operate more than one boiler, and will not have the benefit of continuous flue gas analysis.

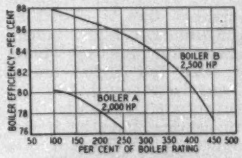
There are 2 practical methods which can be used to determine the relation between boiler efficiencies under test and operating conditions:

1. Since a boiler is usually cleaned thoroughly at periodic intervals, a simple test conducted after the boiler has been in operation for half the usual period between cleanings, will give the average operating performance. The boiler should be operated by the attendants normally assigned to it, without giving it special attention. Constant load should be maintained and sufficient readings taken to determine the efficiency.

2. By comparing the average boiler efficiency obtained over a given period of operation, with the "bogey" average efficiency derived by integrating the test values over a boiler load duration curve for the period. The load duration curve can be easily prepared if the boiler is equipped with reliable steam or feedwater meters. Steam pressures and temperatures, feedwater temperatures, and the calorific value and quantity of coal burned would be needed. The period selected should be in the middle of the interval between cleanings.

The second method is not so desirable as the first because: (a) It may be difficult to determine a reliable value of the actual average efficiency. (b) A single correction factor must be applied over the entire range of boiler output, whereas it is probable that the correction factor varies with the boiler output. (c) Losses caused by load fluctuations should not influence boiler load division; this method includes these losses and thereby may result in too high an operating factor.

The application of the second method and a comparison of both methods are shown in Table II and Fig. 12. Curve *A* shows the efficiency under test conditions, curve *B* the operating efficiency under normal conditions determined by applying a constant



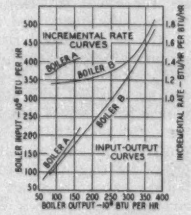


Fig. 10 (left). Efficiency curves of boilers A and B plotted against output in per cent of boiler rating

Fig. 11 (right). Performance curves of boilers A and B plotted against output in heat units

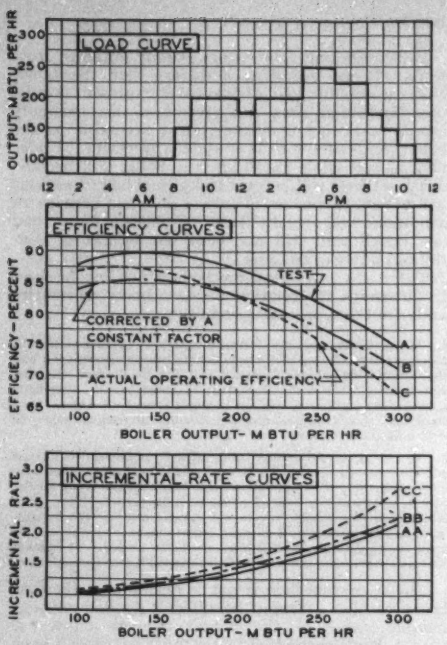


Fig. 12. Determination of operating boiler efficiency from test efficiency using a constant and a variable factor

M Btu indicates million Btu

factor to the test efficiency, and curve *C* shows the actual operating efficiency determined by test as outlined in method 1. Curves *AA*, *BB*, and *CC* show the corresponding boiler incremental rates.

In addition to applying an operating factor, it may be desirable to correct the test efficiency curve for the effect of steam temperature variation on turbine efficiency, and for the power consumption of the boiler auxiliaries. The fact that turbine economy increases considerably with increased steam temperature makes it apparent that if a turbine can be supplied with steam from either of 2 boilers which have equal efficiencies but different steam temperatures, the boiler with the higher steam temperature will require less heat input than the other, for a given turbine output. Similarly, if 2 boilers have the same efficiencies, but the power consumptions of their auxiliaries are different, the boiler with the lower power consumption will have the higher net efficiency.

Since the boiler and turbine performance corrections for any station are so intimately related, the detailed analysis will not be included here, but will be treated in the discussion of station performance.

Maximum and Minimum Steaming Rates

The determination of the maximum steaming rate of an individual boiler presents no difficult problem since a maximum capacity run is usually made during the boiler test. When a group of boilers are served by the same fan equipment or stack, the capacity of this equipment may not permit all of the boilers to be operated at their maximum individual steaming rates. Furthermore, high superheat, increased maintenance costs, or combustion conditions such as excessive carbon monoxide loss or smoke, may limit the operating maximum.

The minimum steaming rate at which a stoker-fired boiler will be operated before being banked will depend upon the practice at any particular station. The more important of the factors which usually determine the minimum steaming rate are the ability to maintain fuel bed conditions, the efficiency, and the responsiveness to sudden demands which may be made upon the boilers while operating at such a low rate. For pulverized coal boilers the minimum rate of operation will usually depend upon the minimum capacity of each burner and whether or not some of the burners can be cut out.

Banked Boilers

During the daily load cycle of most steam generating stations, there is a period in which some boilers are banked. This may be done to eliminate the necessity of operating boilers below their minimum steaming rates or to increase the over-all boiler room efficiency. A study should be made to determine what boilers to bank and when.

The term banking as used in this discussion means the operation of a boiler with no steam output. For stoker-fired boilers, the banking loss is the amount of heat input necessary to maintain the fuel

Table II—Derivation of Correction Factor for Adjusting Boiler Test Efficiency to Operating Conditions

Time	Duration Hours	Output, Million Btu Per Hour	Output, Million Btu Total	Test Eff. Per Cent	Bogey Input, Million Btu
12–8 a.m.	8	100	800	88.1	908.1
8–9	1	150	150	90.0	166.7
9–12	3	200	600	87.3	687.3
12–1 p.m.	1	175	175	89.0	196.6
1–4	3	200	600	87.3	687.3
4–6	2	250	500	82.0	609.9
6–8	2	225	450	85.0	529.4
8–9	1	175	175	89.0	196.6
9–10	1	150	150	90.0	166.7
10–11	1	125	135	89.7	139.4
11–12	1	100	100	88.1	113.5
Totals	24		3,825		4,401.5

Bogey overall efficiency $= \frac{3,825}{4,401.5} \times 100 = 86.9$ per cent

Total coal actually burned, 24 hr, 327,560 lb

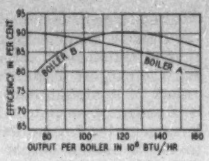
Btu per pound of coal, 14,100

Actual boiler input, 24 hr, 4,618.6 million Btu

Actual efficiency, 24 hr $= \frac{3,825}{4,618.6} \times 100 = 82.8$ per cent

Correction factor $= \frac{82.8}{86.9} = 0.953$

Fig. 13. Efficiency curves used to illustrate boiler banking sequence



bed in a satisfactory condition. For pulverized-coal boilers the total banking loss is the heat input required either to maintain or to restore the boiler setting to its normal operating temperatures when the boiler starts steaming; the average hourly banking loss is then the total loss divided by the duration of the banked period.

Two types of boiler efficiency curves which are important in determining banking practice are illustrated in Fig. 13. The highest efficiency for type *A* boiler occurs at the minimum steaming rate, whereas for type *B* boiler, this occurs at a steaming rate greater than the minimum.

When all of the boilers are identical and have the characteristics of type *A* of Fig. 13, as many boilers should be kept steaming at all station loads as can be operated at or above the minimum rate. The total loads, therefore, at which boilers should be banked are multiples of the minimum steaming rate of a single boiler.

Consider next a group of boilers which are identical, and have the characteristics of type *B* of Fig. 13. The proper loads at which to bank such boilers should be determined by the points of intersection of the over-all efficiency curves for successive combinations of steaming and banked boilers.

In Figs. 14 and 15 are shown the over-all efficiency and input-output curves in the banked boiler region for groups of each type of boiler. The solid lines indicate performance under proper operation. It will be noted that in the case of the type *A* boilers, both the input-output and efficiency curves are discontinuous at the points at which boilers are banked. For type *B* boilers, the input-output and efficiency curves are continuous, because as a boiler is banked the increase in banking loss is exactly neutralized by the decreased input to the steaming boilers resulting from their operation at a higher efficiency.

When groups of boilers operated in parallel differ in size and performance characteristics, it will be necessary to determine not only when to bank boilers, but which ones to bank to give the maximum efficiency. Often there is some operating reason for banking certain boilers in preference to others; if not, the various combinations should be computed to determine which gives the best results. The

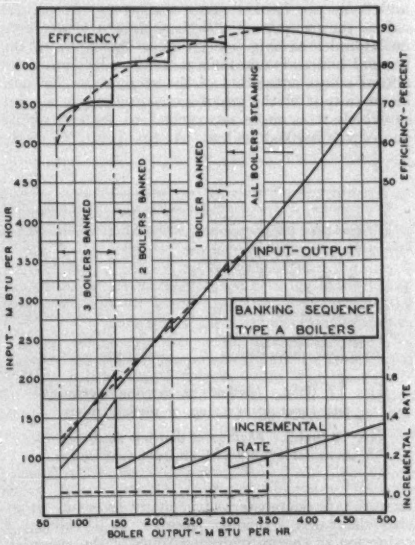


Fig. 14. Banking sequence of boilers with maximum efficiency at minimum output (Type A)

Method of determining average incremental rate curve for banking period
M Btu indicates million Btu

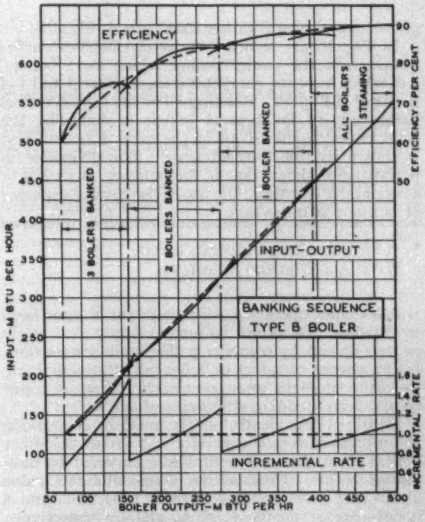


Fig. 15. Banking sequence of boilers with maximum efficiency at an output greater than minimum (Type B)

Method of determining average incremental rate curve for banking period

factors that determine which type of boiler to bank are the relative banking losses, the relative magnitudes and shapes of the efficiency curves, and the number of boilers of each type. It may be stated that, if the size, maximum efficiency, minimum steaming rate, and banked loss of each type of boiler are substantially the same, it will usually be more efficient to bank boilers whose efficiency

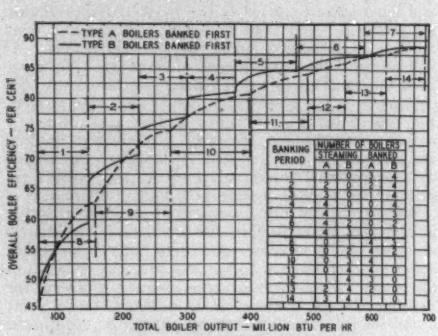


Fig. 16. Effect of boiler banking sequence on overall boiler efficiency

curves are of type B rather than type A, Fig. 13.

In Fig. 16 are shown 2 series of efficiency curves obtained in the banked boiler region for 8 boilers, 4 of which have the characteristics of boiler A and 4 of boiler B of Fig. 13. Banking all of the type B boilers before any of the type A boilers is shown by the solid curve; banking all of the type A boilers first is shown by the dotted curve. The difference in performance shows that if the banking period is of considerable duration, the use of the correct sequence of banking is important.

Boiler Room Incremental Rate With All Boilers Steaming

After the operating efficiency curve has been established, the boiler incremental rate can easily be determined by computing the inputs corresponding to a series of values of boiler output and dividing the differences between successive values of input by the corresponding differences of output.

In Fig. 17 is illustrated the method of deriving the incremental rate curve for any group of similar boilers from the incremental rate curve of an individual boiler. Thus, at an incremental rate value of 1.5, the corresponding outputs for 1, 2, 3, and 4 boilers are at points A, B, C, and D, respectively. The outputs at points B, C, and D are multiples of the output for one boiler at point A depending upon the number of boilers in the group. By repeating the process for other values of incremental rate, sufficient points are obtained for plotting the curves.

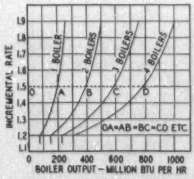
When boilers or groups of boilers are dissimilar, the over-all incremental rate curve for any combination is obtained in the manner shown in Fig. 18. For the purpose of illustration, boilers with different values of minimum output are shown. Since there is a range of output of boiler B during which the incremental rates are less than that corresponding to the minimum output of boiler A, boiler B will first be loaded until its output corresponds to the minimum incremental rate value of boiler A, namely, 1.20. The incremental rate curve for the combination of boilers has, therefore, the same values as the curve for boiler B during the range in which only boiler B is loaded. That portion of the combined curve between points 1 and 2 is obtained by adding the minimum output of boiler A to that of boiler B and plotting the total output against the value of incremental rate corresponding to the output of boiler B.

In the range between points 2 and 3 both boilers are loaded incrementally. Thus the output at point 7 is the sum of the outputs at points 5 and 6.

After boiler B reaches its maximum output, any additional load is supplied by boiler A. That portion of the curve between points 3 and 4 has incremental rate values equal to those for boiler A.

Incremental Rate in Banked Region

If, in a group of similar boilers, some are steaming and some are banked, then the *actual* incremental rate of the group is equal to the incremental rate of an individual steaming boiler; since the input to the banked boilers is constant, it has no effect upon the actual incremental rate of the group. As the combined output of the group increases there is a point at which it is more economical to start steaming one of the banked boilers. At this point the incre-



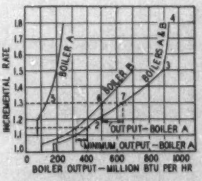


Fig. 17 (left). Method of deriving incremental rate curve for a group of similar boilers

Fig. 18 (right). Method of deriving combined incremental rate curve for dissimilar type boilers

mental rate decreases and in many cases the input also decreases. Adding another boiler allows a reduction in the individual outputs of the steaming boilers and hence a reduction in the incremental rate; if there is a decrease in total input it is because the reduction in input to the group of steaming boilers is greater than any increase in the input to the boiler brought up from bank.

Since it is desirable that the incremental rate of the group shall never decrease as the output increases, a modification of the input-output curve during the banked region should be made. An average curve should be drawn, having an incremental rate curve which never decreases. In Fig. 14 and Fig. 15 are shown the actual and average input-output curves with the corresponding efficiency and incremental rate curves for the 2 types of boilers of Fig. 13. It will be noted that in Fig. 14 the incremental rate curve corresponding to the *average* input-output curve is much lower than the actual incremental rate curve during the banked boiler period.

From the input-output curve of Fig. 14, consider the conditions when a single boiler, and again when all the boilers are operating at minimum output. These are indicated in the following tabulation:

Number of steaming boilers	1	4
Number of banked boilers	3	0
Minimum output, million Btu per hour	75	300
Input at minimum output, million Btu per hour	112.5	342.5
Incremental input, million Btu per hour	230	
Incremental output, million Btu per hour	225	
Incremental rate (230 ÷ 225)	1.02	

It is seen from the above that as the total output is increased from that of minimum to a value which permits the steaming of all boilers at a minimum, the change in input is 1.02 times the change in output. This value represents the *average* incremental rate for the transition period during which boilers are taken off bank. It is now obvious that an average drawn through the discontinuous actual incremental rate curve would be undesirable for the reasons that there would be decreasing values of incremental rate with increased output and that such an average would not be representative of actual operation during the period when boilers are taken off bank.

In drawing an average through the discontinuous portion of the input-output curve, a straight line was used having a slope or incremental rate of 1.02.

In Fig. 15, also, the average incremental rate was obtained from the average drawn through the input-output curve. In this case, the average incremental rate approximates an average line drawn through the discontinuous portion of the incremental rate curve.

When there are 2 or more dissimilar groups of boilers, the banking sequence should be determined to give the highest efficiency. An average input-output curve should then be drawn in the banked boiler range and the corresponding incremental rate computed.

The number of boilers available in a station usually varies from time to time. Since this affects both the incremental rate and efficiency, for any given boiler room output, curves should be computed for those combinations which are likely to occur.

Effect of Coal Cost

If the cost of fuel burned is the same for all boilers, operation of the boiler room to give the minimum heat input also makes the cost of fuel a minimum. In such a case it is sufficient to express the values of input and output in Btu per hour.

When all the boilers do not use the same type or grade of fuel, there usually is a difference in the cost of the fuel per Btu. In such a case, load division which gives the minimum heat input does not result in minimum cost of fuel.

Instead of an input-output curve expressed in Btu per hour, an input-output curve whose input is expressed as fuel cost in dollars per hour can be used. The corresponding incremental fuel cost curve can then be expressed as (cents per hour) per (million Btu per hr), and the boilers be loaded so as to keep their respective incremental fuel costs the same.

In practice it is more simple to adjust the boiler incremental rate curves for difference in coal cost than to convert the input-output curves. Consider 2 boilers which burn different grades of coal having the following costs:

Boiler	*A*	*B*
Cost of coal per short ton	$3.60	$4.25
Btu per pound of coal	13,000	14,000
Cost of coal per million Btu	13.85	15.18

Since the coal burned by boiler *A* is cheaper than that burned by boiler *B*, adjustment can be made by multiplying the incremental rate values of boiler *A* by the ratio $\frac{13.85}{15.18} = 0.912$ or those of boiler *B* by the ratio $\frac{15.18}{13.85} = 1.096$.

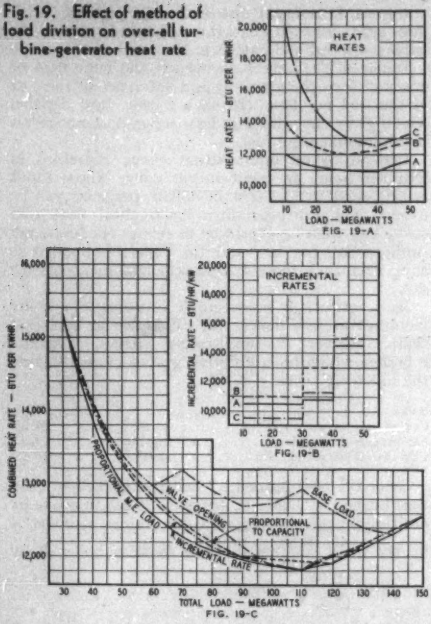
Application to the Turbine Room

Use of incremental rates in scheduling turbine room operation is more complex than in the boiler room. There is a much wider choice as to the number of units to be run and the sequence of adding units as the load increases. Whereas the number of boilers in service is usually determined by the number out for repairs or overhauling, turbines are on the line part of the day or all the day as the station load demands. In the boiler room the problem is how much load shall each type boiler carry. In the turbine room it is how many units shall be put in service; then which units shall be used; finally, how shall the load be divided among them.

The variation in types of turbine units installed in a given station is often greater than the variation of the boilers of the same station. Each unit may be different in size and type. There may be impulse and reaction turbines, straight condensing and extraction, one-stage bleed and multi-stage bleed, constant feedwater temperature and variable feedwater temperature, single-cylinder, tandem-compound and cross-compound.

The heat balance may be further complicated by the type of auxiliaries used. If these are electric, there may be 3 sources of low voltage power: house-turbines; house-generators on the same shafts as the main turbines; and house-transformers may be used. One station may use all 3 sources.

Fig. 19. Effect of method of load division on over-all turbine-generator heat rate



If steam auxiliaries are used, part or all of the exhaust steam may be used to heat feedwater. This is done in many older stations where the main units are straight condensing. In some modern plants, steam auxiliaries are used in combination with extraction type units, and the exhaust, as well as bleed steam, is used for feed heating. Since the pressure of the exhaust steam is approximately atmospheric, it will usually enter the cycle between bleed steam at higher and lower pressures; this makes the turbine performance dependent upon the amount of exhaust steam.

Methods of Turbine Load Division

Results obtained by 5 of the methods most commonly used in distributing load among turbines are illustrated in Fig. 19*C*. The 3 turbines whose heat rate and incremental rate curves are shown in Fig. 19*A* and Fig. 19*B*, respectively, are loaded from minimum to maximum and the combined heat rate curves are shown. (The proper number of units to run at a given load, although important, is not considered at this point, but will be taken up later.) It will be noted that although unit *A* has the lowest heat rate, unit *C* has the lowest incremental rate from minimum load to the first valve point.

The 5 methods used are described below:

1. Incremental rates. The load is divided to keep the turbines operating at equal incremental rates.

2. Base load. By this method, until the most efficient unit is loaded to capacity, the other units are operated at minimum loads. The other units are successively loaded to capacity in the order of their efficiencies. Thus the order in which the 3 units shown in Fig. 19*A* would be loaded to capacity is *A*, *B*, and *C*.

3. Valve opening. The units are successively loaded in ascending order of their heat rates, to their most efficient points. When all units are operating at their most efficient loads, they are loaded to capacity in the same order. Thus for the units of Fig. 19*A*, unit *A* would first be loaded to 40 megawatts (one megawatt is one million watts, or 1,000 kw), unit *B* to 30 megawatts, and then unit *C* to 40 megawatts. The units are then loaded to 50 megawatts each in the same order, *A*, *B*, and *C*.

4. Proportional to capacity. The loads on the units are in proportion to their rated capacities. Since the units of Fig. 19*A* are all of 50-megawatt capacity, they would be loaded equally.

5. Proportional to most efficient load. By this method, the loads on the units are kept in proportion to the loads corresponding to their lowest heat rates. After the units have reached their most efficient points, the additional load on each is made proportional to the difference between the rated capacity and the most efficient load. Thus the loads on units *A*, *B*, and *C* of Fig. 19*A* would be in the ratio of 40:30:40, respectively, until the total load was 110 megawatts. Any increase above this value would be divided among the units in the ratio of (50–40):(50–30):(50–40).

Comparison of the results of the 5 methods as applied to the 3 units used in the illustration clearly shows that the incremental rate method always gives the lowest over-all turbine heat rate, and is never equaled by any of the other methods except when the load division is the same. Although the 2 methods based upon proportional loading will rarely give the best distribution, they would apparently be fairly reliable for load division in a small standby station, where detailed performance data cannot be obtained. The valve opening and base load methods show up unfavorably in this illustration. Under some circumstances they would come much closer to the correct loading, but it may be stated that if there are enough data available to make either of these 2 methods trustworthy, there are enough to use the incremental rate method, by which the correct results can be obtained.

Turbine Performance Data

In order to apply incremental rates to the operation of a turbine room, performance data from which the heat rate curve for each turbine can be established, are necessary. The heat rate curves should represent the performance of the turbines under actual operating conditions of steam pressure and temperature at the throttle, vacuum at exhaust corresponding to the particular circulating water temperature under consideration, and the particular heat balance cycle. Data determined by tests under actual operating conditions are the most reliable and should be obtained whenever possible. Guarantee data should not be used if it can be avoided since frequently the actual performance is considerably different.

Tests on extraction type units should be run under normal extraction conditions. An approximation of feed heating performance can be calculated from a careful nonextraction test, but it is not so reliable as an actual extraction test. The calculated performance may be substantially correct in

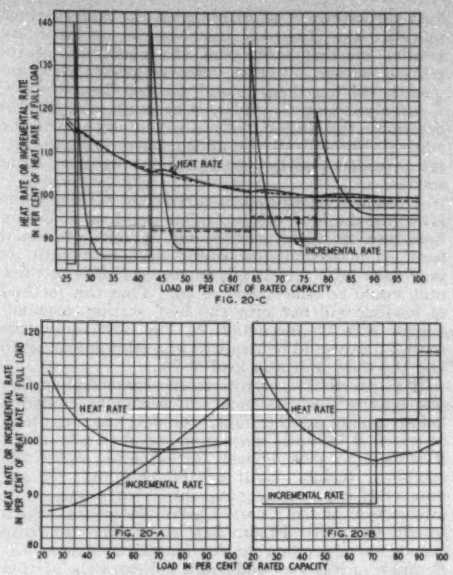


Fig. 20. Typical performance curves of turbine-generators

magnitude and yet show a very incorrect incremental rate.

Additional desirable data are the power consumption of steam and electric auxiliaries, curves showing operating vacuum at varying circulating water inlet temperatures, and correction curves for variation of steam pressure and temperature at the throttle and vacuum at exhaust. The use of these data to correct the turbine room performance to actual operating conditions will be discussed later.

Turbine Heat Rate and Incremental Rate Curves

Turbine heat rate curves usually fall into one of the 3 types shown in Fig. 20*A*, *B*, and *C*. In Fig. 20*A*, the heat rate curve is one continuous smooth curve; its incremental rate is continuous, smooth, and always increases with the load. In Fig. 20*B*, the heat rate curve is continuous but has definite breaks at the loads at which valves start to open. The incremental rate curve is discontinuous, having step-like increases at the loads corresponding to the break points of the heat rate curve. Between valve openings, the incremental rate is constant.

In many recent large turbine installations, heat rate curves are obtained similar to the solid curve shown in Fig. 20*C*. The heat rate curve is continuous with breaks at the valve points. Over a short load range following each valve point, the heat rate curve has a slight hump, which causes the incremental rate to increase suddenly and then gradually decrease to a constant value until the next valve point is reached. The difficulty in using an incremental rate curve of this type lies in the fact that since there are several loads corresponding to the same incremental rate, considerable computation may be required to determine the division of load that will result in the minimum input. The simplest case to consider is that of 2 identical machines with incremental and heat rate curves represented by the solid curves in Fig. 20*C*. Suppose a total load of 110 is to be divided between the 2 machines, then the incremental rates for each machine will be equal for the following combinations of loads: (27, 83), (28.25, 81.75), (44.5, 65.5), (46, 64), and (55, 55). (At the break points such as at 43 and 64, the incremental rate is assumed to contain all the values on the vertical lines.) Figure 21 shows for various total loads, the heat rates (in per cent of the heat rate of one machine at maximum load) plotted against the per cent load on one machine, and indicates that the actual minimum input for the 110 load corresponds to the combination (46, 64). It is important to note that for machines having this type of heat rate curve, the minimum total input *is not obtained when the load is equally divided between 2 or more identical machines.* In fact, for a total load of 170 (see Fig. 21) dividing the load equally actually gives the highest input of any possible combination. Since the 2 machines are identical, each curve of Fig. 21 is symmetrical about the load corresponding to half of the combined load. The circles show, for each total load, the combination which gives the minimum input. It will be noted that, for all of the loads worked out, the best combination is that in which one of the machines is operating at the break point which is most nearly equal to one-half of the total load.

In the more complicated case involving several machines which are not identical it will be found that the minimum input is obtained when all of the machines except one operate at valve points. To facilitate the selection of the best combinations,

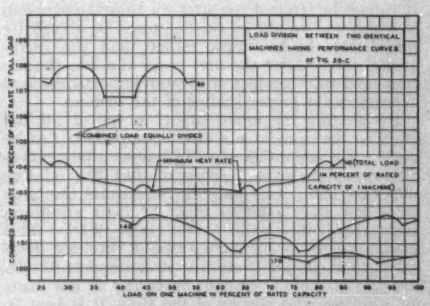


Fig. 21. Effect of load division on over-all efficiency of 2 identical turbine-generators having performance curves of Fig. 20C

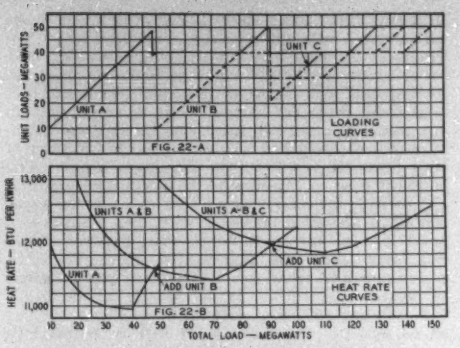


Fig. 22. Determination of loading sequence for 3 turbine-generators

adjusted heat rate and incremental rate curves are drawn similar in shape to those shown in Fig. 20*B*. The average incremental rates between valve points are plotted; these are obtained by dividing the differences in successive inputs corresponding to the valve-opening loads, by the corresponding differences in output.

The total load is then divided among the machines as if the average were the actual incremental rate with the exception, however, that all but one machine are operated at valve-opening loads. The relative values of the average incremental rates indicate which machines should be operated at valve-opening loads and which machine should carry the increase in total load.

Sequence of Adding Turbine-Generators

Determination of the proper order of putting units on the line is very important. It is usually quite simple since in most stations the latest equipment to be installed is the largest and most efficient. It cannot be stressed too strongly that the problem of which unit to put on the line must be solved by considering the heat rate, rather than the incremental rate. After the unit is on the line the incremental rate becomes of greater importance, and determines the proper loading of the turbine.

By plotting the input-output curves of all the units on the same axes a direct comparison can be made. The advantage of using input-output curves rather than heat rate curves is that the relative slopes are more easily judged. Sometimes the large units may have a higher input at their minimum loads than other units at the same load. This should not be given undue weight, because it is only at low station loads that it is important. In the case of standby stations operating at low loads for a considerable portion of the time, it is best to operate those units which have the lowest inputs at minimum operating loads, unless the additional capacity of larger units is needed. When the low-load periods are of short duration the factors which influence the choice of units to be operated are relative starting losses and the possibility of increased outage of large units resulting from frequently starting them up and shutting them down.

After selecting the order, it becomes necessary to determine the station loads at which units should be added. Units should be added when economy dictates, unless safety considerations require them sooner.

A method often used in scheduling turbine loads is to run the best unit up to its point of minimum heat rate, then add another unit to take additional load. The second unit would take load until its minimum heat rate has been reached when a third unit would be added, and so on. That this method of loading will not give the best station economy can be seen by inspection of Fig. 22*B*, since the second unit would be required at a station load of 40 and the third unit at a load of 70.

It is practically always more economical to run one unit beyond its point of maximum efficiency before adding another unit. To determine the load at which it becomes more economical to add a unit it is best to plot against station load, either the combined turbine input or the heat rate for the number of units running and for an extra unit. The intersection of the 2 curves gives the load at which to add the unit. Figure 22*B* shows the heat rate curves corresponding to combinations of units *A*, *B*, and *C* of Fig. 19*A* and *B* and indicates the station loads at which units should be added. Figure 22*A* shows a loading schedule which corresponds to the most economical sequence of adding units and Table III is a complete loading schedule for the same

Table III—Turbine Loading Schedule

	1 Unit	2 Units		3 Units		
Station Load	Unit A	Unit A	Unit B	Unit A	Unit B	Unit C
10	10					
15	15					
20	20	10	10			
25	25	15	10			
30	30	20	10	10	10	10
35	35	25	10	10	10	15
40	40	30	10	10	10	20
45	45	35	10	10	10	25
48.5	48.5	38.5	10	10	10	28.5
50	50	40	10	10	10	30
55		40	15	15	10	30
60		40	20	20	10	30
65		40	25	25	10	30
70		40	30	30	10	30
75		40	35	35	10	30
80		40	40	40	10	30
85		45	40	40	15	30
90		50	40	40	20	30
91		50	41	40	21	30
95		50	45	40	25	30
100		50	50	40	30	30
105				40	30	35
110				40	30	40
115				40	35	40
120				40	40	40
125				45	40	40
130				50	40	40
135				50	45	40
140				50	50	40
145				50	50	45
150				50	50	50

combinations. The portions of the schedule between the horizontal lines correspond to correct operation; the remainder of the table would be used when the proper combinations could not be run, for safety or other reasons.

As previously mentioned, the starting losses must be considered in connection with determining the economy of adding an additional unit to the bus. This can be best illustrated by an example using the curves of Fig. 22*B*.

Suppose that 2 units are supplying a load of 90 megawatts and the station load is increased to 95 megawatts. Then an additional unit is indicated. If the 95 megawatts be supplied by 3 units, the heat rate would be 11,920 Btu per kwhr; if supplied by 2 units the heat rate would be 12,080 Btu per kwhr. For every hour that 2 machines are operated at that load there would be a loss amounting to 95,000 × (12,080 − 11,920) = 15.2 million Btu. If the starting losses of the third unit amount to 50 million Btu, then the station load of 95 megawatts must be maintained for $\frac{50}{15.2} = 3.3$ hr before the addition of the third machine can be justified.

Thus the problem resolves itself into the consideration of 2 factors:

1. The starting losses of the additional unit.
2. The duration of the additional load.

Appendix A

Derivation of Conditions for Maximum Efficiency

Following is a mathematical analysis establishing the conditions for maximum over-all efficiency when 2 units of different characteristics are operating in parallel to supply a common load.

Let

O_t = total output of the 2 units
O_1 = output of unit No. 1
O_2 = output of unit No. 2
I_t = total input to the 2 units
I_1 = input to unit No. 1
I_2 = input to unit No. 2

It is assumed that $I_1 = F_1(O_1)$ and $I_2 = F_2(O_2)$ represent 2 continuous input-output curves, and have continuous derivatives, $\frac{dI_1}{dO_1}$ and $\frac{dI_2}{dO_2}$, respectively, which always increase as O_1 and O_2 increase. Therefore the second derivatives, $\frac{d^2I_1}{dO_1^2}$ and $\frac{d^2I_2}{dO_2^2}$, and hence their sum, are always positive.

$$I_t = I_1 + I_2 \tag{1}$$

and

$$O_t = O_1 + O_2 \tag{2}$$

The problem is to determine for any given value of O_t, for example O_a, the values of O_1 and O_2 which will make I_t a minimum. Then

$$O_1 + O_2 = O_a, \text{ a constant} \tag{3}$$

$$O_2 = O_a - O_1 \tag{4}$$

$$I_t = I_1 + I_2 \tag{5}$$

Now, since its second derivative is positive, I_t will be a minimum when its derivative with respect to O_1 vanishes.

Or

$$\frac{dI_t}{dO_1} = 0 \tag{6}$$

But

$$\frac{dI_t}{dO_1} = \frac{dI_1}{dO_1} + \frac{dI_2}{dO_1} \tag{7}$$

$$= \frac{dI_1}{dO_1} + \frac{dI_2}{dO_2} \times \frac{dO_2}{dO_1} \tag{8}$$

Furthermore

$$\frac{dO_2}{dO_1} = \frac{d}{dO_1}(O_a - O_1) = -1 \tag{9}$$

Hence

$$\frac{dI_t}{dO_1} = \frac{dI_1}{dO_1} - \frac{dI_2}{dO_2} \tag{10}$$

Equating eqs 6 and 10

$$\frac{dI_1}{dO_1} - \frac{dI_2}{dO_2} = 0 \tag{11}$$

Or

$$\frac{dI_1}{dO_1} = \frac{dI_2}{dO_2} \tag{12}$$

This means that the minimum input for a given combined output is obtained when the incremental rates of the 2 units are equal. Furthermore, there is only one pair of loads for any given output at which the incremental rates will be equal.

The second and concluding part of this paper on "The Theory of Incremental Rates and Their Practical Application to Load Division" is scheduled for publication in the April 1934 issue of ELECTRICAL ENGINEERING. In the present issue, the theoretical background, the application of the method to the boiler room and to the turbine room, and Appendix A, have been given, thereby laying the groundwork for the application of the method to the generating station, which phase of the subject will be treated in the second part. The conclusion, Appendixes B, C, and D, and references to further reading also will be included therein.

Discussions

Of A.I.E.E. Papers—as Recommended for Publication by Technical Committees

ON this and the following pages appear those discussions of A.I.E.E. winter convention papers that were received in complete and acceptable form at Institute headquarters up to Feb. 5, and subsequently reviewed by the various technical committees and recommended for publication. Discussions received subsequent to Feb. 5 and prior to March 1 are scheduled for publication in the April issue, subject to the recommendations of technical reviewers. It appears that these 2 groups will account for the bulk of the total discussion of the winter convention papers as published in the Aug., Nov., and Dec. 1933, and the Jan. 1934 issues of ELECTRICAL ENGINEERING. However, discussions received after March 1 will be given the same attention as those received earlier, and will be judged on the same basis for possible publication.

Authors' formal closures are scheduled for inclusion in the April issue, and will embrace all discussions received and accepted by March 1.

THIS new department in ELECTRICAL ENGINEERING marks a further step in the evolution of the unified publication plan adopted by the A.I.E.E. board of directors in August 1933, the purpose of which is to carry to every member of the Institute all technical and related material as promptly as it can be released and published. Another wish is to stimulate and facilitate a broader participation on the part of Institute members everywhere in the study and discussion of current technical papers. Therefore, members anywhere are encouraged to submit written discussion of any A.I.E.E. paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions should be: (1) concise; (2) restricted to the subject of the paper or papers under consideration; (3) typewritten and submitted in triplicate to C. S. Rich, secretary, technical program committee, A.I.E.E. headquarters, 33 West 39th Street, New York, N. Y.

The Pitt-Westinghouse Graduate Program

Discussion of a paper by H. E. Dyche and R. E. Hellmund published in the January 1934 issue, p. 103–8, and presented for oral discussion at the education session of the winter convention, New York, N. Y., Jan. 24, 1934.

A. M. Dudley: Having been associated with the Pittsburgh-Westinghouse program since its inception, as an instructor, and having in addition worked out the requirements for his own Master's Degree, the writer has an intimate knowledge of the arrangement which stimulates him to make some practical observations on points not covered in detail by the authors.

Experience with the process of recruiting technical graduates for industry showed that there were always a number of men of high mentality who wished to take graduate work, but who financially were unable to stay in school, or who feared becoming rusty on undergraduate training if they waited too long to try their hand on practical problems. These men found in the Pittsburgh-Westinghouse combination a chance to start their professional career immediately and, at the same time, proceed with their graduate work. As a result, the graduate work was much more effective and progress toward financial independence was expedited by nearly 2 years.

Many present-day graduates are imbued with the idea so ably championed by Dean Sackett that an engineer must pursue a course of "continuous education." The Pittsburgh-Westinghouse arrangement not only encourages this, but it provides a means for capitalizing graduate study and making it count toward an advanced degree.

The arrangement stimulates older engineers whose college days are several years behind them to take courses in physics and mathematics to bring their theory up-to-date. This creates a friendly rivalry between older and younger men, which gives the older men a chance to demonstrate that accumulated experience and ripened judgment help even in such matters as acquiring new knowledge.

The arrangement preserves a most desirable contact between education and industry as institutions and bears out the conclusion held by the writer for some time that among the ablest educators and practicing engineers are those who have had experience both in industry and in teaching. Also, the fact that university credit is given adds dignity and authority to the industrial training itself. The teaching experience gained by practical engineers serves to clarify and coördinate their own technical ideas in a way that would otherwise not develop.

The entire scheme has had a marked effect in raising the cultural standards of every one connected with it and has had much weight in combating the tendency to consider engineering as a trade instead of a profession.

It is to a considerable extent the answer to the problem so ardently pursued by the Society for the Promotion of Engineering Education of broadening and enriching the engineering curriculum without extending the span of the average undergraduate course beyond 4 years.

In closing I must pay my respects to Dean Sieg and C. S. Coler and their associates who have had the keen vision to combine and coördinate a natural growth or tendency with a competitive situation which concerns the student's time and life work and make from the two a practical contribution to American engineering education which is an outstanding accomplishment in that field.

E. B. Roberts: The authors point to the essential characteristics of engineering as a profession of creation and accomplishment. The necessity follows for the highest type of professional engineering education to nurture the desire and ability to create and accomplish. There is no concern here with preparing mediocre engineering graduates for the routine of design, testing, or application. There are grades of engineering and of engineering training, that are vocational, and there are grades that are professional. It is to the professional level of engineering that the authors of this paper have addressed themselves.

It is the relationship which engineering of creation and accomplishment bears as a step beyond scholarship and in the direction of the application of scholarship that makes the coöperative plan ideal in the graduate field. The period of apprenticeship to industry—the field of accomplishment and creation—proceeds in an atmosphere of university scholarship and research. The years of mental, physical, and social flexibility are used as they should be—for adjustment to life—but that adjustment proceeds in an atmosphere of scholarship and professional guidance.

The measure of success and recognition that has come to the plan rests upon the happy communion of vigorous teachers of character with able students. Problems of administration are few, and there is little mechanism of procedure. Unit courses there are, but these merely are the means of introduction of the students to their leaders and to the problems. The harmonious relationship of a superior student with a great leader, introduced through the mechanism of a course and maturing into the mutual study of an important scientific, mathematical, or engineering problem, is the aim. It does not seem so significant to us who are close to the program that educators who examine the plan find the Master's theses of our graduate students worthy of recognition as dissertations. The mind of the student is not much on the degree, or when he will receive it. Two-year and 3-year programs are not laid out. We prefer the lapse of three years for the Master's degree, and of 6 for the Doctor's. Continuous growth at a slow rate we value. Great capacity for sustained creative professional life, we believe, comes that way. It must be significant that the number of degrees granted is not affected by business and employment conditions. We shall continue to be satisfied with a dozen Master's and 2 or 3 Doctor's a year. The number of degrees granted is by no means a measure of the amount of work accomplished.

The faculty is balanced between the university and the industrial groups. The former are professional teachers of mathematics, physics, and economics. The writer is told by the university dean that there is a good deal of good natured competition in these faculties for assignment to Westinghouse classes. The industrial teachers of engineering subjects and leaders in the research are not professionally teachers, and but little effort has been made to develop in them a pedagogic viewpoint. They are selected because of their preëminence in their fields of science or engineering, and not because of degrees. While there are, as we look at the faculty roster, a considerable number of Ph.D.'s, several of those who have made the greatest contributions have no degrees except, perhaps, honorary doctorates. Each is left to his own way in developing his subject. Pedagogic tactics are unnecessary with the type of student involved. There are no undergraduate students in any of these classes, and no ordinary graduate students.

As we look back over 6 years of operation and progress of the plan, we see 3 significant values:

1. The development of an improved creative engineering ability among our younger engineers.

2. Continuing growth of the able few through those difficult years that should mark progress out of vocational engineering into professional engineering.

3. Important by-products in research and design, contributions to the literature of engineering, and in the sending out of a portion of those trained as engineering teachers or engineering leaders in other fields.

4. Mutual and favorable reaction on university faculty and design and research engineers, each developing a broader view through the contact.

The whole relation has proved a congenial and happy one. The entire effort of all concerned—university faculty, industrial faculty, students, and administrators—has been devoted to the creative side of the project. There have arisen no great differences of opinion or conflict of interests that have had to be arbitrated.

W. H. Timbie: In scheduling at the winter convention a session conducted by the committees on education and student Branches, the A.I.E.E. gives added evidence of the high value it puts upon the continued training of members of the profession, and certainly the 2 committees are to be congratulated in the choice of this paper. One of the greatest needs of engineering education at the present time is a closer coöperation between industry and the engineering colleges. The fact that very substantial and very definite benefits to the students, to the industrial organizations and to the engineering colleges result from such coöperation has been demonstrated again and again. But the combinations of different geographical situations, educational philosophies, and industrial policies are so varied, that each coöperative plan presents new possibilities and new advantages, all of which make it highly profitable from time to time to bring before the membership of the A.I.E.E. the details and the results of outstanding projects.

A study of these various projects might well form a starting point in the program of the committee on professional training of the Engineers' Council for Professional Development. This committee ought to find here a fertile field of ways and means in which we can take still greater advantage of the opportunities which already exist in our very midst.

Features which The Pitt-Westinghouse plan incorporates have been tried out either separately or in various combinations in several other localities.

The Bell System in New York City for years has been operating a plan whereby engineers associated with the system are able to complete graduate work at Columbia University in New York City, and the Polytechnic Institute in Brooklyn. The same arrangement exists between the General Electric Company and Union College at Schenectady. In both of these plans the young engineer gets his practical training in the industry but receives instruction in graduate studies at an engineering college, and is taught by members of the professional teaching staff of the college, rather than by members of the industrial organization.

The "Advanced Course" conducted by the General Electric Company at Schenectady (formerly called the Doherty Course) illustrates another variation. Here, while the young engineer is receiving his practical experience at the company's plant, he is instructed in advanced engineering theory by prominent members of the engineering staff of the company itself.

The coöperative course in electrical engineering, in which the General Electric Company and the Bell System coöperate with the Massachusetts Institute of Technology, offers still another variation. It utilizes this feature of instruction of students by prominent engineers of the industrial companies, but it does not limit this work to graduate study. In this coöperative arrangement the students spend alternate full terms at the Institute and at the plant of the coöperating company. While the students are with the company 2 classes a week are held, which are taught by outstanding engineers belonging to the industrial organization, but the subjects taught are not the particular subjects in which the engineers are specialists. Rather the subjects are integral parts of the course of study which make up the mathematical-physics backbone of the course in electrical engineering at the Institute. During those periods which the students spend at the Institute they are taught these subjects by members of the staff whose major interest is in teaching, but who, I venture to say, are just as good engineers as those employed in industry, but who have teaching as the major part of their work. Their outlook in general is not confined to one particular corner of the field of engineering. Thus the coöperative students take up successive vertebrae of their backbone course, first under an engineering teacher at the Institute and then under a teaching engineer at the plant of the coöperating company. The teaching engineer merely gives to the students at the plants the same subjects that they would have studied under an engineering teacher had they been at the Institute during that particular period. But these company engineers invariably bring to classrooms, viewpoints and sidelights differing from those with which members of the Institute staff endeavor to enrich the basic material of the same subjects. Such a dual approach to these fundamental theories affects a marked increase in the student's breadth of view, and in a decided whetting of his intellectual curiosity, 2 results which are prime objectives of all good engineering teaching.

Two other companies coöperating with the Institute on this plan have plants located in Boston. The students who receive their engineering practice with these companies, come to the Institute 2 evenings each week during their coöperative periods, and continue their studies under the instruction of members of the Institute staff. Thus, regardless of where the student is located, there is no break in his progress in the fundamental course of mathematical-physics which constitutes the backbone of his engineering curriculum. The success of this course has been marked and is evidence of the soundness of the underlying educational philosophy.

The variation in the method of utilizing the services of the outside engineer, whereby he teaches subjects which are unitary parts of the main stem of a student's course, rather than more or less isolated specialties, is due, in essence, to a different educational philosophy from that underlying the Pitt-Westinghouse plan, and is indicative of the wide variety of combinations and permutations that can be advantageously worked out in the coöperation between industry and technical colleges.

There still is another form of coöperation which has been in operation between the General Electric Company and the Massachusetts Institute of Technology since 1925. This plan represents yet another feature in educational philosophy and procedure. The General Electric Company for years has recruited its young engineers from among the graduates of engineering colleges located in all parts of the United States and Canada. To graduates who are qualified, the General Electric Company offers an opportunity to pursue graduate work at

the Massachusetts Institute of Technology leading to a Master's degree. The candidate makes application in the regular way to the Institute for graduate work. After he is accepted by the Institute the General Electric Company assigns him to the Lynn plant where classes are set up by the Institute in specified graduate subjects. The Institute sends regular members of its instructing staff twice a week to Lynn to conduct these classes. The young engineers carry on their work toward the Master's degree at one-third the usual rate at which they would progress were they attending the Institute full time. This continues for 3 terms, during which time the students have completed 1 term of graduate work. To those who have successfully completed the work, the General Electric Company grants a leave of absence for 1 term, which is spent in residence at the Institute. The young men are thus able to complete the work for the Master's degree in 2 years. Educational authorities agree that, in general, there are certain advantages to be gained when a student takes his undergraduate course at one engineering college, his postgraduate work at another, and at least part of his practical experience with a company outstanding in the comprehensiveness of its activities and in the high quality of its output. The last named course combines all 3 of these features. Business conditions have caused a temporary break in the operation of the course, but since the beginning of the course in 1925 40 men have received Master's degrees in Electrical Engineering, and 15 in Mechanical Engineering. From the Institute's viewpoint we are glad to state that these men constitute some of the best students enrolled in graduate courses in these departments. Their success is indicative of the effectiveness of the General Electric's recruiting organization, and of the appreciation which the higher type of engineering graduates have for the opportunities which this form of coöperation affords.

There is no doubt that in many localities in this country, conditions must exist which are favorable to setting up in several fields of engineering some form of coöperation between engineering schools and industry. In this connection there comes immediately to mind the automotive, chemical, and steel industries. We have seen the excellent pioneer work that has already been done. There is every indication that greatly increased opportunities will be opened up by the work of the committee on professional training of the Engineers Council for Professional Development. The reason that the Institute coöperates with the General Electric Company in the training of students who wish to enter the electrical manufacturing industry is because the great works of this company are in the vicinity of the Institute. It is our opinion that such coöperation should preferably be between engineering schools and industrial plants which are in the same vicinity. We also are proponents for definite arrangements whereby the students are placed in comprehensive companies and carry on their works employment with the same industry throughout the college course. Both of these features are characteristic of the Pitt-Westinghouse arrangement and in our opinion it is appropriately planned to meet the local situation.

Charles F. Scott: For the first time the committee on student Branches and the committee on education are functioning together. Two groups are concerned, the student before graduation and the student after graduation. These are recognized by the new Engineers' Council for Professional Development in which one division is concerned with engineering schools and another with professional training—the progress of the young graduate during the 4 or 5 years during which he is preparing through experience and study and all-'round development for full professional status. These groups will later on constitute the membership of the A.I.E.E. on which the standing and usefulness of the profession will rest.

These men are in the making; they are not yet experts. But our Institute functions largely through its technical committees—a score of groups of experts and super-experts. Each converses with itself on topics and in terms which may have little interest or meaning to the as yet uninitiated student and young engineer. Technical papers are apt to dominate our publications. Without lessening them, let us endorse the means now being taken in the special educational series to supply articles suited to our young members and urge that our joint committee on branches and education develop ELECTRICAL ENGINEERING as an aid in preparing these men for the New Deal and after.

Articles of this type will be welcomed by older members who appreciate the explanation of the fundamentals and the progress in fields other than their own.

C. C. Whipple: I have been giving quite some thought recently to the question of student membership in the A.I.E.E., especially as to how to make membership more attractive and more valuable to the students. It seems that about 70 per cent of the membership comes in through student membership. This being so, I believe that the Institute can well afford more specific attention to the student in its official publication, ELECTRICAL ENGINEERING. It has always fostered student activities in a very commendable fashion, but has omitted some possibilities in its official publication.

My suggestion is that the Institute devote at least 2 pages in ELECTRICAL ENGINEERING to matters of especial interest to students. Primarily the student is interested in having technical articles, which are up-to-date, but written more from the point of view of explaining to the student, and even to others, the matter at hand. My criticism, from the standpoint of the student only, is that the great majority of the articles in ELECTRICAL ENGINEERING are not written with this point of view. Rather the standpoint is that of the desire on the part of the author, or ones behind the author, to put on record their accomplishments, than to explain the subject carefully. Moreover, most of the articles or papers, are very technical, and involve previous knowledge which the student does not have. Please understand that this criticism is not necessarily one of Institute policy in general, but it does apply very directly to the student's standpoint.

These 2 or more pages could contain 1 or 2 short, rather complete technical articles, which might explain some new theory, new machine, instrument, method or procedure, or method of calculation, new or different standpoint on any of the many older theories. Every professor with a few years of experience has found in the course of his teaching that a certain method of explaining some theory, or the operation of some machine, or the solution of a problem, is especially effective in putting over the idea. These pages might include such of these articles as are of merit. But in all cases the idea behind the paper should be that of clear explanation. Furthermore, no one article should try to cover too much ground, either superficially or thoroughly. One idea fully covered would be of much greater value.

As a concrete example of the general type of article I have in mind, I can suggest reference to the *Electrician* published in London. This paper runs a "Student's Page" containing short technical articles, written with the idea of explaining something to the student, and I imagine in addition they are of considerable interest to others, who are engineers, but are not in their work dealing directly with the details of the matter at hand.

Also, I can suggest that throughout the Journal, or what is now ELECTRICAL ENGINEERING, there has appeared from time to time articles which could be included on these pages. I mention only a few: "A New Method of Calculating Circuits" by Kowenhoven and Pullen, November 1933, p. 776–9; together with the discussions; "Filters in Action" by Lane, December 1933, p. 813–16, although I think the explanation should be somewhat amplified and improved upon; "Alternating Current Analysis" by R. D. Mershon, January 1926, p. 43–5; and "Theory of the Autovalve Arrester," by J. Slepian, January 1926, p. 3–8. This last paper, together with several othet articles by Doctor Slepian could include a series of articles, perhaps modified or clarified. This list, taken at random from papers at hand, is not quite typical, but is to indicate possibilities only. If such articles were edited, and arranged on a page, headed in some suitable manner, to indicate that it was of special interest to students, I believe it would be an effective way of getting the students throughout the country more interested in ELECTRICAL ENGINEERING, and in the A.I.E.E. I believe also that students should be encouraged to write in discussion of these articles.

Included in this student's page, also might be, as suggested by Professor Weil, from Florida, and by Professor Seely, items with respect to student activities within the branches. I believe a record of the branch meetings of value, from the standpoint of record, and also other branches are anxious to know what is going on, and any event of especial interest might be written up in some detail. I believe that these matters should be secondary to the articles of technical interest.

I am very much in favor of having this "Student's Page" put in ELECTRICAL ENGINEERING rather than in a separate leaflet and by all means not mimeographed The students are a part of the A.I.E.E. just as much as any other type of member, and the "Student's Page" should therefore be an integral part of our official publication. It should not be separated therefrom, giving the student the idea of being an appendage.

Moreover, having it in ELECTRICAL ENGINEERING will create a greater desire for ELECTRICAL ENGINEERING on the part of students and they will thereby become acquainted with it, the men of the industry, and what the problems of electrical engineering are.

I am very much in favor of trying out this idea, for I believe it will grow, if properly done and allowed suitable scope. I suggest that the committee on education propose to the proper authority that this plan be carried out under its direction. My suggestion is that the material be edited by a group of engineering teachers, working in cooperation with the committee on education, the editors of ELECTRICAL ENGINEERING, and the papers committee.

Trolley Wire Lubrication Improved

Discussion of a paper by J. V. Lamson published in the November 1933 issue, p. 771–6, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934.

Reinier Beeuwkes: Some years ago consideration of the use of a solid graphite lubricant in place of the graphite grease lubricant was developed, while the electrification department of the Chicago, Milwaukee, St. Paul & Pacific Railroad was making investigation with respect to the possibility of definitely determining what the constituents of the more liquid lubricant should be to develop the most satisfactory results with respect to current collection and the securing of minimum wear of trolley wire. This investigation was being made at and about the time the recent business conditions were being severely felt and among other similar activities it became necessary to curtail this particular work. Mr. Lamson, who had been one of those engaged in this work on the railroad suggested, after his becoming connected with the University of Washington, that it might be possible for him to arrange to continue his investigation at the University. We of the railroad expressed the opinion that such work would be very valuable and that we would be glad to cooperate with him in every way possible. Mr. Lamson, as brought out in his paper, has been able to construct apparatus which, at least relatively, would in a short time enable correct conclusions to be drawn with respect to the advantages and disadvantages of the different lubricants considered. On basis of the early results Mr. Lamson secured, the railroad decided to make extensive trial of the solid graphite form of lubrication. Two methods of using solid lubricant are being tried out on the railroad:

1. In one method a soft mixture containing graphite and other ingredients furnished by one of the graphite manufacturers is packed around a reinforcing screen which extends across the hollow part of the pan between the copper contact strips, the screen being held in place by clamping it down under the contact strips. When the paste has been packed around the screen it is baked and is then ready for use. Care must be taken, of course, to see that no part of the lubricant extends above the copper strips.

2. The second method we are trying consists in the use of an auxiliary lubricating block, also formed of the baked paste mounted adjacent to the regular collecting pan as referred to in method No. 1.

We have been running these 2 arrangements on the Coast division of the railroad for a year or more, and during the late summer also extended their use to the Rocky Mountain division. There have been complaints by the mechanical department that the graphite lubricant results in considerable grooving of the contact strips. Recent grooving, at least on the Rocky Mountain division, has occurred with both forms of lubricant, and has been due to heavy frost conditions, in some cases not enough care having been taken to see that both pantographs were raised, as is called for by our instructions when frost conditions are encountered.

It may be that the question of the amount of current to be collected, that is, the current density, has an influence on the relative advantages of the soft and solid lubricant, respectively; or, other conditions may affect the situation. Therefore, I should have liked very much to have seen laboratory tests carried on a sufficient length of time to enable the answer to some of these questions to be determined, or at least indicated. Such further tests, however, we have not been able to arrange for, and we are still depending on actual operation to determine finally the relative advantages of the solid and soft lubricant. We think the solid graphite has important advantages, and would wish to determine definitely that there are still more important disadvantages before we gave up considering its use. On this basis, the results so far obtained have justified continuing with the tentative use of the solid lubricant.

Harry Brown: Mr. Lamson's paper on trolley wire lubrication is timely; it is indicative of the increasing amount of interest in, and of the amount of study and experiment being devoted by many engineers to this subject.

It is generally conceded today that lubrication is necessary for the proper operation of a sliding collector on a contact wire, whether for high speed heavy electric traction service, or for the lighter traction services, such as is represented by the modern trolley bus. There are 2 major prevailing opinions as to the best method of applying the lubricant. One method, the oldest and perhaps the easiest method, is to lubricate the collector. Nearly all sliding collecting devices are designed for lubrication of this kind, as mentioned by Mr. Schaake in his paper on pantograph design. Where runs are short, and in busy sections like yards and terminals, this method may be entirely satisfactory, if persisted in, since in time the contact system becomes more or less covered with lubricant transferred from the collecting device. The second method, which I am inclined to believe is the better one, is to apply a lubricant of some kind directly to the wire itself, by some means other than the pantograph, often enough to replace that amount removed by friction or by the action of the elements.

The New Haven Railroad has for years been lubricating the pantographs on its electric rolling equipment, in accordance with the first method. During the past year we have been making extensive experiments with lubrication applied directly to the wire itself, on certain parts of the overhead system at a distance from the terminals, keeping a record of the wire wear. Definite quantitative data on relative wear will be obtained, it is hoped, by the time these tests are concluded. Lubrication of the pantograph is also being continued, as in the past. There are many kinds of lubricants on the market today designed for this purpose, ranging from soft grease to be smeared on the wire, to harder putty-like graphite compounds in the form of sticks to be rubbed on the wire, and also including compounds containing finely divided graphite in solution in a volatile vehicle which is quick drying and is sprayed on the wire. No data is yet available as to the superiority of any of these various kinds of lubricants. The stick graphite, is perhaps, the method most easily applied to our overhead system.

The exact nature of the lubricant referred to in Mr. Lamson's paper is not given. One serious objection to the method used is the added weight to the pantograph shoe, at the very part, which Mr. Pickens in his paper shows should be of minimum weight and inertia for high speed operation. The method, however, may be perfectly satisfactory for slower speeds.

W. H. Bassett, Jr.: Mr. Lamson is to be congratulated on his careful study of a very important transportation problem. Especially interesting are his remarks regarding the polishing of the surface of a trolley wire or a copper bus bar wheel ring after extensive tests with solid lubricants. It has been the experience of the Anaconda Wire & Cable Company that the burnishing of the wire and pantograph collecting strip to a commutator glaze results thereafter in minimum wear of both electrical and mechanical origin on the contact surfaces.

In 1928 we built at the Ansonia laboratory, of the Anaconda company a test machine designed to test various kinds of trolley wire and pantograph material. It was hoped that by running these tests, we would be able to evaluate resistance to wear of various pantograph materials and

Fig. 1. Machine built in 1928 at the Ansonia laboratory of the Anaconda Wire & Cable Co. for testing trolley wire and pantograph material

of the amount of wear these alloys would cause on the copper and copper alloy trolley wires. Figure 1 shows the general arrangement of this testing machine.

A $^3/_8$-in. thick copper disk was mounted on a vertical axle which was rotated so that the periphery of the disk traveled at a speed varying from 10 to 30 mph. The wearing surfaces consisted of $^3/_{16}$-in. thick hot rolled low carbon steel rings which were riveted to the top and bottom surface of the $^3/_8$-in. thick copper disk. In order to prevent overheating of the steel rings, the copper disk was cooled by means of a water chamber which kept the temperature of the disk from rising above a maximum of 212 deg F.

The 3/0 B&S gauge trolley wire samples were placed against the top and bottom steel rings at 6 equidistant points around the circumference of the wheel. The pressure of the trolley wire samples against the wearing ring was varied by means of levers and dead weights. It was found necessary to make the levers carrying the specimens out of copper and mount a water chamber on same in order to keep the temperature of the trolley wire below 212 deg F. The 3/0 B&S trolley wire test pieces were cut $2^1/_4$ in. long. A slot $^1/_4$ in. wide and $^1/_8$ in. deep was cut in the middle so that a countersunk screw could be used in attaching the sample to the lever arm.

After preliminary trials, we standardized on the test procedure as follows:

Speed	10.2 miles per hour
Load	2.5 lb per linear inch
Length of run	500 miles of rubbing contact

No lubrication was used in these tests. The trolley wire samples had the standard hard drawn mill finish which they receive in normal manufacturing operations. The steel wear plates were machined smooth and finished with No. 00 emery cloth.

It was found that the rate of wear of the trolley wire samples increased quite rapidly during the first 10 miles of the run after which the rate of wear dropped off again reaching an approximate constant value at 40 miles and changing very little from that point up to the end of the 500-mile run. The copper was worn away from 3 to 4 times as fast as the bronze trolley wires.

In later tests, a graphitic steel known as "gunite" was used. In addition to the ferrous rings, we also experimented with nonferrous wear rings having a relatively high copper content. Where the samples were subjected only to mechanical wear, it was found that the amount of wear on the trolley wire was entirely dependent on how soon the surfaces became burnished or glazed. As soon as the surfaces obtained the high polish, the test could be continued indefinitely without any appreciable change in the trolley wire samples or the wear rings.

When the samples were subjected to both mechanical and electrical wear, it was found that the arcing and pitting of the surface affected the rapidity with which the surfaces became glazed. A current of approximately 70 amp was used to produce the effect of electrical wear.

All of the tests seem to indicate the importance of using highly polished pantograph wearing surfaces in order that the pantograph as well as the trolley wire might become burnished or glazed as rapidly as possible so as to reduce the amount of wear to a minimum. As may be noted, no lubricants were used in these tests, and it may be that the use of solid lubricants by Mr. Lamson will materially hasten the formation of the so-called commutator glaze on the wearing surfaces of the current collectors.

Investigation of Rail Impedances

Discussion of a paper by Howard M. Trueblood and George Wascheck published in the December 1933 issue, p. 898–907, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934.

K. L. Maurer and E. D. Sunde: The method mentioned in this paper of substituting for a steel rail an equivalent round conductor of unit permeability and zero internal reactance was utilized in some measurements made in 1931 of the electrical constants of several rail samples of dimensions differing somewhat from those described in the paper. These tests were made jointly by the Pennsylvania Railroad and the American Telephone and Telegraph Company in connection with studies relating to inductive coordination of communication and railway electrification facilities.

The tests covered rail weights of 100, 130, 131, and 152 lb per yard, all being standard Pennsylvania Railroad sections. For all but the 100-lb size, 2 samples of each size were tested, new rails being used in all cases. The 100- and 130-lb samples although differing somewhat as to dimensions and chemical composition from the samples of corresponding sizes described in the paper, gave average values of a-c resistance and total reactance that are in practical agreement with results given in the paper. Dimensions of the 131-lb rail, which is an A.R.E.A. standard, and of the 152-lb rail are given in Fig. 2 in which the experimental results are plotted. The measurements were made at 25 and 60 cycles and for rail currents up to 700 amp. The results are shown in a form that enables extension of the values at the above 2 frequencies to other frequencies over a limited range and with precision sufficient for ordinary engineering purposes. The justification for this use of the data is given in the following paragraphs.

The testing arrangement used was essentially similar to that shown in Fig. 1 of the paper except that the loop supplying current to the rail was in a horizontal plane and the loop for measuring the impedance drop in the rail, also in a horizontal plane, was about 30 ft wide and 30 ft long. With a given rail energized at different currents I, the voltage V appearing in the voltage measuring loop connected to the rail at 2 points 30 ft apart was measured for each value of I. Upon completion of these measurements, the rail was removed and a $^1/_8$-in. copper pipe of the same length as the rail was substituted in its place, parallel to which

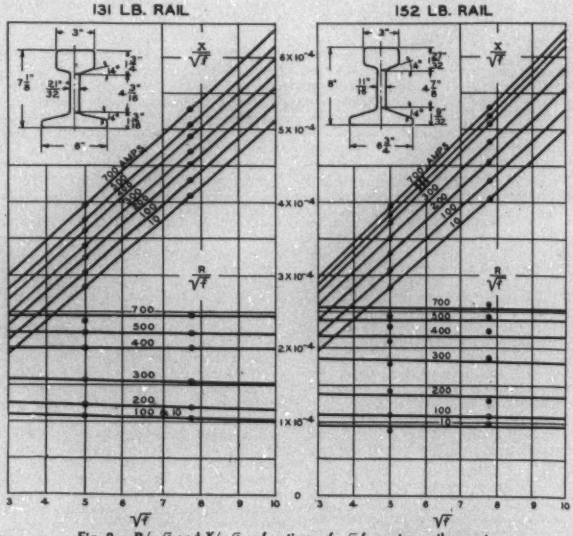


Fig. 2. $R/\sqrt{f}$ and $X/\sqrt{f}$ as functions of $\sqrt{f}$ for various rail currents

R and X are resistive and reactive components of voltage measured in test loop per ampere rail current; f = frequency in cycles per second. Length of test section 30 ft. Temperature of rails during test 102 deg F for 131-lb, and 93 deg F for 152-lb rail. D-c resistance of test section 243 × 10^{-6} ohm for 131-lb rail and 204 × 10^{-6} ohm for 152-lb rail. Rail perimeters 28 in. and $30^3/_8$ in. for 131- and 152-lb rails, respectively

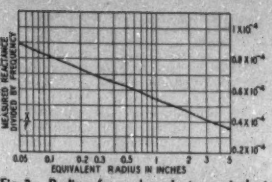


Fig. 3. Radius of round conductor equivalent of rail as function of 1/f times the reactive component of the loop voltage per ampere

exploring wires, also 30 ft long, were arranged at separations ranging from approximately 0.4 to 5 in. With the exception of the rail portion, the primary or current loop, and secondary or voltage measuring loop, were left unchanged. With a current I_1 in the primary loop, the induced voltage V_1 was measured in the secondary loop closed by each of the above wires in turn. The ratio V_1/I_1 was then plotted against the separation of the exploring wires. The real components of the ratios V/I for the rail are the a-c resistance values corresponding to currents I for the test length; the reactance component of V/I corresponds to some equivalent radius which is found by taking the separation in the plot of V_1/I_1 to which this reactance component corresponds. Since the primary and secondary loops were exactly the same for the 2 sets of tests the results are independent of their size and arrangement; except that the primary loop must be made large enough so that the distribution of current in the rail is unaffected by the return current, and the secondary loop must be large enough so that the position of the pipe with respect to the centroid of the rail sample is not critical.

On the accompanying Fig. 2, giving the average results of 2 samples each of 131- and 152-pound rails, the impedance components measured in the secondary loop divided by $\sqrt{f}$ are plotted against $\sqrt{f}$, and straight lines are drawn through the points. This linear extension of the results is theoretically justified, since for a conductor having a high permeability and a large perimeter, such as a rail, the internal resistance and reactance are nearly proportional to $\sqrt{f}$ when the frequency is not too small. The reactive loop voltage includes 2 components, one of which (the internal reactance) is nearly proportional to $\sqrt{f}$ and the other (the external reactance) proportional to f. Hence, the reactive component divided by $\sqrt{f}$ is approximately a straight inclined line when plotted against $\sqrt{f}$. This may be verified by plotting the total reactances given on Fig. 14 of the paper in this manner.

With the pipe substituted for the rail, as described, the induced voltage per ampere in the secondary loop divided by the frequency was the same at 25 and 60 cycles, as, of course, should be the case. On Fig. 3 this quantity is plotted against the separation at which it was measured. This separation is equivalent to the radius of a round conductor of zero internal reactance located coaxially with the pipe.

In order to calculate the total impedance of the rail its equivalent radius at the desired frequency and rail current is obtained as follows: The value of $X/\sqrt{f}$ in Fig. 2i s divided by $\sqrt{f}$, and the equivalent radius corresponding to the value of X/f thus obtained is taken from Fig. 3. The resistance of the continuous rail per mile is obtained by multiplying the values of R obtained from Fig. 2 by the numerical factor 176. With the resistance and equivalent radius known, the impedance is readily calculated as for ordinary conductors except that the internal reactance of the equivalent conductor is to be taken as zero. In calculating mutual impedances the equivalent conductors, of course, should not be used for separations so small that the proximity effect is important and in no case for separations less than about the diameter of the "external reactance circle" described in the paper, which, as there mentioned, can for practical purposes be taken as the rail perimeter divided by π.

Harry Brown: Trueblood and Wascheck in their investigation of rail impedances have contributed a valuable addition to the meager bibliography existing on this subject. The graphical and tabular data presented are concise enough to be included in all forthcoming editions of the several reference handbooks dealing with electric railway data. In connection with the investigation of bonded joints, it is to be noted that the bonds used are somewhat heavier than would ordinarily be used in operating practice on a-c electrifications, but the difference is without doubt a very small portion of the total impedance. It would have been of interest to have included data on the impedance of unbonded joints, since in actual operating practice there is, no doubt, a large amount of current carried through the splice bars themselves, through the areas in close contact with the rail, kept bright by the vibration and rubbing action of the various parts under traffic conditions. This, however, may be too much of a variable, under varying conditions of temperature and moisture, to be tabulated accurately, but would seem to warrant some careful study.

It would be of interest also to have information on the impedance values when 2 similar rails are in parallel at gauge distance apart, a condition usually found in propulsion current returns, as well as impedance of a similar parallel rail circuit, with rails in series as found in signal current circuits. It is assumed that the presence of the earth as a parallel conductor, is a minor factor in such impedance investigations.

Pantograph Trolleys I—Design Features

Discussion of a paper by W. Schaake published in the January 1934 issue, p. 182–9, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934.

Harry Brown: In his paper, Mr. Schaake has presented, for the first time, the actual design details, relative advantages and disadvantages, and limitation of the various types of pantograph current collectors now in use. One change in original design not mentioned in his paper, which was made to the New Haven pantographs, has been the cambering or bowing upward of the original flat shoe. This was done for 2 main reasons:

1. To reduce the tendency of the pantograph, as it swayed transversely to the track, from hooking into crossover or turnout wires with its high end (the radius of the camber being made approximately equal to the radius of transverse oscillation) thus allowing no part of the pantograph to be higher than the point of contact with the wire, regardless of amount of swaying.

2. To reduce the possibility of a worn pantograph from becoming concave or "broken backed," and having its ends higher than the center, from hooking into, or striking steady wires, and crossover or turnout contact wires. Our experience with this bow shaped shoe has been very satisfactory. As Mr. Schaake states, except for minor improvements, in bearings and joints, and also in insulation, the pantograph now in use on the New Haven has been changed but little from its original design.

The use of side guards shown in Fig. 9, and applied, I believe, to the Virginian, the Milwaukee, and the Cleveland Union Terminal pantographs, never has been quite clear to me. I cannot see how a shoe that has slipped off a contact wire ever can get back again under the wire, even with guards, and the pantograph will necessarily foul the first obstruction encountered in the overhead contact system, even with guards. For the additional weight and inertia, the advantages of this feature should be more readily apparent.

Pantograph Trolleys II—Operating Features

Discussion of a paper by B. M. Pickens published in the January 1934 issue, p. 190–4, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934.

Harry Brown: In his very admirable paper Mr. Pickens shows very clearly the desirability of limiting the normal contact wire height to the lowest value consistent with operating safety. Since other economic factors in contact system design also influence this feature, it might not be inappropriate at this time, with over a quarter of a century of operating experience to draw upon, to urge the adoption of a standard contact wire height. One of the committees of the Electrical Section of the American Railway Association indeed is working on this very problem, as it is closely associated with the subject of standard clearances. The consensus of opinion of engineers familiar with the design and operation of contact systems, seems to favor the adoption of a standard nominal height of 22 ft with standard rolling equipment of present day dimensions.

Another conclusion clearly indicated by Mr. Pickens is the importance of coördinating the contact system design and the design of the pantograph collector. There has been without doubt, too little done along these lines in some of the earlier installations, and there are many features in contact system and pantograph designs that are still capable of improvement, in spite of changes and improvements that already have been made. His analysis of

high speed pantograph operation on 300-ft catenary spans, again points out the fact that this length of span, while almost universally used in this country as a standard, seems to be a little too great for satisfactory high speed operation, as well as for certain features of the contact system design itself, which limitations I have previously pointed out (see A.I.E.E. TRANS., 1925). In this connection, it was this limitation which prompted the adoption of the so-called compound catenary by the New Haven railroad, when it extended its original electrification from Stamford to New Haven, Conn., in 1912. On this section, although the supporting structures are 300 ft apart, nominally, the effective span length for the contact catenary is only $^1/_2$ of that distance, or 150 ft. Thus the temperature variations in the catenary are only $^1/_4$ of what they would have been for a 300-ft span. With the adoption of speeds appreciably higher than those now in use, it may be necessary to resort to flexible or "lifting hangers" especially at or near the supporting structures, to increase the flexibility of the line, although in the past many disadvantages have discouraged their general use. The use of an auxiliary pantograph carrying the collector shoe also becomes more apparent, with higher speeds. In the past, terminal clearances have limited the use of this feature on many installations where its desirability has been recognized.

The 3-Phase Electric Arc Furnace

Samuel Arnold, 3rd, December 1933 issue, p. 839–43.

Transformers for Electric Furnaces

H. O. Stephens and L. S. Schell, Jr., December 1933 issue, p. 822–5.

Electrodes—Carbon and Graphite

Frank J. Vosburgh, December 1933 issue, p. 844–8.

Electrical Equipment for Induction Furnaces

C. C. Levy, January 1934 issue, p. 43–8.

Rocking Indirect Arc Electric Furnaces

E. L. Crosby, January 1934 issue, p. 132–8.

High Frequency Induction Furnaces

C. A. Adams, J. C. Hodge, and M. H. MacKusick, January 1934 issue, p. 194–205.

Cast Iron and Its Production

M. V. Healey, January 1934 issue, p. 120–3.

Discussion of a group of papers presented for oral discussion at the session on electric furnaces of the winter convention, New York, N. Y., Jan. 23, 1934.

N. R. Stansel: A more complete title for this symposium is "Electric Furnaces for Melting Metals and Alloys." An important topic in the metal industry is "improvement in methods of melting," and this symposium on electric furnaces is a contribution to that general subject as well as a presentation to electrical engineers of the present status of the electrical industry in a particular field of the utilization of electric energy.

Samuel Arnold's paper contains many interesting points for discussion. Some of these are noted in the following paragraphs.

Furnace Ratings. The adoption of a standard method of rating arc furnaces would be of much benefit to the metal industry. Along with this is the pressing need for the standardization of 3-phase arc furnace voltages. The necessity of using a given size of furnace shell for a considerable range of production and for more than one class of melting service may prevent the standardization of sizes of transformers for different sizes of furnace shells, but the flexibility of the variable ratio transformer described in the paper by Stephens and Schell appears to make it practicable to standardize furnace voltages.

Thermal Insulation of Arc Furnaces. The paper states that the major problem of this insulation is power limitation.

Large Furnaces. A feature of electrical apparatus is convenient and efficient divisibility. During the past few years a number of comparatively small 3-phase arc furnaces have been installed as supplementary units. The small furnace is supplied by the electrical equipment of the companion large furnace, but not, however, simultaneously. The variable ratio transformer makes this procedure easily possible. There is often a marked advantage in having a small furnace to meet low production conditions, special orders, etc.

The secondary bus of a 3-phase arc furnace is an important element of the installation. The following recent papers deal with this subject:

ELECTROMAGNETIC FORCES ON CONDUCTORS WITH BENDS, SHORT LENGTHS, AND CROSS OVERS, C. W. Frick. *G. E. Review*, May 1933.

BOLTING OF BUS BAR JOINTS, E. B. Shand and C. E. Valentine. *Elec. Journal*, Sept. 1933.

ENGINEERING CALCULATIONS OF INDUCTANCE AND REACTANCE OF RECTANGULAR BAR CONDUCTORS, O. R. Schurig. *G. E. Review*, May 1933.

CALCULATION OF INDUCTANCE AND CURRENT DISTRIBUTION IN LOW VOLTAGE CONNECTIONS TO ELECTRIC FURNACES, C. C. Levy. A.I.E.E. TRANS., Dec. 1932.

The increasing use of the single phase arc furnace in the iron foundry industry is a phase of load building that is unusually attractive to the central station industry. E. L. Crosby's paper, in addition to describing the single phase furnace, contributes much useful information on a new engineering material, electric gray iron.

The paper by M. V. Healey continues the discussion of electric gray iron in a way that should be of much interest to electrical engineers. Gray iron is a material of widespread use, and the utilization of the electric furnace in gray iron foundries is thus attractive to every central station.

The essential feature in the production of this new gray iron, after correct analysis, is a temperature-time relation for the molten metal, i. e., a heat treatment process applied to the molten metal, before pouring. The general method for the production of this new engineering material is electric furnace melting; first, because of the temperature required, and second, for economic reasons which pertain to the utilization of scrap and to production schedules. Hence, the term "electric gray iron" which is coming into use is well suited to this new material and parallels the long established term "electric steel."

It should be noted that Table I of the paper by Mr. Healey is a comparison of the local costs of unlike products. Industrial electric heating is a branch of product engineering, that is, the criterion of its use is the product. Hence, in all cases the character of the product is the basis of the economics of the method rather than a comparison of unlike products as in the case cited above.

Attention is invited to the recent publication entitled "A Symposium on Cast Iron" by The American Foundrymen's Association and The American Society for Testing Materials. Also many important articles on the production of gray iron in the electric furnace have appeared in the technical press during the past year.

One feature that distinguishes the arc furnace from the induction furnace is the electrodes. Improvements in electrodes have kept pace with the developments of arc furnaces and of the auxiliary apparatus for this class of equipment. The paper by Frank J. Vosburgh brings to engineers essential information on this important element in arc furnace operation.

The paper by Prof. Adams, Dr. Hodge, and Mr. MacKusick includes design features, metallurgical considerations, and operating characteristics of the coreless induction furnace. It is thought the term "coreless induction furnace" is better than the term "high frequency induction furnace" often used, and used as the title of this paper. The term "high frequency" is indefinite, and particularly so now that so many frequencies above 60 cycles are in use for various purposes.

The continuous growth in the use of alloy steels is noteworthy and of particular interest to the electrical industry because of the extent of the use of the electric furnace for the manufacture of these steels. A particular use of the induction furnace in stain-

less steel production is described in a paper entitled "Stainless Steel Production—Equipment and Manufacture" by E. C. Smith, with discussions by V. B. Browne and Walter Mathesius published in *The 1932 Year Book* of the American Iron and Steel Institute.

The special features of the electrical equipment for coreless induction furnaces are described in the paper by C. C. Levy. Both this paper and the preceding paper refer to the inductor generator. Further information regarding the design of this type of generator is given in the first part of the paper entitled "Inductor Alternators for Signaling Purposes" by F. W. Merrill, which appeared in the January 1934 issue of ELECTRICAL ENGINEERING, p. 78.

In conclusion, a paragraph from the annual report of the A.I.E.E. committee on electrochemistry and electrometallurgy for the years 1929–30 (ELEC. ENGG., v. 50, 1931, p. 570) seems of sufficient significance to warrant repeating it here. After noting the magnitude of the electrochemical and electrometallurgical industries of the United States this report continues:

"Quantities and percentages such as these would seem to warrant the liveliest interest on the part of men having electrical training, particularly the younger men who find themselves faced with limited opportunities for advancement in those more standardized fields of the electrical art involving the design and manufacture of apparatus for the production and distribution of electric energy. The development of new materials or processes based upon the utilization of this power is a field requiring talent of a high order and one which it seems should be very attractive to men of electrical training who can and will superpose on an electrical background a knowledge of the fundamentals of physical chemistry."

C. L. Dudley: The metallurgist is interested in quality of product and its control while the foundryman is interested in producing to the limit of his mould capacity at the minimum cost for materials and energy.

It is my understanding that the melting efficiency (pounds per kilowatthour) is not directly proportional to the increase in kilowatt rating of the furnace, but increases at a greater rate. This naturally would tend toward the foundryman's demand for a larger unit.

These installations are not always of such size as to make supply source voltages of 13 kv or higher an economical proposition for either the customer or the utility company. Loads on a 4-kv distribution system that require starting currents of the order of 50 or 100 amp per phase begin to be serious problems because of the voltage disturbances caused to other customers.

In the direct arc type of furnace the violent fluctuations of current inherent during the melting down process are even more serious.

We are therefore faced with 2 problems:

1. The initial starting condition which may last several minutes.
2. The normal operating condition which may last an hour or more.

It is gratifying to note in Mr. Crosby's paper (p. 135) that, "If it is desirable to hold the fluctuation or current surge to lower values than these (2 or $2^1/_2$ times normal) this may be readily accomplished by inserting an additional reactor in circuit when starting a cold furnace, very simple switching equipment being provided for short-circuiting this reactor after the arc has been in operation for a few minutes." This partially at least solves one problem and gives our regulators a chance to pick up the load.

The only general answer to the direct arc furnace seems to be a motor generator set which, of course, is very expensive.

Apparently the indirect arc furnace as described by Mr. Crosby overcomes some of the difficulties of this second class. This is probably especially true for ferrous metal uses though in nonferrous production, with which the Public Service (N. J.) Electric & Gas Company has had considerable experience, it leaves a lot to be desired.

There is, however, one serious objection to the indirect arc type of furnace as now constructed. It is a single-phase device and as such produces a bad line load unbalance in the case of the consumer who has only one unit.

This unbalance does 2 things: first, it ties up considerable valuable circuit capacity from which the utility cannot obtain any return; second, it causes polyphase rotating apparatus on other customers' services to try to rectify the unbalanced conditions and thereby penalize them for no fault of their own.

Most of these furnace installations obtain energy at off-peak rates and it would seem only fair that the single-phase user should be penalized in some way, perhaps in rate structure—which is already complicated enough—or in use of motor generator set, phase-balancer set, or in the installation of 2 or 3 furnaces which can be balanced on the circuit for normal operation. Possibly the indirect arc furnace can be redesigned as a polyphase device.

Mr. Crosby is to be congratulated for the inclusion of the oscillograms in his paper. I am sure the operating engineer would appreciate more data of this nature.

The 3-Phase Electric Arc Furnace

Discussion of a paper by Samuel Arnold, 3rd, published in the December 1933 issue, p. 839–43, and presented for oral discussion at the electric furnace session of the winter convention, New York, N. Y., Jan. 23, 1934.

Frank W. Brooke: Mr. Arnold has brought out 2 phases of electric arc furnace practice that I would like to discuss.

First: Thermal Insulation. This has been tried. In the first experience I had some 18 years ago, a $2^3/_4$-in. lining of "Sil-o-cel" was used on a 6-ton melting furnace and the lining after a few heats broke down. Since then more conservative insulation has been used. There is a balance between the permissible heat insulation and the cost of refractories, particularly in basic operation.

It is difficult to compare the open-hearth with the electric furnace under this heading. The open-hearth has much greater areas of heat surfaces. There are the furnace chamber, ports, checkers, flues, etc. Parts of these are at temperatures that permit insulation. A more important difference between heat losses in the open-hearth and the electric furnace is brought about by the air infiltration. The electric furnace from the very beginning was encased in a steel shell. Its design permitted this and this great advantage has not been sufficiently realized.

Second: Furnace Rating. Let us confess that we furnace builders have been more responsible for this confusion than anyone else. As Mr. Arnold points out there is no one cure-all; however, we can eliminate some of this confusion by cutting out such items as theoretical bath contour referred to by Mr. Arnold, and extravagant overload figures. I would like to suggest a full discussion of the problem by the 3 manufacturers of direct arc melting furnaces along the following lines:

(*a*) *Holding Capacity.* Arrive at a standard of furnace shell diameters and eliminate nominal capacities and the *XYZ* sizes. Establish a relation between these diameters and some vertical dimension so as to define the scrap holding capacity. Define a recommended lining thickness to conform with brick standards. This will entail sacrifices on the part of each manufacturer, but similar sacrifices have been made in nearly every other industry and I can assure the full coöperation of my own company along this endeavor.

(*b*) *Electrical Capacity.* Agree upon an understanding of transformer capacity, such as the A.I.E.E. temperature rating based on an assumed full load for 24 hours. Eliminate any time cycle rating. Establish a "name plate" that gives the necessary information to the furnace user. Makers of electric furnace transformers have in the past been anxious to help in such a standardization and will, I am sure, do all in their power to arrive at a fair result. Let us cut out for instance all "in between" kilovoltampere capacities using as a suggestion such figures as:

500	1250	2000	4000
750	1500	2500	5000
1000	1750	3000	7500 etc.

(*c*) Establish a recommended set of combinations of holding capacities and electrical capacities for typical conditions.

It will still require an expert furnace engineer to study each application, but he will have definite factors to work from and the prospective user will be in a much better position to know what he is getting and to know what the operator should produce.

C. C. Levy: After reading Mr. Arnold's excellent paper on the subject of the 3-phase electric arc furnace, particularly as used in the production of ferrous materials, it occurred to me that while excellent treatment of the various types of ratings and the reasons for them had been given in the paper, no conclusion as to the standardized practice had been reached.

According to the paper, a furnace rating may be any of the following:

1. The nominal rating based upon the dimensions of the bowl and meaning the tons of molten metal charge when the furnace is first installed.
2. The tons per hour production which is explicit only when associated with a certain product and is explicit only for acid work on account of the variable time of refining.
3. The diameter of the shell.
4. The transformer capacity.

It appears that all of these features are necessary to the complete understanding of a furnace rating from one point of view or another. Unfortunately the number of these is too great to be convenient in describing a furnace except in a formal specification. As a suggestion for ordinary descriptive use we would like to ask Mr. Arnold whether the diameter of the shell

and the nominal charge rating followed by a statement as to the maximum net tons which can be charged would not be a satisfactory method of describing a furnace rating. Any operator desiring to know his tonnage could readily work this out from a knowledge of the process, whether it were acid or basic, and the type of product he was melting.

Another feature of interest on which we should appreciate additional information from Mr. Arnold is the subject of furnace insulation. This subject is mentioned rather briefly and we feel sure that a discussion of the problem, and any experimental work that has been done together with results obtained would be of great interest. The paper appears to be that when insulation is used the rate of energy input must conform to the rate of heat dissipation as otherwise refractory failures would occur. Experimental difficulties in determining the rate of heat dissipation are doubtless the cause for failure to reach a successful operating condition. Another difficulty seems to me to lie in the fact that for melting-down the rate of energy input usually is made high and it is not at all likely that this rate of input would conform to a desirable rate for an insulated furnace.

Transformers for Electric Furnaces

Discussion of a paper by H. O. Stephens and L. S. Schell, Jr., published in the December 1933 issue, p. 822–5, and presented for oral discussion at the electric furnace session of the winter convention, New York, N. Y., Jan. 23, 1934.

S. S. Cook: It seems to me that the paper by Stephens and Schell stresses too strongly the desirability of providing conservators or expansion tanks for furnace transformers. Their use may involve difficult tank construction and furthermore they may not be as necessary as might at first appear.

In order that the conservator may function properly the tank, including the joint between the low voltage leads and the cover, must be oil tight. If the low voltage current is small enough to permit the use of ordinary oil tight bushings, an oil tight joint between bushings and cover easily is obtained. Such bushings are, however, not good for more than about 4,000 amp each and there is not cover space for many of these bushings in parallel—particularly on a 3-phase unit. For heavy current units, therefore, many bus bar leads are essential, which, because of space limitations and to minimize lead reactance, must be spaced close together. Making these bars oil tight under pressure where they come through the cover is difficult and expensive. It could be done, and estimates have been prepared covering furnace transformers with oil conservators and with "inertaire" protection, which I consider preferable. However, the additional expense and risk of leaks involved does not seem justified.

The paper states that several furnace transformers with conservators have been built, but there are none indicated in the illustrations which all show heavy current units with bus bar low voltage leads. I should like to ask if those built with conservators were large units for furnace operation, and what low voltage currents were involved?

I do not believe there is any great need for a conservator on the usual furnace transformer because:

1. Furnace transformers are usually in a separate room where the air is reasonably free from dust and it is not difficult to provide sufficient packing around the low voltage leads and other cover openings to prevent the entrance of dust and dirt into the tank.
2. These transformers are of the water cooled type with reasonably high temperature gradients between copper and oil; hence the oil rise is not great (about 25 deg C for a 40-deg unit). Therefore, the variation in oil volume with variation in load, and consequently the breathing, is not as great as in an ordinary power transformer. With a very small amount of breathing there is not much likelihood of moisture entering the tank. This is particularly true since these units are invariably of the indoor type and are installed in a dry place of reasonably uniform temperature.
3. The temperature of the oil in a furnace transformer is low, probably never more than 60 deg C; at this temperature sludging is very slow even when in contact with air.

For these reasons it seems that the conservator is not needed and that it would not materially improve the life or performance of the unit. If provision for breathing is required, a good chloride breather is all that is necessary.

The scheme of paralleling the high voltage winding as shown in Fig. 1 of the article, so that operation on the taps will affect the paralleled low voltage coils equally, is a good one unless the high voltage current is too low to permit many subdivisions.

A somewhat simpler modification that gives the same effect, is to design for parallel connection only the parts of the winding containing the taps, having one part in each high voltage group. The remainder of the winding can be designed for series connection throughout and connected in series with the tapped circuit. This improves the space factor of the winding and lessens the number of leads that must be connected to terminals or tap changer.

It is well known that in paralleled transformer coils the load divides inversely as the impedances, other things being equal. One should not be misled by the fact that the difference in the impedances given in the paper for paralleled low voltage coils at the top and bottom of the stack of a core type transformer with interleaved windings, is only 0.14 per cent. That 0.14 per cent is 0.14 in 100; but expressed in terms of the impedance of the shortest circuit, it is 3.6 per cent. This means that the current in the top coil would be 3.6 per cent more and the loss about $7^1/_2$ per cent more than the corresponding values in the bottom coil. This difference in loss could be observed quite readily.

The paper states that the observed rise of the top coil above the surrounding oil was 15.8 deg C and of the bottom coil 15.1 deg C. Since the oil surrounding the bottom coil is perhaps 10 deg C cooler than that surrounding the top coil, it appears that the temperature difference between the 2 coils is greater than the values 15.8 deg and 15.1 deg above surrounding oil would lead one to believe.

The percentage lead impedances given will hold if the low voltage is fairly high, say 200 volts. If, however, this voltage is low, say 50 volts or lower as is often the case, the per cent lead reactance with the same current will be some 4 times or more as great. This would give impedances of the shortest and longest bars of 0.76 per cent and 1.32 per cent, respectively. Taking the winding impedance at 3.68 per cent as before we have

Total impedance of longest circuit.....5.00%
Total impedance of shortest circuit.....4.44%

In this case the top coil would take about $12^1/_2$ per cent more current and would have 26 per cent more loss than the bottom coil. It follows that there would be a marked difference in the temperatures of the 2 coils.

In closing I should like to refer to an article on furnace transformers that appeared in the *Electric Journal* of September 1933. This article describes furnace transformers of the shell form of construction with vertical coils and all leads coming from the tops of the coils. The low voltage leads are all of approximately the same length. The high voltage leads go directly to the tap changer or terminal board and do not involve the complicated arrangement shown in Fig. 3 of the Stephens and Schell paper.

Rocking Indirect Arc Electric Furnaces

Discussion of a paper by E. L. Crosby published in the January 1934 issue, p. 132–8, and presented for oral discussion at the electric furnace session of the winter convention, New York, N. Y., Jan. 23, 1934.

J. V. Alfriend, Jr.: The paper by E. L. Crosby calls attention to an electrometallurgical tool developed under the stimulating pressure of the World War; yet unlike many of the war developments this rocking indirect arc furnace has stood the test of peace time requirements.

Mention is made on page 135 to the effect that "The present tendency both here and abroad is toward a greater number of relatively smaller furnaces instead of toward the concentration of operation in a single unit." This statement must apply to a certain section of the field of electric furnaces as otherwise it must ignore certain very large arc furnace installations that have been made in this past few years. To mention a few of these that come to mind there are:

The 50-ton arc furnace at the Rotary Electric Steel Co. requiring a 10,000-kva transformer.

The 40-ton arc furnace of the Imperial Japanese Navy requiring a 12,000-kva transformer.

The 80- to 100-ton arc furnace of the Timken Roller Bearing Co. requiring 2 12,000-kva transformers.

The banks of 15-ton arc furnaces of the Ford Motor Co. each requiring a 5,000-kva transformer.

The numerous carbide and ferro-alloy furnaces each requiring transformer capacity of 3,000 kva to 5,000 kva.

It would be appreciated therefore if Mr. Crosby would define more accurately the field of application of the rocking hearth furnace and also give us an expression of his opinion as to kilowatt capacity he anticipates as the future of an individual single phase rocking hearth furnace.

It is noted that an external reactor

mounted within the transformer tank is used for the purpose of obtaining arc stability and that this reactor usually is connected to the 20-per cent reactance tap. It is further noted that the low voltage leads from the transformer are interlaced from the transformer up to connections to the furnace flexible cables for the purpose of reducing reactance. It is felt that some economy would result from a careful study of the use of noninterlaced low voltage busses with a consequent reduction in the amount of external reactance necessary.

This is not an argument in favor of noninterlaced low voltage high current bus work, as in very many instances the reactance must be kept to a minimum and interlacing is an essential. There are other furnace applications requiring adjustment in the matter of stabilizing reactance and this factor may force the apparent contradiction of interlaced bus bars and external reactors.

Clyde L. Frear: Too much emphasis cannot be placed on certain points brought up by Mr. Crosby in his excellent paper on electric furnace melting of nonferrous and ferrous metals. The writer is in entire agreement with him that the electric furnace is probably the only type of melting equipment that can use the cheapest grade of raw materials obtainable, and yet turn out the highest grade of castings. The electric furnace also permits the production of any grade of iron desired with close control of the composition and the physical properties of each grade. These excellent properties are a result of the superheating and refinement as well as the thorough mixing which the molten bath undergoes while in the furnace, with the result that the bath of metal, and also the resulting castings will be perfectly homogeneous.

Of course, Mr. Crosby does not intend to convey the impression that the rocking indirect arc type of furnace is the only kind of electric melting furnace in which the bath is thoroughly mixed. In a direct arc and in an induction furnace, in both of which the electric current passes through the metal bath, there is just as much or even more mixing of the bath than is possible by mechanically rocking the furnace. Almost any high school physics course teaches us that when an electric current passes through a conductor magnetic forces are set up around that conductor. In this case these forces will surround the direct path of the electric current but will be confined mostly to the bath of metal. As a result of these magnetic forces produced directly in the bath, there will be a continual stirring of the bath of molten metal. This stirring action, while very efficient in producing complete homogeneity of the bath, is very gentle in its action so that there is little or no chance of eroding the hearth.

As an example of this complete mixing in the direct arc furnace, the writer has added 500 lb of sheet steel scrap to one side of a 2-ton bath of molten cast iron, then allowed the furnace to run quietly on low transformer tap. In 3 minutes after this addition, samples were taken from different parts of the bath. Chemical and microscopical analysis of these samples showed complete homogeneity of the bath.

By using a direct arc furnace, a slag of any desired composition may be used on the surface of the bath, which slag is necessary for efficient refining of the metal. This slag in no way hinders the heating of the bath, in fact, a layer of slag on the surface is really an aid in heating the bath as it holds the heat in the metal. At the same time it protects the roof and side walls to such an extent that when the bath is heated to 3,000 deg F, the color of the roof is usually only a bright red.

Cast Iron and Its Production

Discussion of a paper by M. V. Healey published in the January 1934 issue, p. 120–3, and presented for oral discussion at the electric furnace session of the winter convention, New York, N. Y., Jan. 23, 1934.

Clyde L. Frear: Mr. Healey is to be congratulated upon this paper. It is the first one to come to the writer's attention that gives a distinct comparison between the cost of cast iron production in the cupola and in the electric furnace.

The writer agrees with Mr. Healey that the improved qualities of iron produced in the electric furnace are due almost entirely to the control of the graphite in the resulting castings, such control resulting from a superheating and refining which causes a controlled solution of the graphite nucleuses in the molten iron with the result that the number, size, and distribution of the graphite flakes in the solid castings are such that there will be a distinct improvement in the physical properties.

The readers of this paper may have received the impression that the electric furnace is suitable only for the production of castings having high strength, where machinability has been sacrificed to obtain these high strengths. This type of melting equipment is just as suitable for the production of the so-called soft irons. The writer has been connected with a manufacturing concern which installed an electric furnace for the production of just such castings, using as raw materials: machinery scrap, steel scrap, steel chips, and cast iron borings—in fact nearly all ferrous scrap produced by this company during its regular manufacturing operations. Soft irons can be produced as economically in the electric furnace as in the cupola. Furthermore, due to the control of the graphite precipitation, these soft irons are finer grained, and withstand higher hydraulic pressures than irons with the same machinability produced in the cupola. As a general rule it may be stated that any iron produced in the electric furnace will be finer grained and will have better physical properties than will an iron of the same machinability produced in the cupola; this may be stated in another way: an electric furnace iron will have better machinability, and will be closer grained than will a cupola iron of the same strength.

Concerning machinability, the writer, as a result of long experience, cannot agree entirely with Mr. Healey that for maximum machinability the combined carbon should be zero. In gray irons as cast, containing no free cementite, it has been the writers' experience that a combined carbon content of 0.30 to 0.50 per cent will give better all around machining properties than will a lower content. The distribution and fineness of the graphite has so much bearing upon the machinability that it is impossible to set any hard and fast rule comparing this property with the content of any single element in the iron.

The writer further agrees with Mr. Healey concerning the use of alloying elements. In a number of foundries the use of alloys has been discontinued except where specified in the purchase orders by the customer. The reason for this was that the improvement effected was not sufficient to permit the increased cost due to the use of the alloys. This lack of improvement in the properties should not be blamed upon the alloys, however, but upon the fact that the iron to which they were added was a low-grade iron in the first place, and little improvement can be effected in a low-grade iron by the addition of any alloy. Furthermore, greater improvement in properties may be produced in an unalloyed iron by refinement in the electric furnace than could be obtained by the addition of any amount of alloying elements to poor cupola metal.

High Frequency Induction Furnaces

Discussion of a paper by C. A. Adams, J. C. Hodge, and M. H. Mackusick published in the January 1934 issue, p. 194-205, and presented for oral discussion at the electric furnace session of the winter convention, New York, N. Y., Jan. 24, 1934.

P. H. Brace: During the past few years the Westinghouse company has carried out extensive investigations in the induction furnace field and a brief outline of some of our experiences with 60-cycle coreless induction furnaces may be of interest.

We started with a 100-lb unit with a 7-in. diameter crucible in which mild steel was melted successfully. Following this a brass melting unit capable of holding 800 lb was constructed and successfully operated over a period of more than a year. A variety of brass foundry alloys was handled and with few exceptions castings of superior grade were produced. The best results were obtained with manganese bronze. In the case of leaded bronzes, particularly a leaded phosphor bronze, it was found difficult to maintain the furnace lining which consisted of a preformed clay-graphite shell separated from the inductor coil by an annular packing of zircon sand. The power factor of this furnace was approximately 15 per cent with normal charge and it was found unnecessary to use a starting slug, since the pigs normally used for foundry melting stock proved quite satisfactory.

The 60-cycle idea was pursued still further and an 800- b unit was constructed and successfully operated on nickel-base alloys. In this case it was found necessary to use a starting slug and at the high melting rate, the agitation was unduly violent and caused

rapid pick-up of oxygen and nitrogen by the charge. Experiment showed that control of the furnace atmosphere would eliminate contamination of the melt. The inconvenience of the starting slug, and the need for atmosphere control, when working a fast melting schedule, caused the replacement of this furnace by a conventional high frequency unit operating at 960 cycles.

The success of the 2 small units from the melting standpoint led to the construction of a 4-ton unit powered direct from a motor generator set without capacitors. This was practical since the power factor was between 20 and 25 per cent. This unit was first applied to the melting of cast iron scrap, borings, etc., and for making miscellaneous small castings. Numerous difficulties were experienced with linings, and in the end satisfactory results were obtained with a rammed lining of sharp silica sand bonded with as little as $2^1/_2$ per cent of ball clay and prefired in place with gas. Zircon brick from the Titanium Alloy Manufacturing Company showed promise. In melting cast iron, built up linings were found difficult to maintain because the superheat required caused the temperature of the refractory at points within a short distance of the coil to rise to the melting point of the iron. Therefore any small crack allowed metal to come uncomfortably near to the coil before being stopped by freezing. It seems desirable in most cases to have a lining of granular nature firmly rammed in place and of such constitution that the space next to the metal just becomes plastic at working temperature.

Changing foundry and business conditions caused the furnace to become uneconomical for its original purpose and a number of experiments were conducted to see what could be done with it as a steel melting tool. It was found possible to remelt low-silicon and high-silicon steel scrap with little loss of silicon, and successful runs were made in which very creditable medium carbon steel was made by refining miscellaneous iron foundry scrap.

The agitation was vigorous and it was found that the progress of refining operations was very rapid. No difficulty was found in getting high temperatures. In fact, on one occasion when a charge was held molten overnight to relieve an overworked experimental crew, disaster almost occurred due to a misjudgment of the bath temperature owing to its being hidden by a layer of slag. The silica lining became plastic and began slowly to float to the top of the charge. Rising power factor readings warned of the danger in time to prevent a "break out." The charge was poured out at the first opportunity and the lining patched and used in subsequent runs without difficulty. It is our impression that a lining of nearly pure silica bonded with a minimum of clay and preheated to fit the surface before attempting normal use presents attractive possibilities where an acid hearth can be permitted.

The results of these experiments led to the conclusion that for the sizes likely to be used in the near future, frequencies higher than 60 cycles would be demanded and developments since then have provided motor generator equipment suitable for various frequencies from 120 cycles up to 5,000 cycles. These units are particularly adapted to furnace work, and I think we may be regarded as having explored the frequency field quite thoroughly from the practical standpoint over the range between 60 and 15,000 cycles.

The controlling importance with respect to the choice of frequency, of the conditions surrounding particular applications is indicated by the fact that we now have in commission units operated at 60, 360, 500, 5,000, 10,000, and 50,000 cycles ranging in capacities from 10 to 125 kw; these are in use for melting and refining and heating ferrous and nonferrous alloys and other materials in vacua, in controlled atmospheres, and in air.

All these are based on high frequency electromagnetic induction, but it may not be out of order to call attention to the fact that high frequency electrostatic induction is showing some interesting possibilities in connection with processes that may become of interest to electrometallurgists.

Electric Power Switching

A. H. Lovell, January 1934 issue, p. 147–8.

Switching at the Hudson Avenue Station

C. M. Gilt, December 1933 issue, p. 868–75.

Switching at Richmond Station

Raymond Bailey and F. R. Ford, January 1934 issue, p. 156–61.

Switching at Long Beach Plant No. 3

A. A. Kroneberg, O. R. Bulkley, W. A. Andree, December 1933 issue, p. 826–30.

Switching at the Connors Creek Plant

A. P. Fugill, January 1933 issue, p. 162–8.

Switching at State Line Station

T. C. White, January 1934 issue, p. 148–56.

Discussion of a symposium presented for oral discussion at the session on electric power switching of the winter convention, New York, N. Y., Jan. 23, 1934.

F. H. Hollister: To open the discussion this afternoon on the papers on switching energy, perhaps it would not be out of place for me to give, briefly, some observations with respect to each of the 5 papers, and then follow with a few remarks regarding trends as gleaned from a review of the plants taken as a group.

The paper on the Hudson Avenue station indicates how rapidly stations may grow, and how they develop in size of units in switching and bus equipments, also how the engineer's conception of the general problem of plant design and operation may be affected and changed by a rapidly growing demand for power. Changing factors, such as amount and location of bulk load demand, often force serious consideration of a change in fundamental plans and arrangements. At this station, with a plant growth and demand apparently unexpected, the margin in breaker rupturing capacity was rapidly overtaken. The scheme of feeder supply to the substations interests me very much, also the ingenious expedient of a synchronizing or tie bus for tying bus groups together with load transfer and for back-up supply when the occasion requires.

The paper on Richmond station supplies considerable food for thought. Many important design features are suggested for future study and development, particularly in oil circuit breakers. The author has been very frank in giving a report of their troubles, which apparently have been very serious. Of much interest is the author's brief review of the experience with and description of the connections between generators and busses. We note also the emphasis placed upon the straight double bus scheme with selector circuit breakers for switching to give maximum operating simplicity and reliability.

The paper on the Essex-Connors Creek station is of particular interest in showing how a radial system can be expanded to take care of increased demand. It describes also the new developments in metal enclosed equipment, tube busses and oilless circuit breakers. The author concludes that if a new station were being built today, it would be essentially a duplicate, and indicates also that there have been no system or equipment difficulties or troubles worthy of note. I am wondering if in these 2 respects the answer will be the same 5 or even 3 years hence?

The paper on the Long Beach plant and the discussions should appeal to those who have the problem of linking together large blocks of power from hydroelectric and steam-electric stations separated by long distances. Of outstanding interest also are: the scheme for paralleling on high voltage; the method of control of short circuits; the unit plan for generators and transformers; the automatic frequency control, and the quick starting turbine-generators at Long Beach.

The paper on State Line describes in a general way the initial installation and scheme of connection and operation for a bulk power station where the most of the load is taken out at 66,000 volts under-

ground. The outstanding design features of note are: the double ring bus system of connections, the use of 22-kv metal-clad switchgear, and the large capacity of generators and feeders.

As regards trends, when I read these papers I reviewed them with the idea of seeing whether I could find any major trends, considered in a broad sense, and it seemed to me there were a few general conclusions that might be drawn.

Looking into the future, having in mind particularly large power stations for large power consuming areas, generating at a suitable voltage, and transmitting some distance, say, 3 to 15 miles, to load centers or substations, or 30 to 75 miles or more to high voltage terminal stations or subtransmission systems, I feel that we shall see more and more installations of generators and step-up transformers handled as units and bussed at some higher voltage. Trenton Channel in operation in 1925 is an early example of the former, except it has low voltage as well as high voltage switching, and Philo No. 3 triple unit, in operation in 1927, is an example of the latter. Such is also broadly and recently illustrated by Long Beach. The economic considerations, and to some degree continuity, reliability, and safety of service, will force that result, however much one may not want to give up a system scheme of generation and transmission upon which he is already launched. There will be many involved engineering problems to analyze carefully and to solve. An important one will be system stability, requiring the study of generator and transformer reactances, short-circuit bus excitation, system voltage regulation, speed of relays and oil circuit breakers, etc.

I believe we shall see more high voltage (66-kv and 132-kv) transmission terminals located near the theoretical load centers of areas of distribution and low voltage substations. Low voltage, high current capacity, expensive switching installations at generator voltage, with complicated and hazardous interlocking arrangements are sometimes necessary, but in this industry, which has not yet reached its ultimate possibilities, many power stations are already weighted down with serious problems arising from their present switching schemes.

I look forward to and hope for the day when the major power stations will be more strictly "power stations," considered electrically, and not a combination power station, high voltage terminal station, and low voltage distribution station all in one. Naturally the situation where power stations can be treated as one problem, terminals as another problem, and substations as still another problem, is ideal for the designing engineers, but that is not the reason I am emphasizing this point. It is true, we will probably never be able to do without the combination arrangements. Under many conditions, combination electrical station switching arrangements are economical and therefore of distinct advantage, but in the case of power generated at one place and transmitted several miles at generator voltage, say, at some voltage between 11,000 to 22,000 volts, to several low voltage distribution substations, a thorough and comprehensive study might possibly reveal that economics would dictate quite a radically different system arrangement. The correct solution from a system planning engineer's point of view is often obscured by close association with a system scheme adopted when load demands were small and scattered, when the art had not progressed, or the developments in generation, cables, and switching reached the place where we find them today. Why not generate at some suitable voltage, and step up directly by autotransformers if you like, to 66,000 volts for large stations with large power demands in large cities, and to 130,000 or 220,000 volts for such situations as Long Beach? Eliminate the low voltage switching at the power stations to a considerable degree; save and relieve the congestion of switching and large cables at power stations; provide more simple plant operation; work for greater reliability, therefore for greater continuity of service and less hazard to men and equipment; and withal secure marked economies in investments.

Another major trend I would mention, that I think I see, more or less paralleling the above, but adapted more especially to cities like Kansas City and Cincinnati, is that I believe American engineers are going to adopt and some day use more extensively still higher voltage generators and distribute at generator voltage. Generator designing engineers have said that 16,000 to 18,000 volts is the best voltage for which to design large generators, taking all factors into consideration. That may be true today, but who will say that it is always going to be true? I do not believe the possibilities in generator design have been exhausted.

In England, some of the engineers for utility companies coming under the scope of the activities of the Central Electricity Board, who are working for one large unified power system for Great Britain, are finding it not only possible but feasible, more efficient and economical to use 33-kv to 36-kv generators. C. A. Parsons & Co. have built 7 machines for 33 kv to 36 kv. The first one—a 25,000-kw unit—has been in successful operation since August 1928. It is reported this company is ready to wind direct for 50-kv certainly, and perhaps as much as 66-kv, in units of from 25,000-kw to 75,000-kw capacity. I would like to hear what the American manufacturers' designers have to say on this subject!

Some of the papers refer to troubles and developments in circuit breakers, and these indicate still another major trend which possibly might better be spoken of as a "continuing and expected improvement," namely: toward better circuit breakers and relaying, or switching in its larger sense. I feel sure there will be further developments in circuit breaker design and use. It seems to me that circuit breaker designers are barely keeping pace with other improvements in the power plant field, particularly as regards rupturing capacity, current carrying capacity, operation, reliability, method of breaking the arc, and other details in construction.

H. Y. Hall: The papers presented here today indicate that switching equipment used in the large electric power systems is still far from standardized, in fact it appears to be in a state of flux. Not only are radical changes being made in the switches themselves, but methods of assembly and arrangements of the various elements of a complete switching station vary greatly.

The fact that all the stations described have given such satisfactory service speaks well for the equipment itself, the station designers, and also for the skill and care of the operating personnel.

Apparently the trend is away from the isolated phase concrete construction exemplified by earlier stations, including Richmond and to some extent Hudson Avenue, and toward some form of metal clad construction.

Essex uses air insulated switching and is attempting to reduce the amount of oil used to a minimum. In line with their desire to eliminate entirely the oil in future installations, they have made a trial installation of the new deion circuit breaker. All of us are oil fire conscious these days and realize that as long as oil is used, there will always be trouble from oil leaks and danger of oil explosions and until a noninflammable substitute for oil is obtainable at a reasonable price, it will be impossible to entirely eliminate dangerous oil fire hazards.

A recent transformer oil fire at Hell Gate illustrates this. The explosion of a 27-kv pothead shot a piece of casting into and punctured the radiator of the adjoining transformer, letting out a stream of oil, which sprayed onto the hot pothead and ignited. Both the compound in the pothead and the oil caught fire and considerable damage was done to overhead bus work and switches before it could be extinguished. This experience indicates the need of a rugged barrier between the pothead and the transformer, so that flying pothead parts will be prevented from striking the transformer radiators, especially where the radiators are made of very thin metal. It also indicated the desirability of providing each radiator with valves.

Such an explosion might conceivably occur in any of the oil or compound-filled metal-clad switching stations and with a large supply of oil available to feed a fire, it is possible that considerable damage might be done, not only to the equipment itself, but also to adjacent structural work. Also, the hazard to operating personnel is always present.

As pointed out in the State Line paper, there are very real restrictions imposed on the maintenance of outdoor switching equipment during several months of the year. Even the changes suggested by T. C. White, would not, in our opinion, satisfactorily overcome the difficulty where the winters are cold and snow storms frequent. In extensive switching stations where equipment is heavy, the unfavorable working conditions might be a serious matter, especially if a major failure should occur. For heavy equipment, men especially trained for that class of work are required and it greatly simplifies the problem of organizing a suitable maintenance crew if a few men with the proper training can be kept busy on the necessary inspection and maintenance work throughout the year. In this way, defects can be remedied promptly before serious failures occur.

One advantage of the metal clad switchgear cited at Essex station is that better protection to busses and equipment may be obtained by insulating all metal enclosures, except for ground connections, and so by this means obtain simple and reliable relay protection against faults in all busses and switching apparatus. Apparently this has

not been done at State Line; possibly they did not think the additional expense justified. Perhaps Mr. White can enlighten us on this point.

Unless the ground connections to these insulated enclosures are properly installed and maintained, they might present a real hazard to the operating personnel during short-circuit periods.

One advantage of the metal enclosures, not stated, is the greatly reduced thickness of the barrier, permitting a corresponding reduction of switch center dimensions. Essex claims short length of busses resulting from the arrangement used.

Although it does not appear so on first thought, it is a fact that for the same switch-pot centers, the length of busses for a segregated phase system is about one third of that for the mixed phase system. All circuit breakers now in use on segregated phase systems have tanks so large that they are placed on 3-ft to 4-ft centers. A segregated phase system using deion type breakers and metal enclosures would be economical of busses and also of floor space.

Both Hudson Avenue and Essex make use of an equalizer or synchronizing bus for better distribution of load to the power sources. Hudson Avenue makes use of a very unusual and ingenious bus arrangement which they term "star bus" in absence of a more fitting term. It is a flexible arrangement particularly with respect to generator connections. In the case of Essex, according to the diagram submitted, interconnections to other power stations can be obtained only through the equalizer bus as a medium and if it should be out of service for any reason, apparently the station ties would have to be cut out.

Sectionalized duplicate ring busses provide a very reliable and flexible arrangement and the simple layout is easy to operate. We are inclined to agree with the author of the State Line paper that this is the most desirable arrangement to meet all requirements.

In recent years many of the power stations have become so large with reference to the systems supplied, and continuous power supply so important, that some companies have found it advisable to operate stations in 2 or more distinct parts on the electrical end (and also on the steam end as far as practical) so as to minimize the extent of any major fault that might occur. These separate sections are usually further subdivided by reactors into small groups of feeders. Moreover, when feeding into distribution network system with their transformer and network protectors, problems of voltage and phase angle control become important considerations.

With the above conditions in mind, the wisdom of installing very large turbine-generator units is open to question. In addition to the usual objections to such large units, such as the large reduction of station capacity when they are out of service for repairs, the larger reserve capacity required to replace possible outage and the uneconomical loadings of very large units, there are difficulties of distribution of the output to different bus sections, which under present-day layouts is usually required. The difficulties referred to are those of voltage and phase angle control on the branch circuits of the generator or its direct connected step-up transformer. The use of double-wound generators does not overcome these difficulties.

Smaller generators meet the above requirements much better and should be just as economical. Also their use would reduce the required rupturing capacity, size, and cost of switching equipment. The lower cost per kilowatt of very large units is largely offset by the necessity of supplying additional reserve capacity above that of the small unit installation.

In this connection, it is interesting to note that State Line No. 2 unit is 50,000-kw smaller than No. 1 unit.

Richmond Station is using copper channel with frequent expansion joints for connecting the 165,000-kw generator to the bus. For this purpose, large stranded rope center copper cables possess some distinctive advantages, especially when it is desired to use insulated conductors.

J. K. Ostrander: An analysis of the various systems of connections for main bus circuits applying to all large power stations constructed during the past 25 years would show that by far the most common system is the one with 2 main busses, to which all circuits are connected by 2 selector oil circuit breakers. In most cases the busses are sectionalized with reactors in the bus or in the individual circuits.

This system of connections has become almost a universal standard, probably because of the indisputable merits of such an arrangement. However, many power stations of the future for several reasons will not follow this design. First, problems of economy may prevent the use of more duplicate equipment than is absolutely necessary; second, problems peculiar to the very large station may dictate other courses of procedure; and third, interconnection of stations, such as is now quite common practice, has a tendency to make unnecessary most of the duplication of equipment formerly considered essential. In many power systems it is possible to lose a generating unit with all the electrical circuits associated with it, without any adverse effect on the load.

It is quite possible that conditions over which the operating company has no control, such as the necessity for lower property costs to make possible unavoidable low rate schedules, may make it necessary to give more attention to the cost element than heretofore required.

The future cost of transmission and distribution per kilowatt of energy generated will undoubtedly be reduced from necessity. If a 13,000 or 26,000-volt feeder be connected to the station bus with a circuit breaker installation costing more than the feeder itself, any saving effected in the distribution system may be offset by excessive costs in the switching equipment group of apparatus. This does not mean that a sacrifice must be made in operating reliability. During recent years great improvement has been made in circuit breaker design and breakers rarely fail in service. Development of the metal-clad equipment has not only reduced the liability to failure but has made it possible to localize the disturbance if failure occurs.

A system of connections using only one circuit breaker per feeder, as provided at Hudson Avenue and Connors Creek, indicates how duplication of equipment may be avoided without sacrifice of reliability.

In general, unit costs are reduced as the size of the station is increased but this is not necessarily true of the switching equipment. In fact the large size of the station may in itself be the cause of high unit costs for the electrical installation.

Considering the electrical system only, it should be more economical to build a group of moderate size stations than one very large station. This is chiefly due to the expensive equipment necessitated by a large concentration of power on the bus. The expedient of designing the large station so that it becomes similar in its electrical connections to a group of smaller stations is often quite effective in reducing costs.

Synchronizing at the load is one means for accomplishing this result. Another is the use of the synchronizing bus which has possibilities of being very effective under certain conditions. The bus connections at both Hudson Avenue and Connors Creek provide one apparently successful method of coping with the problems incident to a large concentration of power on a single bus.

Several recently constructed stations have apparently obtained good results from the use of the fault bus. The principle of this device is no doubt good but it has the objection of introducing complexities into the layout of the switching equipment. Before the fault bus scheme is adopted, I believe a strong effort should be made to devise a simple and effective system of differential protection which does not require any special type of construction for the bus and its connections.

A generating station whose load is transmitted by a comparatively few high voltage circuits generally requires a radically different electrical design from that of a station with a large number of low voltage circuits. Due to the high investment in each transmission line, it is highly important that no line shall be out of service due to outage of switching equipment; therefore a high investment may properly be made for the switching equipment of each line. Duplicate busses and other elements of high cost may be justified. The systems of connections used for the State Line and Long Beach plants are good examples of what might be proper for this type of station.

K. C. Randall: The committee sponsoring this switchgear symposium and the authors who have contributed papers are to be congratulated on the very interesting and informative data which has been presented. A. H. Lovell pointed out that although originally an economic survey was contemplated, it could not be carried out. In such a survey of these stations with their widely differing generating capacities, bus arrangements, and types of load, it is immediately apparent that any attempt to set down dollars against results will be very difficult. In 10 years—1922 to 1932—from the earliest (Hudson Avenue) to the latest (Essex) both apparatus and assembly designs have progressed, naturally reflecting those years of research, design, manufacture, and operation. It would not be fair to compare directly such structures, built 10 years apart, even were they intended for identical conditions, which is not the case. Never-

theless, much data is given to warrant some conclusions of an economic nature.

The first of these stations used metal-built gear for its auxiliaries and so do the others. That original gear has performed satisfactorily, but it in no way compares with the present designs. The recent advance in the coördination of apparatus design and assembly design is conspicuous. Where formerly individually good apparatus was available, now completely assembled equipments are available in which the separate devices are coördinated, both mechanically and electrically, into a harmonious functioning whole. Such factory-finished, tested and proved, fully assembled equipment, is shipped ready to run. Formerly, it was common practice to spend a lot of time and money in the field in detailed checking of wiring and mechanical clearances. The equipment had to be proved and that was the way of doing it. Better designs and improved manufacturing facilities have of course done much toward this progress, but extensive and very heavily powered testing equipment has contributed most to making tests, where previously only opinions prevailed.

The economies from convenience in shipping, handling and ease of installation of fully assembled equipment are distinctly a case of foreseen problems matched with a carefully planned design. The reliability of the ultimate service is not only considered, but also the time, effort, and cost previous to beginning regular operation.

Modern metal-built gear is adaptable to every power purpose regardless of capacity. The high order of demonstrated reliability of this type of equipment is significant. It is already generally used for station auxiliaries and in a number of cases for the main switchgear. It is interesing to note that the initially planned periods for inspection and maintenance are gradually extended as experience justifies this increased confidence and associated economy. Surge trouble immunity is also significant in the fact of recorded experience of very high peak values.

To summarize: the evidence of these papers certainly suggests economic justification is thoroughly back of the increasing use to which we find metal-built gear is being put.

C. H. Sanderson: The 5 papers comprising this symposium serve as illustrations of the lack of similarity in the design of switching equipments for generating stations. They are the product of dissimilar specifications; therefore, the dissimilarity of design was inevitable. The same may be said of any other group of stations.

Even though the designs were based upon identical specifications it is quite probable that they would still be lacking in similarity as has been indicated recently in the various solutions to hypothetical problems. This also is inevitable, as there are so many ways of arriving at some kind of a solution. As C. M. Gilt has said in his conclusion, choice often has to be made between the advantages and limitations of one design and the somewhat different advantages and limitations of another. And in the same paragraph he has given the words for a legend which might be placed over the door of any station—a compromise between cost and a closer approach to technical perfection.

One feature, however, in which similarity appears to indicate more than a trend is the group operation of equipment. The single or solid bus and the closed ring bus have given way to the operation of the station and system in groups or sections with proper relay protection to localize troubles that otherwise might be system disturbances.

Differential protection of group busses appears to be giving satisfactory operation. Every one will agree, however, that it should not be called upon to demonstrate under operating conditions if this can be avoided at any reasonable expense. The insulation of the busses and connections thereto at least as far as the first protective breakers, also between generator and breaker, merits particular attention. Dependence upon many single porcelain units within this area appears to be a potential hazard which might be greatly reduced by the use of other forms of insulation having a less abrupt characteristic of deterioration and, therefore, more subject to control through some method of periodic testing.

The disconnecting device between bus or generator and the first protective breaker is another potential source of serious trouble. The bayonet type disconnectors employed with the elevating or truck type breakers have given some trouble. One recent instance is recalled where an entire plant was shut down because of failure of the bayonet type connector between a generator and its breaker. For the more important locations the conventional knife switch disconnect or the later oil insulated disconnect appear to be more dependable and more readily maintained.

The State Line installation has contributed greatly to the perfection of heavy duty outdoor switching equipment. It has a good operating record and the popularity of oil filled metal clad switching equipment has increased in that district. However, considering the suggested improvements, such as adding of decking and siding, and control system safeguarding, and considering weather conditions in the northern states as they affect the equipment and its ready maintenance, especially for circuits of such great capacity and importance, it would seem that an enclosure as represented by an inexpensive form of building shell, with low roof and sides, permitting some decrease in cost of equipment and considerable decreased cost and added convenience in maintenance, would provide an installation which would prove a serious competitor.

The Essex switching station at Connors Creek is of particular interest as it is the culmination of many years of experience in the design and operation of this class of equipment. Future operating and maintenance experience will be of general interest because of the elimination of formerly used housing materials for metal compartments and housings throughout.

The use of armored control cable is another step in advance and should prove cheaper in cost and maintenance or extension than any form of rigid conduit installation.

The Hudson Avenue ground and test switches, partially shown in Fig. 6 of that paper, should be of particular interest wherever 2 or more feeders are to be connected to a single feeder circuit breaker, especially where the feeders supply network load. By means of this device any feeder may be opened under load without disturbing the others, may be left free, or grounded or connected to the test bus. They may be designed for manual or electrical remote operation or a combination of both. It is to be hoped that the manufacturers will produce a simplified and compact design at moderate cost so that their application can be greatly extended.

Philip Sporn: Station and substation design papers have altogether too frequently been open to the criticism that they give a description of what has already been accomplished and do not go into the fundamental basis of design, with the result that they are of little use to the practicing engineer or the student trying to find out the "whys and wherefores" of the existing practice. In this regard the aim for this symposium, as stated by Professor Lovell, is entirely praiseworthy and it is to be regretted that the papers as a whole do not stand up when measured by this criterion.

Professor Lovell states that the trend is toward higher voltage for bussing at the generating stations, and even for the generators. I do not believe that any general statement that a tendency for the generator voltage to go upwards is true. In the case of the Philo 165,000-kw unit, a generator voltage of 11,000 volts was selected and if this machine were being installed today I believe that it would be at the same voltage. We recently had a case in connection with the rebuilding of a small hydroelectric plant in which the original generators were designed for 13.2 kv. A study of this particular plant showed that 4,150 volts was the most economical design. In another case 6,900 volts was originally considered but 4,000 volts was finally used. Each case must receive individual attention before the generator voltage can be determined, and it is a case of considering the combination machine and switching design and not simply a question of amperes to be switched.

The paper on State Line station is an elaboration of the paper on the same subject presented about 4 years ago by A. M. Rossman, and was discussed at that time by several, including the speaker. There are, however, 2 points I should like to call attention to in connection with this paper:

1. In the original discussions as to the safety and the economics of this type of switching, the discussion mainly centered around the question of whether or not the economics were sound. One of the factors that influenced the choice of outdoor gear was the expected greater safety of outdoor equipment. It is interesting to note that at another station having the same type of switchgear, there occurred about 2 years ago one of the most disastrous fires ever experienced at a power station.

2. The economics of the plan which were discussed and questioned at the time Mr. Rossman's paper was presented are, I believe, still not settled and personally I doubt if today the economics of this type of gear are particularly favorable.

The paper by Raymond Bailey and F. R. Ford covering the Richmond station of the Philadelphia Electric Company is a descriptive paper and is open to the same criticism previously indicated; namely, that the authors do not thoroughly discuss the basic reasoning behind the adoption of the particular switching arrangement.

The paper by A. P. Fugill covering the switching station for Connors Creek is again in the descriptive class, but the infor-

mation is of special interest in that it does show that considerable progress has been made toward simplifying the switching scheme. The operation of the generator and transformer as a unit and tied to a single main bus and the elimination of high voltage breakers at the distribution substation, shows progress in the simplification of switching. Comparing this switching arrangement, for example, with Fig. 2 of the paper by Messrs. Bailey and Ford, one cannot help but raise the question whether the Richmond layout having 2 busses with selector breakers and in certain cases 2 switches in series can be justified in any but the rarest cases.

Mr. Gilt's paper on the Hudson Avenue station shows a switching layout that is somewhat similar to that of Connors Creek. However, Connors Creek having been built later than Hudson Avenue, shows, as would be expected, further progress toward simplification. It is interesting to note that after careful consideration it was decided that one feeder breaker per feeder at the generating station was all that could be justified when considered from the standpoint of costs, complications, and hazards. I believe that thorough consideration of all factors involved will lead to similar conclusion in 9 out of 10 cases.

At the Hudson Avenue station reactors are used in the radial feeders; it is interesting to note that for Connors Creek switching station a study of costs showed that it would be cheaper to use the higher interrupting capacity breaker and eliminate reactors. This difference in practice may be and probably is entirely due to progress made in breaker design in the period intervening between the time when the 2 designs were laid down.

There are 3 points I should like to make in connection with the paper covering the switching at Long Beach plant No. 3. The authors mention that they recently found that it was possible to synchronize by means of the 220-kv oil circuit breakers rather than the generator oil circuit breakers. On our own system we have been following the practice of synchronizing by means of the 132-kv oil circuit breakers since about 1925. Prior to that time breakers were included on the generator side because it was felt that there might be some difficulty in synchronizing on the high voltage side.

While it has no particular bearing on the switching, I should like to say a few words with reference to the subject of frequency control. The authors state that on their system they hold speed within a fraction of a cycle so as to maintain an average frequency of exactly 50 cycles over longer periods of time and that sudden swings of 10,000 kw are a rule rather than an exception. An average frequency of exactly 50 cycles over long periods of time does not, of course, mean anything nor is this an indication of good frequency regulation. On some of the large eastern interconnected systems it has been found advisable to hold frequency within very close limits at all times, at least within 0.1 cycle; in some cases the time deviation has been kept within 15 cycles, that is, within 0.25 sec. On the large interconnected systems about which I am speaking, swings greatly in excess of 10,000 kw are not uncommon. On these extensive interconnected systems involving several million kilowatts capacity, experience has demonstrated that economical operation demands that frequency be held at all times within about plus or minus 0.1 cycle or less. Frequency regulation and power transfer across tie lines are closely related and if frequency is not continuously closely regulated system performance invariably suffers.

Regarding the question of auxiliary power, I do not believe that either a separate house generator or a direct-connected house generator can be justified and that the only scheme that can be justified is one taking the auxiliary power off the main generator through a directly connected transformer bank. In most cases the interconnections will always furnish at least sufficient energy for starting the plant auxiliaries; anything more elaborate than the above arrangement can only be justified, therefore, by blinking at economics.

In conclusion I should like to repeat that I believe these papers are entirely too descriptive and it is to be hoped that some day we can get a symposium giving a frank analysis of a series of switching schemes, the ends aimed at, how nearly the ends were attained, and what changes, in fundamental design, in material, or in detail would be made if the switching scheme were restudied in the light of current thought and in the light of experience with the old one.

C. W. Taylor: There are references in the papers on switching of energy at power stations to certain fundamentals that are of particular interest to the designer of switching stations, as follows:

The double bus arrangement with sectionalizing reactors has been recognized as having considerable flexibility, but State Line has had occasion to use some of the less frequent switching combinations during normal operation, as indicated in T. C. White's paper. The particular system of major transmission connections existent in and around Chicago, combined with the unforeseen changes in load conditions and the interrupted construction schedule, have introduced operating problems at State Line station requiring redistribution of load among the feeders paralleled or tied together at remote points of the system. It was found possible with the twin busses to select the switching so that advantage could be taken temporarily of the bus reactors as a load balancing agent. With the unexpected advanced installation of a large feeder without its intended source of power, it was found a certain section of the bus would be overloaded, but by using a section of the reserve bus this could be avoided.

The development of switching and current handling facilities has scarcely kept pace with the demand for larger power circuits, and to some degree has retarded the use of large circuits. Some designers therefore have resorted to higher voltages. It is gratifying to note that where higher generating voltages have been used, apparently no real difficulties have been encountered because of the higher voltage, up to and including 22,000 volts, so that now probably 33,000 volts would prove satisfactory.

The advantages of ground fault protection have been recognized for a number of years by many engineers. The metal-clad design is particularly adapted for this form of protection of the bus structure. This is true whether it is a metal cell structure of a more or less conventional design assembled in the field, or a so-called unit type metal-clad gear built in the factory; whether it is installed indoors or outdoors. It will be noted both the Essex and the State Line stations, where metal enclosures are used, have sectionalized ground fault protection.

Interlocking has been one of the designer's problems in providing safety features. He has resorted to electrical and mechanical interlocks, and combinations of the 2, and in some cases has purposely omitted interlocks almost entirely. They are liable to become intricate and cumbersome, even to the extent of becoming a hazard in themselves. Irrespective of whether the designer tries to go the limit, or to restrict himself to the minimum, the factory built metal-clad unit design lends itself to the maximum degree of safety as to interlocking features, with the greatest degree of ruggedness and simplicity, and because of its inherent design, the minimum number of gadgets with a greater degree of precision.

Fire hazards have been referred to in some of the papers. Most designers give some consideration to hazards from indoor switching, but, except to meet the insurance companies' requirements, there seems to be a tendency to give this subject only a casual consideration in other respects. Insurance regulations must necessarily be quite general and therefore are a poor guide for design. There have been instances where a sufficient amount of training of the operators on duty in the proper use of perfectly good fire fighting equipment has been conspicuous by its absence. Combine this condition with a fear of explosion at a switching or transformer station, and the opportunities of a good fire are unlimited. It would be of value to the operators and designers of switching and power stations if a complete report of all fires could be made available for comparison and study, such a report to describe the relative location and details of equipment, operating conditions, cause of fire, how combatted, and suggestions as to how fire could have been avoided or its severity decreased.

H. L. Wallau: The method of operating our 132-kv lines is very similar to that outlined for the 220-kv lines of the Southern California system.

The fundamental idea involved is that high voltage lines shall not be operated in parallel. At both the Avon and the Ashtabula plants the generators supply unit busses which in turn feed step-up transformer banks connected to individual high voltage lines.

There is also provided a 13-kv synchronizing bus to which the generator unit busses are connected through reactors. This connection enables the kilowatt loading of the generators to be equalized and also enables their operation at different voltages (within the plus or minus 5 per cent range permissible) thereby providing some control over the reactive output of the generating units.

At the receiving stations paralleling is done on the low voltage side. Opening the synchronizing bus tie breakers at the generating plants permits operating synchronized at the load.

The means of providing reliable supply

for auxiliaries has been previously discussed. (See A.I.E.E. TRANS., v. 51, 1932, p. 349–50.)

This 132-kv system, now comprising 416 miles of 3-phase, 4/0 circuit, is tied into the Lake Shore plant through 2 ties, each consisting of a 132 to 66-kv and a 66 to 11-kv transformer bank joined by 8 miles of 66-kv underground circuit. No high voltage paralleling occurs in this connection.

It is evident that for this system also the transmission lines and transformers operate in parallel to the load and in series to a short circuit.

It has been calculated that with these 3 plants fully developed to their expected maximal combined capacity of 1,000,000 kva and no interconnections with other systems the maximum short circuit to be interrupted will be, line to ground, 260,000 kva, and 3-phase, 730,000 kva. With the existing interconnections closed, these values increase to approximately 325,000 kva for line to ground, and 975,000 kva for 3-phase. Interrupting ratings of breakers called upon to perform this duty are 1,500,000 kva.

That these short-circuit values are much lower than would be obtained with parallel operation of high voltage circuits is illustrated by the following (d-c board) calculation.

A bushing failure at a time of light load when all interconnection ties were open produced a line to ground short circuit of 133,000 kva. Under similar conditions, except for line operation paralleled on the high voltage side, its value would have been about 312,000 kva, a value almost as great as calculations indicate will result when the complete development has taken place.

Auditory Perspective—Basic Requirements

Harvey Fletcher, January 1934 issue, p. 9–11.

Auditory Perspective—Physical Factors

J. C. Steinberg and W. B. Snow, January 1934 issue, p. 12–17.

Auditory Perspective—Loud Speakers and Microphones

E. C. Wente and A. L. Thuras, January 1934 issue, p. 17–24.

Auditory Perspective—Amplifiers

E. O. Scriven, January 1934 issue, p. 25–8.

Auditory Perspective—Transmission Lines

H. A. Affel, R. W. Chesnut, and R. H. Mills, January 1934 issue, p. 28–32, 214–6.

Auditory Perspective—System Adaptation

E. H. Bedell and Iden Kerney, January 1934 issue, p. 216–9.

Discussion of a group of papers presented for oral discussion at the session on communication at the winter convention, New York, N. Y., Jan. 24, 1934.

H. H. Spencer: [Ed. Note: This discussion deals primarily with the subject of radio transmission of music and its reproduction in homes, whereas the papers of the symposium under discussion deal with wire transmission of music and its reproduction in large halls.] The remarkable achievement of transmitting and reproducing symphonic programs so that auditory perspective is maintained should not tempt us to neglect some of the more fundamental factors which contribute to satisfactory musical reception. One of these is the variation in relative loudness level throughout a given selection; the quality in a performance which musicians frequently refer to as color.

Careful monitoring of the transmission circuits either manually or automatically can eliminate most of the unintentional variation in energy level at the transmitting antenna. The development of modern receiver circuits utilizing automatic volume control further protects the fidelity of the signals up to the loudspeaker. The problem still exists, however, for the listener to adjust the average volume of his loud speaker output on the one hand so that the loudest passages will not be unpleasant either from distortion due to overload of the receiver or simply from being too loud for the location of the receiver, and on the other hand so that the softest passages will not be lost.

It would seem to be entirely practical just before the start of a symphonic program for the transmitting station to broadcast a test note. The listeners would be instructed to adjust the output level of their sets to bring this note just to the threshold of audibility. By prearrangement with the performing artist—the conductor in the case of symphonic broadcast—the transmitted energy level of the test note could be so adjusted that the entire program would be within the range of high grade receivers.

The listener then would be relieved of the distraction of having to find the correct volume level adjustment by repeated trial. The artist would have the gratifying assurance that the listeners were receiving the program with exactly the same color as his original performance.

Stabilized Feed-Back Amplifiers

Discussion of a paper by H. S. Black published in the January 1934 issue, p. 114–20, and presented for oral discussion at the committee on communication of the winter convention, New York, N. Y., Jan. 24, 1934.

G. Ireland: To engineers concerned with the operation of the long distance telephone plant the many transmission advantages of the stabilized feed-back amplifier, as outlined by H. S. Black (ELEC. ENGG., Jan. 1934, p. 114–20), will be welcome; those involving greater stability and freedom from modulation effects being of especial importance.

With the long toll cable circuits of today involving a considerable number of voice frequency telephone repeaters, variations in the overall net losses of the circuit represent one of the important limitations on the minimum net losses that can be obtained. With the greater number of repeaters to be used in cable carrier circuits of the future and the greater gains and attenuations involved the problem of holding the circuit variations to a low value becomes more difficult. Consequently, the arrangements described by Mr. Black which, under normal maintenance conditions, practically removes the amplifiers in the circuits as a source of variations will be very helpful. Furthermore, the freedom of these amplifiers from variations and modulation effects not only will simplify the circuit maintenance but in the future is expected to permit the operation of the additional stations, which will be required, on a partially attended or unattended basis. Also, transmission testing equipment can be provided which will be capable of measuring large gains and losses and yet through the application of the feed-back arrangements to the vacuum tubes in the testing circuits will be much less subject to changes in battery voltages which will require recalibration of the measuring equipment.

Although the first vacuum tube telephone repeater was not placed in operation in the telephone plant until about 1913, today there are more than 100,000 telephone repeaters and about 4,000 carrier amplifiers in the telephone plant of the United States. Nearly half the telephone repeaters are of the 4-wire type and are applied to the 4-wire circuits employed for distances of more than about 150 miles.

Looking to the future application of stabilized feed-back amplifiers, it is probable that practically all new carrier repeaters in the future on both open wire and cable will be of the stabilized feed-back type. Since the cable in carrier systems of the future is expected to be used not only for the longer circuits, but also circuits as short as 100 miles or less in length, it is probable that the stabilized carrier repeaters will be largely used where 4-wire repeaters have been used in the past and in some cases where 2-wire cable circuits and repeaters have been used. Consequently, it is expected to find very important application in both the toll cable and open wire plant of the Bell System. In addition, it is expected to be used in the future on transmission testing equipment, as noted previously in connection with program amplifiers and even in the voice field

where perhaps greater emphasis may be placed on the securing of economies in the design of the amplifiers through the application of the feed-back principal. In conclusion, it may, therefore, be stated that the stabilized feed-back repeater should find very general application in the telephone plant and due both to its extended application and its many advantages should considerably change and simplify the present method of operating and maintaining long distance telephone circuits.

H. W. Dudley: The stabilized feed-back discussed by H. S. Black (ELEC. ENGG., Jan. 1934, p. 114–20) was tried out on a 20/500-kc amplifier. The main requirements were 0.5 watt output and 65 db gain with 25 db feed-back loss in the 20/500-kc range.

The most important problems encountered in this amplifier were: first, to get sufficient gain and, second, to prevent the amplifier from oscillating or "singing." The chief difficulties in both cases are due to stray capacitances. These produce shifts in phase that make the amplifier become unstable and oscillate at some frequency.

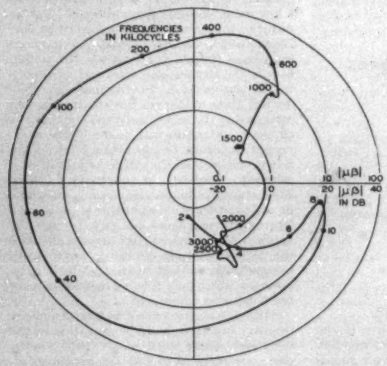


Fig. 1. Measured $\mu\beta$ characteristic of first 20/500-kc amplifier

Again the stray capacitances between vacuum tube electrodes make for low impedances. At each tube a high plate resistance is then working into a low capacitive reactance. The result is that the voltage amplification in a 3-stage amplifier drops off almost as the cube of frequency. As an example an amplifier modified to work to twice the frequency will have 18 db less gain before feed-back is applied. This means that a broad band amplifier must be made with less gain at the higher frequencies unless a better design is used. The better design may be one having better tubes or one having less stray capacitance.

The amplifier was built having two stages of voltage amplification and a power stage. The gain problem was solved by using a specially designed tube with 2 extra grids in the voltage stages and another in the power stage. One extra grid shields out the effect of the tube capacitances. In the voltage tube the second extra grid increases the gain by reducing the space charge effect; in the power tube it prevents secondary emission. The oscillation problem was overcome in part by cut-and-try methods and in part by allowing for the stray capacitances in the design.

In Fig. 1 of this discussion is shown the measured $\mu\beta$ characteristic of the first amplifier of this type that was built. It is seen that the point 1,0 (this is the stability criterion proposed by H. Nyquist in "Regeneration Theory," *Bell Syst. Tech. J.*, Jan. 1932) is not enclosed by this curve. Whenever a $\mu\beta$ measurement showed this point enclosed it was checked that the amplifier would sing when set up again as a feed-back amplifier. Another model of this amplifier was built having about 10 db more gain before feed-back. In Fig. 2 of this discussion is shown its measured gain-frequency characteristic. These amplifiers gave the expected improvements in general. They indicate that the feed-back principle can be used advantageously up to frequencies of 500 kc at least.

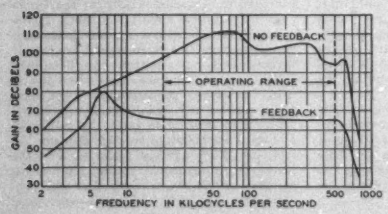


Fig. 2. Measured gain of second 20/500-kc amplifier

Petersen Coil Test on 140-Kv System

Discussion of a paper by J. R. North and J. R. Eaton published in the January 1934 issue, p. 63–74, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., Jan. 23, 1934.

J. E. Clem: In the Appendix outlining the mathematical treatment the authors have defined C_e as the zero sequence capacitance to ground of transmission system with one conductor grounded. This designation is not quite exact and might lead to a misunderstanding. By definition, the zero sequence capacitance of a transmission line is the capacitance to ground (and ground wires if present) of one conductor when all 3 are in parallel. This apparent inconsistency has not affected the results of the calculations because the proper value of capacitance was used.

It can easily be shown (reference 7 of paper) that the charging current in the fault which flows to ground when one line is grounded and the 2 sound lines are at phase-to-phase potential above ground is exactly the same as the current which would flow if the 3 lines were in parallel and phase-to-neutral potential applied. This is the value of capacitance which the authors actually used in their calculations.

The prime function of the device as indicated by the authors is the removal of faults from the system without anywhere near as great a shock as that occasioned by the same fault without the Petersen coil. Curves shown by the authors indicates that the exact tuning is not a requisite for the function. There is another advantage from the use of the Petersen coil and this was the purpose of the original invention. That is, the reduction of arcing ground overvoltages. When the Petersen coil is in use, it is impossible to build up arcing ground overvoltages whether or not the fault is actually extinguished and exact tuning is not a requisite for this effect.

Whether or not arcing grounds exist is a fact questioned by many. While it is true that staged tests have invariably failed to reveal their presence, it is also true that isolated delta operation in the early days was rendered exceedingly difficult and in some cases impossible by arcing grounds. From time to time a sufficient number of instances of overvoltages which can be accounted for in no other way have come to our attention, and have convinced us that they may actually occur. Present-day insulation levels are usually so high that any arcing ground which might occur is not noticed unless some piece of equipment has its flash over lowered or insulation strength impaired by moisture, dirt, or some other cause.

In a design of Petersen coils it is essential to consider the steady circulating current which might flow. Any unbalance in the arrangement of the line conductors will set up a zero sequence voltage and this in turn will cause a circulating current to exist under steady operating conditions. The thermal capacity of the Petersen coils may have to be increased to take care of this steady current.

C. L. Gilkeson: In connection with its studies of ground fault current limitation one of the project committees of the Joint Subcommittee on Development and Research has been investigating, for the past several years, the subject of overvoltages resulting from line to ground faults on power systems. In addition to the observations on the Petersen coil system discussed by the authors, observations have been made on an extensive isolated neutral system, 2 systems grounded through neutral resistance, and one directly grounded. The voltage disturbances were recorded by automatic magnetic oscillographs which were in operation by the end of the first cycle. In all but one installation string type vibrators were used which have a fairly uniform response for frequencies up to 3,000 cycles, thus permitting a good indication of harmonic frequencies which may be present. On 2 of these systems the oscillographs were supplemented by surge recorders.

Data obtained from these installations cover periods from about $1^1/_2$ to 2 years. As expected, the highest values of overvoltages were recorded on the isolated system. It is interesting to note that for this system, which was from 600 to 800 miles in length, oscillographic records showed that only 1.3 per cent of the records obtained under fault conditions indicated voltages above 3 times normal, with a maximum of 3.9. Similar records from the systems grounded through neutral resistance, or solidly grounded, indicated no voltages exceeding 3 times normal.

In the analysis of the surge records those which indicated only highly damped figures have been attributed to lightning and therefore omitted from this analysis. Since the surge recorder indicates the time of disturbance most of the figures have been correlated with known disturbances on the system. The analysis of the surge recorder records indicates that on the isolated neutral system 13 per cent of the records exceeded 4 times normal, the maximum being about 5.4 times normal, while on the other system 2.7 per cent of the records exceeded 4 times normal, with a maximum of 4.7.

A careful inspection of the oscillograms failed to reveal any indication of the so-called arcing ground phenomenon, that is, the building up of the voltages on the sound phases due to successive restrikings of the arc. The nature of the overvoltage appeared to be 60 cycles, in some cases with lower harmonics adding slightly to the maximum value of the fundamental.

A. U. Welch: The Petersen coils mentioned in the paper are iron core reactors whose reactive kilovoltamperes are obtained by gaps in the core leg, the reactance being adjustable by means of taps in the winding. A motor driven tap changer is provided on each tank arranged for remote operation and position indication. The tap changer is interlocked with a circuit breaker so connected as to prevent current flow through the Petersen coil while taps are being changed. The general construction of the Petersen coil is similar to transformer practice and the appearance of the reactor is very similar to that of a transformer, except that only 2 bushings are provided.

A thyrite resistor permanently connected across the Petersen coil winding and mounted in oil within the tank was provided for the following reasons:

1. It was desirable to use a transformer neutral bushing based upon only the system line to neutral voltage, and in the interests of economy, to design the Petersen coil itself for only neutral voltage. Insulation for neutral voltage is quite safe enough so far as dynamic voltage is concerned, but the neutral circuit will be subjected to lightning voltages of the same or greater magnitude than the transmission line. A resistor or a lightning arrester is required to hold the impulse voltage of the neutral to a value safe for the Petersen coil insulation. The characteristics of thyrite permit its use in an oil-immersed resistor to provide adequate protection from impulse voltage, and capable of withstanding the dynamic voltage for 10 mins. For much longer duration of dynamic voltage, it would be necessary to use a lightning arrester. The resistor, when it can be used, has the practical advantages of low cost and adaptability to assembly in the same tank as the Petersen coil.

2. Operating experience with Petersen coils in other countries has shown that, if no protection is provided in the neutral circuit, impulse voltages will increase in magnitude by reflecting at the transformer neutral and may flashover the neutral bushings even when these bushings are the same as the transformer line bushings. The fact that no such trouble has occurred at this installation indicates the protective value of the resistor.

3. Certain transient circuit conditions, as, for example, nonsimultaneous opening of phases in a circuit breaker, may cause a partial series resonance and a building up of voltage. The negative resistance-current characteristic of the thyrite resistor acts to prevent this resonance and excessive voltage. The Petersen coil cannot be designed to operate at a high flux density (near saturation) on all taps. When the coil operates on the high reactance taps, the resistor offers the only method of limiting voltage rise.

I would like to point out that there are several methods of neutralizing the residual in-phase current in the arc. These schemes involve switching a voltage taken from the transmission line into an auxiliary neutral circuit. The application of residual current compensation will permit self-extinction of line to ground faults on a power system of any size.

A. P. Schnyder: Supplementing the authors' description of tests and discussions of the results obtained, a word emphasizing the fundamental purpose of the Petersen coil and other equivalent equipment of various European manufacturers may be in place. Such equipments prevent disturbance on or damage to the transmission line as caused by line-to-ground faults, which according to the authors constituted 75 per cent of all the disturbances of their system, and on other systems have been reported to be a higher percentage yet. In comparison with these ground current quenching devices the most up-to-date high speed protective relay equipments only will disconnect from the system by breaker operation the faulty section before any damage from power arc could be caused on the line conductor. The former bring about the self-clearing of the line-to-ground faults without any breaker action whereas relays cause tripping of the faulty circuit boundary breakers.

In view of the high percentage of disturbances which are being forestalled by Petersen coils one may speculate if such an equipment is not to be preferred to a second circuit on a transmission line, in case the second circuit is primarily chosen as reserve against interruptions on the first. Without knowing the exact cost of a Petersen coil it is safe to say that this will amount to a small fraction of that of a second circuit even if this is carried on a common tower. Labor costs are an important item on a transmission line construction and these constitute a higher proportion in America due to normally higher wages all around than those in Europe which even increases the economic value of the Petersen coil hereabouts.

Regarding the clearance of permanent ground faults, the authors seem in disagreement with the experiences obtained on the German systems, where it is said that the line can remain in service in presence of a sustained ground and permits exchange of insulators many hours after ground occurrence. However, the objections to a permanent ground on the 140-kv system in Michigan may be primarily due to corona currents which naturally are less felt on voltage systems of 110 kv or lower upon which German engineers base their conclusions.

The Petersen coil application may not be as desirable on an extensive utility transmission line network with generating stations at various points, as on straight transmission line from a remote hydroelectric station to a consumer step-down station of an industrial plant or domestic service. The recent transmission line system of the Nippigon-Fort Alexander power developments by the Ontario Hydro-Electric Commission has adopted metallic connections only on the low voltage side of both the step-up and step-down transformers, omitting any high voltage breakers. If such a system can be considered a pointer for future system designs, the application of Petersen coils is simplified, inasmuch as the main bug-a-bear of tuning in of the coil can be calculated without complications from complex high voltage line interconnections, and field adjustments will be reduced to a minimum.

In conclusion be it stated that the foregoing remarks are based upon the following papers by German engineers:

1. Petersen Ground Coil, Dr. Ruedenber, *Elec. World*, Nov. 30, 1930.
2. Selective Erfassung von Erd-und Deppherdschloss, Dr. Kesselring.
3. Erdschloss und seine Bekampfung, G. Oberdorfer. 1930.
4. Nippagon-Fort Alexander Power Development, Dr. Gaby. Engg. Inst. of Canada, 1931.

Paul R. Sidler: First; The authors speak of "Petersen coil" throughout the paper. It is quite true that Dr. Petersen has played a prominent part in this field, but it must be noted that his extinction coil, as originally conceived and applied, was based upon the assumption that the resulting fault current, after connecting the coil to the neutral, *must* be zero—this, of course, when neglecting loss-currents due to conductance and corona. This is the ideal operating condition for perfectly symmetrical networks.

In practice, however, there will always be certain differences in the capacitance of the 3 phases of a system to ground which cause an asymmetry-voltage between neutral and ground when connecting an extinction coil. This voltage produces a current through the coil which in turn causes a voltage difference across it. The value of this asymmetry-voltage depends therefore upon the inductance of the coil and it can be shown that it reaches a maximum value when the coil is completely tuned; i. e., when the inductance of the coil is exactly the same in value, but opposite in direction, to the capacitance to ground. It is obvious that with a larger

asymmetry-voltage the permanent losses during normal service are bigger.

This disadvantage of the Petersen coil can be eliminated by incomplete tuning, where the vectorial sum of inductance and capacitance is not zero, but leaves a small difference. This small residual voltage does not affect the usefulness of the coil for eliminating phase-to-ground faults. It is precisely this idea which has been incorporated by Julius Jonas (of Brown, Boveri & Co.) as early as 1918 in the so-called "dissonance extinction coils," as opposed to the resonance coils of Dr. Petersen. It would therefore be desirable not to speak of Petersen coils when referring to such devices in general, but to call them extinction or extinguishing coils.

As has been mentioned in the paper the question of saturation plays an important part in this connection. This diagram (Fig. 1) shows the influence of the tuning of coils with different saturation on the asymmetry-voltage in normal service. Curve 1 represents the asymmetry-voltage of the system under consideration. *A*, *B*, and *C* are the magnetizing curves of various extinction coils:

A = a coil unsaturated with normal operating voltage, tuned for resonance
B = a heavily saturated coil, tuned for resonance at normal phase voltage
C = a dissonance-tuned coil with small saturation and slight positive tuning

Positive and negative tuning is understood to mean a value of the coil inductance, in excess or below, respectively, of the value of the capacitance to ground. It appears

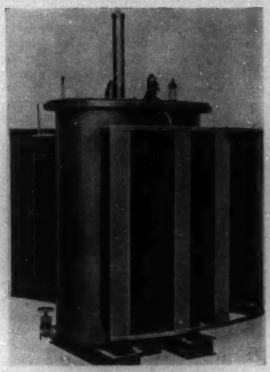


Fig. 6. Dissonance extinction coil, 2,320 kva during 2 hr, for protecting a 125-kv network

from this diagram that resonance or Petersen coils cause high asymmetry-voltages with corresponding permanent losses and have no stable operating point when saturated. The dissonance coil produces a small asymmetry-voltage and has one operating point only.

In Figs. 2–5 are shown arcs to ground with different tuning of an extinction coil, these pictures having been obtained during extensive tests in a 50-kv network. In Fig. 3 the coil is tuned for resonance, in Fig. 2 it has a positive tuning of 23 per cent, and in Fig. 4 a negative tuning of 20 per cent. No difference can be observed in the arc. Only with the negative tuning of 45 per cent, as shown in Fig. 5, the extinguishing effect of the coil is no longer satisfactory.

Second; On p. 64 of the paper it is stated that extinction coils have come to be standard practice in Germany. While this is true, it must not be concluded that Germany is the only country where they have been adopted to a considerable degree. We can name numerous installations of dissonance extinction coils in a great many countries:

20 are, for instance, in operation in Spain
8 in Denmark
14 in Poland
5 in Sweden
10 in the Dutch East Indies
and even far off China has 6 installations of this kind

Third; In the lower left corner of p. 70 appears the remark that Petersen coils can be effective only for clearing momentary faults. Again this is true for the 2 coils considered in the paper, which are rated for 10-

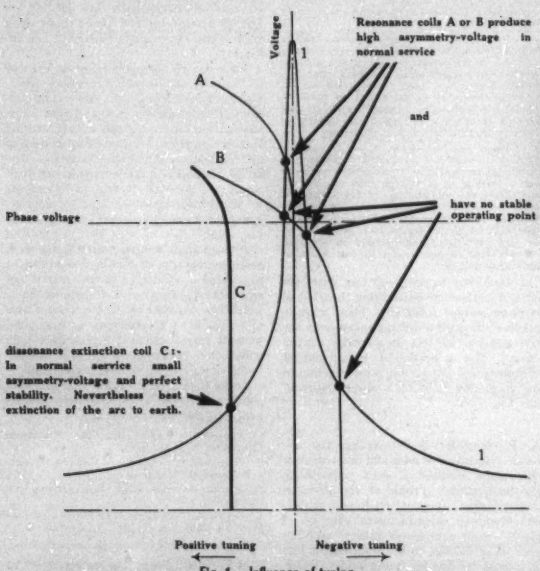


Fig. 1. Influence of tuning

Fig. 2. Arc to earth with the extinction tuned for + 23 per cent

Fig. 3. Arc to earth with resonance tuning

Fig. 4. Arc to earth with the extinction coil tuned for — 20 per cent

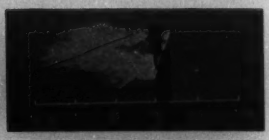


Fig. 5. Arc to earth with the extinction coil tuned for — 45 per cent

min operation only. With such a short time rating the most valuable characteristic of an extinction coil is lost, which consists precisely in the possibility of continuing the operation of the network with an existing phase-to-ground fault and without appreciable losses. Of course, such an operation is not to be continued indefinitely, but at least for a length of time sufficient to locate the fault and possibly remove its causes. For this reason extinction coils are usually rated for several hours' operation, 2 hr being considered adequate for a majority of cases.

In Fig. 6 is shown a dissonance extinction coil, rated for 2,300 kva during 2 hr for a protection of a 125-kv network in Eastern Europe.

Lightning Measured on 4-Kv Overhead Circuits

Discussion of a paper by Herman Halperin and K. B. McEachron published in the January 1934 issue, p. 33–7, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., Jan. 23, 1934.

H. N. Ekvall: The results of this investigation supplement and lend support to conclusions arrived at previously through investigations of fuse blowings and transformer failures. These data, when combined, give a composite picture which should be of much value in the design of transformers, lightning arresters, etc., and also in correcting existing lightning trouble conditions through more effective distribution and application of lightning arresters.

Of particular interest to us is the similarity of operating experience in Chicago and Philadelphia. We concur for example in: (*a*) the apparently small amount of trouble from direct strokes, (*b*) less tendency for trouble on urban than suburban circuits, and (*c*) the decided reduction in trouble by use of the interconnection. I should like to comment briefly on the last of these.

Operating experience with the interconnection on over 1,300 transformers on the 2,300-volt 2-phase 3-wire ungrounded system in Philadelphia during the unusually severe lightning season of 1933 indicated a 75 per cent lower rate of trouble on transformers with the interconnection than on those without it. Also, all sizes and ages of transformers were benefited by its use. It was further disclosed that use of the interconnection did not augment trouble on customers' premises as indicated by analyses of meter troubles and house fuse blowings. This experience is comparable to that in Chicago in which use of the interconnection reduced trouble about 65 per cent and caused no adverse condition on customers' premises.

C. Francis Harding: The authors have not only made available to the profession through the Institute the possible economies of their studies over a period of years by means of statistical and check test analysis, but they have demonstrated the favorable results of a method of analytical attack upon an empirical problem which might well be followed in other branches of the profession.

After having reported in 3 Institute papers by D. W. Roper the results of a statistical analysis of lightning arrester operation and transformer failures in several sections of Chicago over a period of years it seemed probable that the interconnection of the secondary grounded neutral with the primary arrester ground might prove to be an additional protective device which could be cheaply installed and yet which seemed to have no objectionable features. To prove the efficacy of this interconnection and its lack of hazard to equipment or consumer by means of trial installations in the field was found to be too expensive, too long delayed and possibly associated with some risk.

An extensive laboratory research and experimental line investigation, under the auspices of the Utilities Research Commission of Chicago, was therefore undertaken at Purdue University by means of a surge generator and cathode ray oscillograph. The favorable results of such an interconnection and its lack of hazard were reported by Sprague and Harding in the papers referred to as Nos. 4 and 5 in this bibliography. It is therefore particularly gratifying to the speaker to find that the conclusions from laboratory and experimental line tests have been borne out in the field check tests reported in this paper.

In many other comparable cases such a carefully planned sequence of initial statistical studies, laboratory research and field check tests following the adoption of a new engineering principle worked out in the laboratory has not been adopted with one of the 3 following results:

(*a*) A new project has never been adopted, to the mutual disadvantage of the consumer, the public utility and the manufacturer, or
(*b*) Expensive and none too accurate statistical analyses have been exclusively depended upon, often with unfavorable results, or
(*c*) Competitors or other corporations with more progressive policies and foresight, but with less claim upon the original improvement, have subsequently undertaken the new development to their ultimate credit but with delayed value and unnecessary expense to the public.

This series of papers should, therefore, have a marked educational and illustrative value, looking toward the encouragement of research in practical engineering problems which may be undertaken in unbiased university laboratories whose results may be disclosed to the advantage of the profession and the public through the agency of the Institute.

D. D. MacCarthy: The data in the paper by Herman Halperin and K. B. McEachron which deals with voltages measured at distribution transformers is of great interest. It shows that the protection obtained with interconnection is much superior to that obtained with the old method. If the resistance of arrester grounds were not low in Chicago (97 per cent less than 25 ohms) the difference between the 2 methods would have been greater. This was shown in the McEachron-Saxon paper and the accompanying discussion. It should be noted when comparing the results of the 2 methods of protection, as shown in Table III, that the 5 line to ground voltages averaged for the interconnection are 12 kv more than for the standard, so that the incident surges must have been more severe. In spite of this, the voltage between the transformer windings is much less where interconnection is used.

The paper states that voltages of 30 and 37 kv were measured across the secondary leads of the transformers. The existence of such voltages must be very short. The insulation in the conduit of the customer's lead-in will spark at about 4 kv, as was stated in the McEachron-Saxon paper. Since the distance between the transformer and nearest lead-in is small, the effect of this breakdown will be to reduce the magnitude and duration of the voltage across the transformer secondary.

The paper states that the highest voltage recorded at an open end of a primary main was 205 kv and that the studies of D. W. Roper show that transformers installed within 100 ft of the end of a line have a 20 per cent lower rate of failure than other transformers. It may be incorrect to conclude on the basis of the data presented in this paper, that the voltage at the end of distribution circuits is not appreciably above the average. In Fig. 2 of the paper is shown an arrester between phase *B* and ground at the transformer and the recorder on the open end to be also on phase *B* 325 ft away from the transformer. The arrester at the transformer may have had a considerable effect in reducing the voltage at the open end. In the present study there were only 2 installations of this type, the next highest voltage measured at another installation was 158 kv, the lower rate of failure of transformers located near open ends may be due to the lower number of feet of exposure of the primary.

It is stated that Fig. 6, the plot of the profiles of the voltages measured on the long circuits, may represent distribution of the bound charge. Before making this conclusion it should be noted that the voltage at one end of the circuit is limited by an arrester which modifies the shape of the profile. The effect which the arrester has at points on the line other than its location depends upon the wave front of the surge or the rate of release of bound charge. It is seen from Fig. 6 that the voltage is also low at the end of the line opposite to the arrester. It would be of interest to know if this is due to the presence of branch circuits, other arresters, or what the cause may be.

Control of Distance Relay Potential Connections

Discussion of a paper by A. R. van C. Warrington published in the January 1934 issue, p. 206–13, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., Jan. 23, 1934.

E. E. George: A. R. van C. Warrington has presented a most comprehensive view of the subject of "Relay Potential Connections." The Tennessee Electric Power Company has used switching of both potential and current connections with a reactance type of distance relay which was manufactured in Europe. The operating features of this switching arrangement were designed to

take care of special conditions and would probably be satisfactory on a system with lines protected entirely by relays of this same type and design. We have discontinued the current and potential switching features on most of these relays.

We believe that the switching arrangements shown in Mr. Warrington's paper are intended for use with potential transformers instead of bushing potential devices or other substitutes. Most distance relays now on the market will cause an appreciable change in the voltampere burden of the current circuits, potential circuits, or both, when different portions of the relays operate. Bushing potential devices have been found to have objectionable errors in ratio and phase angle when subjected to changes in burden, particularly at the low voltages encountered during short-circuit conditions. It is our opinion that any changes in burden should preferably be made in the potential circuit since one set of potential transformers on the station bus with bushing current transformers on the outgoing lines will usually be more economical and certainly more reliable than bushing potential devices and wound type current transformers on each line. We also prefer potential circuit switching instead of current circuit switching for other reasons as brought out by Mr. Warrington.

We wonder if due weight has been given to the fact that the nature of many faults may change even before high speed relays and breakers have a chance to operate. It is necessary for the switching arrangement to be exceedingly reliable in operation to take care of such conditions.

Up to the present time we have preferred to confine the use of added devices to those desirable for making 1 set of 3 distance relays extremely accurate under all faults involving 2 or more phases with or without ground current (such as the use of wye-delta auxiliary current transformers) and to depend on current directional ground relays for protection against single phase to ground short circuits. Probably the circuit shown in Fig. 3 using one distance relay for the protection of single phase to ground short circuits would be advantageous with or without a current directional ground relay, particularly in those cases where it is impractical to coördinate substation switching and grounding capacity, so as to provide fast and accurate relaying with inverse time overcurrent ground relays. Probably the use of potential switching arrangements will be influenced greatly by the cost and reliability of the various switching devices.

J. H. Neher: While the many advantages to be gained by the use of distance relay protection are almost self-evident, this type of protection is inherently more expensive, more complicated, and requires more panel space than other simpler forms of protection. It is therefore interesting to a relay engineer to find a manufacturer sponsoring some system whereby any or all of these factors may be reduced.

The old theory that the more relays you have the better off you are, because there is less probability that a given relay failing to operate can result disastrously, has very little engineering justification, and in these days no economic justification.

In the most complete distance relay protection the relay of one phase effectively backs up the relay on another phase, only in the case of 3-phase faults, which are rare, and practically no back-up is afforded in the case of the more frequent types of faults. Even at that, the back-up is confined to one link of a chain extending from the plates of the control battery to the contacts of the circuit breaker, and in which, I venture to say, the primary relay is not necessarily the weakest link.

If the potential selector system can be made as reliable as the relay itself, and the combination results in a simplified or less costly system which will perform the duties of the conventional multi-relay system in a satisfactory manner, it would seem hard to justify the multi-relay system.

In Fig. 2 of the paper, the effect of delta-connected current transformers is obtained from the wye connection by the use of a double current winding relay. I should like to point out that a single current winding relay may be used in this arrangement, provided a center tapped autotransformer is connected between the A and C phase current leads, with the center tap connected to the common return. The current coil of the relay is connected between the center tap and one end of the autotransformer. The operating conditions are identical with those given in Table II.

All of the systems presented are based upon the assumption that the potential supply to the directional element is obtained from the same phase as the potential supply to the distance element. Relays requiring different phases for these supplies will require separate switching for the 2 elements. Independent switching, while adding to the complexity of the arrangement, permits the application of overvoltage to the directional element potential coil during the duration of the short circuit. In this manner, the directional element may be made more sensitive than is possible in the conventional multi-relay scheme. In fact, in the case of close-in 3-phase faults, where high speed operation is most essential from a stability standpoint, the net time of operation may be decreased despite the addition of a transfer relay which must operate before the distance relay proper can start to function.

In many of the systems shown, the potential circuits of the distance elements are normally open. Since the modern high-speed distance relay is not directional controlled, this means that normally the contacts of the distance elements are closed; and when a fault which should not cause instantaneous tripping occurs, a race must take place between the distance element on opening and the directional element on closing. This race must be won by the distance element. Granted that the distance element has the advantage of being circuit opening, and that this same race can take place under certain circumstances with the conventional relay set-up, nevertheless it is something which should be avoided whenever possible. In certain cases, it is possible to arrange the potential selector system of the distance element so that this element is normally energized between phases and then is switched to ground or to another phase, cutting the series impedance out or in as may be required without opening the circuit.

In the discussion of Fig. 5, the author explains that the system must not be switched to wye voltage in case of a double ground fault, and introduces a slight time delay in the transfer relay to prevent this. I should like to point out that should a double ground fault develop from a single ground fault after the transfer to wye voltage had taken place, incorrect operation might occur before the system can transfer back to delta voltage.

Automatic Reclosing of Oil Circuit Breakers

Discussion of a paper by A. E. Anderson published in the January 1934 issue, p. 48–53, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., Jan. 23, 1934.

E. E. George: In Table I is a tabulation showing the instantaneous reclosing record of The Tennessee Electric Power Company during 1933. The percentages are based on about 1,500 operations using a cycle of zero sec—120 sec—lockout in most cases. We agree with A. E. Anderson that the third reclosure is desirable and we are changing to a cycle of zero sec—15 sec—120 sec—lockout, especially on the lower voltage circuits.

Table I

	Breaker Remained Closed		
Reclosure	Attended Substations	Non-Attended Substations	Total
First	61.2%	93.2%	73.5%
Second	23.5%	2.8%	15.6%
Lockout	15.3%	4.0%	10.9%

The differences in the performance records of the fully attended substations are noteworthy. For records at the nonattended substations, we use oil circuit breaker counter readings taken on monthly inspection trips and whatever information is available as to interruptions. We are inclined to question reclosing records which depend upon the public or upon nonoperating employees for data on actual interruptions. This company has just developed an inexpensive method of mounting an operation counter inside of the various reclosing relays which records the total revolutions of the timer drum. Absolute accuracy should be feasible from the readings of this counter and the counter on the oil circuit breaker in the case of a 2-reclosure cycle and also in the case of a 3-reclosure cycle if the number of breaker operations between inspection trips is relatively small. These counters are now being installed at all nonattended substations.

It has been our experience that synchronous motors will frequently pull into step after a total interruption of 40 cycles without the use of any field removing devices. The presence of large synchronous motors, not too heavily loaded, at an industrial plant has been found to be advantageous in that voltage on induction motors in the plant will be maintained to a certain extent by the synchronous motors and instantaneous undervoltage releases on induction motors will be prevented from operating during the reclosing cycle.

H. A. P. Langstaff: In A. E. Anderson's paper it is stated that practically all applications of automatically reclosing oil circuit breakers have been on stub or radial feeders and that the discussion is confined to this type of application. The West Penn Power Company has a total of 170 applications, 93 of which are on stub feeders and 77 on interconnected lines. This latter group is composed of 22-kv, 25-kv, and 44-kv, 3-phase 60-cycle circuits; of this latter group, 33 reclose only when the line is energized from the other end. From this it is evident that about 45 per cent of our total applications are on interconnected circuits.

Our records over a 3-year period show about the same number of total operations per year, but the percentage of lockouts is gradually increasing as follows: 6 per cent in 1931, 13 per cent in 1932, and approximately 15 per cent in 1933. The percentage increase may be slightly affected by a reduction from 3 to 2 reclosures, which indicates to us that further consideration should be given to the value of the third reclosure. At present 7 per cent of our total applications are adjusted for 1 reclosure; 43 per cent, 2 reclosures; and 50 per cent, 3 reclosures. Time intervals between reclosures vary from immediate to one minute. Six per cent of our total applications are adjusted for immediate initial reclosure. Our experience with these applications thus far has been quite successful and this percentage will be increased. Careful study is made before changing to the immediate reclosure. The design of quite a number of our reclosing relays is such that the time may be varied from instantaneous to several minutes if desired, which, of course, permits universal application.

An analysis of reclosing operations from a delta versus grounded distribution circuit point of view shows about double the number of lockouts for solidly grounded distribution systems as compared with delta systems. Proper fuse and relay coördination is quite necessary for reclosing performance and may reduce the number of lockouts resulting from short circuits.

In general, I believe breaker designs should tend toward a time reduction in operating cycles. Application of immediate reclosures or reduction in time for reclosures has not increased maintenance on our oil circuit breakers. In only a limited number of cases have we found it necessary to modify existing protective relays to meet the new reclosing time intervals. We found it necessary to change cascaded relay settings to allow for shorter reclosing periods. A timing mechanism eliminating the use of any revolving parts is desirable. All contacting mechanisms should be as rugged and positive as economically possible. I believe there is a decided advantage in having the third reclosure in conventional design when practically no additional expense or complication is added.

About a year ago I considered the application of automatic reclosing equipment in attended stations but our analysis proved that the very limited number of distribution circuit outages per year—less than 2 per circuit—and the few seconds reduction in time of circuit reclosing would not warrant the necessary expenditure for timing relays and control circuit modifications. I might add that the territory covered is not of a metropolitan type.

Counterpoises for Transmission Lines

Discussion of a paper by Charles L. G. Fortescue published in the December 1933 issue, p. 908–17, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934.

L. V. Bewley: Doctor Fortescue's analysis of the counterpoise problem is characterized by the following assumptions and arbitrary factors:

1. A "true" ground plane, common to both the electrostatic and the electromagnetic fields, is taken at a depth varying with the soil resistivity.
2. A factor K, assumed to be between 4 and 16, is introduced to account for the permittivity and leakage of the soil.
3. The surge on the counterpoise is "conceived to consist of 2 parts, one of which moves with the velocity of light and is proportional to s (an empirical factor less than unity) and a second portion moving with a velocity $1/\sqrt{K}$ that of light and whose magnitude is proportional to $(\sqrt{K} - s)$."
4. The s part of the surge on the counterpoise is assumed to have a mutual surge impedance proportional to unity, while that of the $(\sqrt{K} - s)$ part is assumed to be proportional to $(1/\sqrt{K})$.
5. The fraction m of the total ground current is calculated neglecting the effect of the coupling between ground wire and counterpoise.
6. During the transient the surge impedance of the counterpoise is assumed to remain constant.
7. The lightning stroke itself is assumed to have a surge impedance of 200 ohms.

From these premises Doctor Fortescue has built up a theory taking into account surge impedance effects, coupling, and successive reflections up and down the tower. The most remarkable conclusion of his analysis is the very large effective coupling with the line wire. Thus, according to his Table II, at the instant of maximum voltage across the insulators the coupling is 73 per cent, and it subsequently reaches 81.5 per cent.

In an article to appear in the February 1934 issue of the *General Electric Review* I have applied the multiconductor multivelocity theory of traveling waves to the analysis of the counterpoise. In general, I agree with Doctor Fortescue's conclusions, except that according to my calculations:

1. The effective coupling is very much less than he finds, and therefore there is not nearly so much advantage in favor of the parallel counterpoise. For example, with a single counterpoise the coupling is only 44 per cent.
2. There is no practical need to complicate the analysis and increase the labor of computations by taking the successive reflections in the tower into account. I find that only the first 3 or 4 reflections are appreciable, and these will subside by the time that the lightning surge reaches its crest (assuming a front of one microsecond or more). Taking reflections into account makes less than 10 per cent difference in the maximum voltage, but for comparative computations this certainly does not warrant the great increase in work.
3. The surges on the ground wire, line conductor, and counterpoise are, respectively:

$$\left.\begin{aligned} e_1 &= 0.558\,E_s\,(0.78) + 0.220\,E_s\,(0.33) \\ &\quad + 0.221\,E_s\,(0.71) \\ e_2 &= 0.472\,E_s\,(0.78) + 0.254\,E_s\,(0.33) \\ &\quad - 0.289\,E_s\,(0.71) \\ e_3 &= -0.033\,E_s\,(0.78) + 1.028\,E_s\,(0.33) \\ &\quad + 0.006\,E_s\,(0.71) \end{aligned}\right\} \quad (1)$$

where the figures in parentheses are the velocities relative to that of light. Thus no component wave on the system travels at the velocity of light; and moreover, the surge on the counterpoise is essentially a low velocity wave traveling at about $^1/_3$ the velocity of light.

These discrepancies result principally from the differences in our respective concepts of the rôle of the ground. Doctor Fortescue uses a single equivalent ground plane, and therefore calculates both electrostatic and electromagnetic coupling between the counterpoise and the overhead conductors. I hold that the ground is essentially at zero potential with respect to the electrostatic field, and consequently there can be no electrostatic induction between conductors on or in the ground and overhead conductors. Therefore, I calculate a much lower coupling, definite reactions from the isolated line conductors, and consequent multivelocity waves. My multivelocity components are given automatically by the multivelocity theory, and no arbitrary assumptions need be introduced relating to their several magnitudes and velocities. While both Doctor Fortescue and I make an analysis on the basis of a counterpoise of constant surge impedance, it must not be forgotten that the actual surge impedance may decrease considerably by the time the lightning crest is reached. This would result in more current in the counterpoise and greater coupling with the line conductor. I bring this point up because tests may reveal a greater coupling than an analysis based on the initial surge impedance assumed to remain constant. In my article there is an equation and a test curve showing how the surge impedance varies with time.

I believe that the surge impedance of a lightning stroke is nearer 400 ohms than 200 ohms. (See "The Lightning Stroke" in the December 1933 issue of the *General Electric Review*.)

Doctor Fortescue introduces geometric mean radii (G.M.R.) in calculating his surge self impedances. I do not understand by what labor-saving process he arrives at G.M.R. in this problem. Considering 2 ground wires in parallel in the same horizontal plane, carrying equal voltage and current waves, the heights of conductors being h for the magnetic and H for the electrostatic fields, separation s, actual radii r, and corona radii R, the surge impedance on the basis of multivelocity theory is

$$\begin{aligned} Z &= \sqrt{(L_{11} + L_{12})(P_{11} + P_{12})} \\ &= 60\sqrt{\log 2\sqrt{\frac{ha}{rs}}\log 2\sqrt{\frac{HA}{Rs}}} \qquad (2) \end{aligned}$$

where

$$a = \sqrt{4h^2 + s^2} \quad \text{and} \quad A = \sqrt{4H^2 + s^2}$$

Now even if $h = H$, as Doctor Fortescue assumed, this becomes

$$\begin{aligned} Z &= 60\sqrt{\log 2\sqrt{\frac{ha}{rs}}\log 2\sqrt{\frac{ha}{Rs}}} \\ &\cong 30\sqrt{\log\frac{2h}{\sqrt{rs}}\log\frac{2h}{\sqrt{Rs}}} \qquad (3) \end{aligned}$$

which is not algebraically convertible to the form given by Doctor Fortescue,

$$Z = 60 \log\left(\frac{2h}{\text{G.M.R.}}\right) \qquad (4)$$

Incidentally the equations of conventional traveling wave theory fall down completely in this case, for according to them, since $i_1 = i_2$

$$e_1 = Z_{11}\, i_1 + Z_{12}\, i_2 = \frac{Z_{11} + Z_{12}}{2}\,(2i_1) \qquad (5)$$

and the surge impedance would be

$$Z = \frac{Z_{11} + Z_{12}}{2} = 30$$

$$\left\{\sqrt{\log\left(\frac{2h}{r}\right)\log\left(\frac{2h}{R}\right)} + \log\left(\frac{2h}{s}\right)\right\} \qquad (6)$$

The trouble is that as soon as we assume $r \neq R$ or $h \neq H$, the differential equations are no longer uniquely satisfied by single-velocity waves, and so eq 5 ceases to be a complete description of the voltage and current relationships. Of course, if we put $r = R$ and $h = H$, eqs 2, 3, and 6 all become equal to

$$Z = 60 \log \frac{2h}{\sqrt{rs}}$$

which is now agreeable with eq 4. Nevertheless, while eqs 5 and 6 are algebraically different, they give numerical values which differ but little. For example, if $h = 200$ ft, $r = 0.375$ in., $R = 12$ in., and $s = 30$ ft, the surge impedances calculated by eqs 3 and 6 are 304.5 and 303, respectively.

J. E. Clem: Some time ago we had under consideration a proposed design of a transmission line using the buried parallel counterpoise in addition to the customary overhead ground wires. The question arose as to how much additional loss at the operating frequency might be occasioned by the use of the buried counterpoise extending the entire length between the towers. In view of the fact that some fears had been entertained that the additional losses might be relatively great, exact calculations were made and these indicated that the extra loss was practically negligible.

Calculations were made on a horizontal line with an average height of $58^7/_8$ ft and with a conductor spacing of approximately $28^1/_4$ ft. The overhead ground wires were located in a plane approximately $25^1/_8$ ft above the plane of the line conductors and were spaced $42^1/_4$ ft. The buried counterpoise wires were located directly underneath the overhead ground wires and were assumed to be about 2 ft under ground. The line conductors had a diameter of 1.14 in. and a resistance of 0.117 ohm per mile. The overhead ground wires had a diameter of 0.714 in. and a resistance of 0.364 ohm per mile. The buried counterpoise had a diameter of 0.419 in. and a resistance of 0.433 ohm per mile. If the line conductors are numbered 1, 2, 3, from left to right; the overhead ground wires numbered 4 and 5 from left to right; and the buried counterpoise wires 6 and 7 from left to right, the following distribution of current is obtained:

$$\frac{I_4}{I_1} = 0.0945 \qquad \frac{I_6}{I_1} = 0.0228$$

$$\frac{I_5}{I_1} = 0.0745 \qquad \frac{I_7}{I_1} = 0.0222$$

From these figures the total loss in all the ground wires is found to be approximately 1.6 per cent of the total loss in the line.

It is rather surprising to note that the current in the overhead ground wires is not evenly divided. This at first was taken as indicating that there might be some mistake in the calculations. However, further study brought out the fact that the unequal division of current was reasonable and could be altered to give the greater current in the other ground wire by changing the phase sequence of the line conductors.

Bradley Cozzens: At the present stage of the art, to say that some particular method of computation of lightning phenomena is or is not correct should meet with severe criticism; for we yet are not certain of the mechanism of lightning, the potential that may be developed, the currents that may occur in a discharge, or the impedance of the streamer path, though all these values have been estimated with a greater or less degree of authenticity. Therefore, the following discussion is given to call attention to some other methods of computation and a different viewpoint, rather than as an attempt to disprove the values as given.

Doctor Fortescue presents an analysis of the counterpoise methods as used in eastern installations, but his mathematical analysis seems to be applied directly to the counterpoise system as scheduled for the transmission line of the Bureau of Power and Light from Boulder Dam to Los Angeles. Though the method described by Doctor Fortescue was considered in the studies made prior to determining upon the use of a counterpoise, methods substantially different from those presented in this paper were used in the computation.

Doctor Fortescue draws the conclusion (ELECTRICAL ENGINEERING, December 1933, p. 910) that the radial counterpoise gives lower surge impedance than the continuous type of buried counterpoise. It is believed that from previous papers of Doctor Fortescue, and from values of voltage that may appear on the counterpoise as given later in this paper, that the value of a corona radius of 0.166 ft is small. Using this value however, and the more liberal value of 130 ft for the separation of the counterpoise wires, the equivalent G.M.R. (geometric mean radius) of the 2 counterpoise wires would be increased to 4.65 ft, and for the first case (namely, the 50-ft ground plane) the surge impedance of the parallel counterpoise will be $186.6/\sqrt{K}$. ohms. This is lower than the value of surge impedance for the radial counterpoise. However, where the ground level is taken as 200 ft below the surface, the value of the surge impedance for the continuous parallel counterpoise becomes $258/\sqrt{K}$ ohms which is slightly higher than the value of surge impedance for the radial counterpoise. There is thus little difference between the computed values for the 2 systems. There are, however, 2 other very important facts that determine effectiveness of the 2 systems:

1. Tests have shown that radial counterpoises or short sections of buried cable used in dry soil have appreciable voltage reflected from the ends of the wires, thus making the effective surge impedance much greater than the computed surge impedance; whereas for the continuous counterpoise, there is no positive reflected wave, and consequently no building up of potential at the base of the tower.

2. It is known that where the charge builds up as slowly as in clouds, the charges of opposite polarity collect on or close to the surface of the earth, even though the soil is of high resistance, rather than at the theoretical ground plane. This is necessarily true or else rocks and mountain tops could not produce the corona so often observed. It is these charges on the surface of the earth that the counterpoise collects when lightning terminates on a tower, and to which the counterpoise capacitance should be figured in determining its surge impedance. The *inductance* of the counterpoise may be computed with respect to the cloud as the return circuit, though this value is practically the same as that of an isolated wire. Also close to the tower base there is little inductance due to the wires leaving the base in opposite directions, as mentioned by Doctor Fortescue. Though this method of computing the surge impedance of the counterpoise is a little more complicated than that given in the paper, it is felt to be more accurate and to more perfectly represent the action of the lightning discharge.

The values of K for the effective dielectric constant of the soil were checked independently by computing the value of surge impedance by the aforementioned method for the lengths of buried conductor used in the test of Brune and Eaton (A.I.E.E. TRANS., v. 50, p. 1132). It was found necessary to use a dielectric constant or soil factor of between 8 and 10 to make the computed results check the test values.

The Knob Hill experience is of course familiar to all following lightning experience records. It is understood, however, that only one counterpoise wire is used per circuit on this installation. It is felt that even though this is a high rock formation, the frequent rains in that area probably produce much more moisture in the rock seams and interstices of the rock than might be found in the desert area through which the Boulder Dam transmission line of the City of Los Angeles will have to pass. At present, one very important part of lightning information that is lacking is the effect of soil and soil moisture on the action of the counterpoise.

In the study of the lightning protection for the Boulder Dam transmission lines, it was felt that the attenuation in the counterpoise was too rapid to consider it having an appreciable part of the lightning potential impressed upon it for any measurable distance from the tower base. Further, the speed of propagation of the voltage wave in the counterpoise has been found to be about $^1/_3$ of that in an air line, both by computation and by the tests of Messrs. Brune and Eaton. Thus at a short distance from the tower where a stroke might terminate, the potential of the counterpoise would lag behind that of the ground wires. For the case of a stroke at midspan (1000-ft span) the potential of the counterpoise directly below it would require 2μsec to be changed by a wave traveling along the ground wire to a tower and returning on the counterpoise wire. It was thus much more conservative to assume that the counterpoise had sufficient conduction to maintain ground potential below the line, and that for the computation of its surge impedance that only a small part of the lightning potential would appear on the buried counterpoise. The coupling between the ground wires and line wire was thus computed on the more conservative basis using the effective ground plane as the surface of the earth, rather than the water table which might be at considerable depth.

On the Boulder Dam to Los Angeles transmission line, 4 counterpoise cables will be buried, 2 under each circuit, spaced 130 ft apart. The normal center line spacing between circuits is 265 ft. At each point where towers are adjacent, a buried cross tie will connect towers. Where possible, the counterpoise wires will be brought in from their normal spacing to each tower base at an angle of about 45 deg

and connections made to the tower. Thus the advantages of a "crow's foot" or radial counterpoise is obtained by the 4 continuous wires and the one cross tie leaving the tower base, while the wire being continuous prevents any positive reflections of voltage from open ends, or ends terminating in high impedance.

It is believed that Doctor Fortescue's new method of computing the effects of the counterpoise is too liberal, giving better protection than will be found in practice. If it does prove to be the correct analysis, however, the continuous counterpoise as installed on the Boulder Dam lines with other bases of installation will be willing to function as he predicts.

Stanton Hertz: This discussion deals with the treatment of diameters of overhead ground wires, as they might be affected by the system of calculation presented in Doctor Fortescue's paper. Those of us who will design and apply overhead ground wires in the future, and calculate the protective value of the over-all line designs, will wonder whether a new basis for selecting diameters of overhead ground wire will be caused when using the new formulas presented in this very valuable treatise.

Heretofore, the diameter of overhead ground wire to be used in each design (and hence the weight and cost of the ground wire) has generally been determined, not for reasons of the diameter's influence on the amount of electrical protection from lightning, but primarily to suit the physical and structural safety requirements. In other words, sag and tension and safety-factor conditions alone have generally caused the decision as to what diameter of material need be chosen for the ground wire. Is this method of determining diameter to be changed? It seems not.

The formulas in Doctor Fortescue's paper show that the enlarging of the diameter of a ground wire causes a very small and almost negligible improvement in the protective value of the line design. On the other hand, it is seen that an increase in diameter will increase the weight and cost approximately as the square of the diameter. A clear example of the added cost burden when increasing the diameter unnecessarily is shown by comparing a $^3/_8$-in. diameter with a $^5/_8$-in. diameter ground wire, assuming that $^3/_8$-in. is satisfactory structurally. The cost for a pair of $^3/_8$-in. ground wires on 100 miles of line may be about $52,000, while for $^5/_8$-in. diameter of the same material the cost would be about $132,000, an increase of about $80,000 or about 150 per cent. On the other hand, the electrical protective value resulting from increasing the diameter from $^3/_8$ in. to $^5/_8$ in. is shown by these calculations to be very small, on the order of less than 5 per cent, possibly around 3 per cent, this depending on the design. Obviously it is not desirable to seek greater protective value through the enlargement of the diameter of ground wire, because of the resulting disproportionate increase in weight and cost. It is much more economical, when seeking greater protective value, to make changes in spacings or clearances, or by adding another insulator unit to the insulator strings.

The following figures on ground wire diameters in use in the United States have not heretofore been published, but might be of value for inclusion in a discussion of this paper. These figures are summarized from records of ground wires installed during the 10-yr period from 1923 to 1933, covering 339 transmission line installations of "Copperweld" overhead ground strand. They may therefore be said to be indicative of diameters used in recent and modern transmission line design. The mileage of strand in this summary is 5,680 miles. The average diameter of all these installations is almost exactly $^5/_8$-in. Over 95 per cent of the mileage is of diameter from $^5/_{16}$ in. to $^1/_2$ in., while the largest size used, $^5/_8$-in. diameter, constitutes only about 2 per cent of the total. The $^5/_8$-in. size alone is about 40 per cent of the total.

In the future use of the valuable calculations described in Doctor Fortescue's paper, it seems desirable to continue the practice of fixing the ground wire diameter entirely on the basis of sag and tension and safety-factor conditions; that is, to choose that diameter which may be strung somewhat tighter, at a less sag, than the power conductors, and have a slightly higher factor of safety than the power conductors over which it is to be strung.

Herman P. Miller, Jr.: A translation of the theory given by Doctor Fortescue into the language of the radio engineer might assist in studying the subject. A lightning discharge is similar to the spark discharge used in the old spark type of radio transmitters. Only one discharge occurs, instead of a series at periodic intervals, and this discharge is highly damped.

There appear to be a number of resonant circuits in the ground system of a transmission line which might be excited by such a discharge. There is the vertical loop formed by a span of the overhead ground wire, the towers at each end, and the so-called "ground plane." Another possibility is that the ground wire acts as a multiple tuned antenna with the towers serving as down-leads. In the latter case the ground system may be considered as a series of resonant circuits each of which includes $^1/_2$ span of ground wire on each side of a tower, the tower, and the ground plane connected to the base of the tower. The resonant frequency of such a circuit would be extremely high and would be governed by the tower height and spacing.

The effect of a lightning stroke would be to set up damped oscillations in such a circuit. The voltages resulting from these oscillations would depend upon the intensity of the stroke and the coupling with the resonant circuit furnished by the stroke path. Their duration would be determined by the damping of the circuit. To increase the damping, the effective capacitance of the circuit could be increased by bringing the ground plane up closer to the ground wire; the effective inductance could be decreased by using more or heavier conductors between the ground wire and the ground plane; or the effective resistance could be increased by inserting a non-inductive resistance in the circuit at some point.

The potentials impressed on the transmission wires would depend mainly on the coupling between them and the resonant circuits. The coupling would be mainly capacitive and would be roughly proportional to the relative heights of the line wires and the ground wire above the ground plane. When the ground plane is somewhat below the level of the tower footings, these heights are more nearly the same than when the ground plane is raised by the use of counterpoise wires.

From this method of considering the subject it will be seen that the use of a counterpoise in a soil of poor conductivity decreases the excitation of a resonant tower circuit by decreasing the reactance of the stroke path. It increases the damping of the resonant circuit by increasing its effective capacitance, although a part of this increase is counterbalanced by the decrease due to lowered resistance. It also decreases the transient potentials on the line due to less coupling with the resonant circuit.

In studying a counterpoise on the above basis, some help might be obtained from the results obtained on radio antennas as given in various technical publications.

P. B. Stewart and F. E. Sanford: Operating experiences and records of the transmission and distribution circuits of the Union Gas & Electric Company in the territory around Cincinnati, Ohio, do not confirm the conclusion that ground resistance of protection or footings is the only factor to be considered in lightning protection. There is apparently some contributing factor, which has not been entirely explained, that would account for the wide differences of flashovers and operating troubles.

The theory of counterpoise effect advanced by Doctor Fortescue offers a valuable addition to protective considerations dealing, as it does, with the relation between voltages on different parts of the transmission lines, when lightning has struck. It may be still lacking an important factor of comparison, which is the frequency of lightning strokes in a given area. That is, there may be a direct relationship between the earth strata and the frequency which may help to explain the effect of counterpoise and other surge impedance reduction theories and methods.

Perhaps Mr. Fortescue has already considered the possibility of the influence of geophysical factors, which seem to us to offer one explanation for otherwise unexplainable differences in operation. A theory advanced by L. N. Bogoiavlensky (*Nature*, July 15, 1933) is that lightning follows a path of good air conductivity, which may be due to ionization from radioactive earth. This theory is supported by some authors on physics. A survey made in 10 regions in Russia by means of measuring the intensity of the penetrating earth radiations by an electrometer of special type, and by the method of electrical boring of Schlumberger, is the basis for this report. A direct correlation of the frequency of lightning discharges and curves of the intensities of the penetrating earth radiations shows that the highest frequency always corresponds to the place with increased intensity. A sharp pointed (or mountainous) profile of the layers of rock indicates a corresponding increase in the frequency over a smooth or even profile.

Since we have never taken measurements, we cannot confirm this theory, but it would to a considerable extent explain discrepan-

cies in the present theories. We have several examples that dispute the theory of ground resistance. Several years' experience on the 66-kv Columbia-Hartwell circuits show that no direct relation exists between flashovers and tower footing resistance. We have also plotted flashovers against elevation above sea level and find no explanation of the differences, from this standpoint.

Also, 2 33-kv lines of identical construction, operating over similar territory and with similar average ground resistance values, show 2 or 3 times the number of lightning faults for one line compared to the other one.

Another example with 33-kv lines directly disputes the theory. One line, which has many more lightning faults than a similarly constructed line, traverses low, level territory, and has low ground resistance, while the second line traverses a hilly and rocky country with high ground resistance.

A similar comparison on the 4-kv distribution system also disputes the theory of ground resistance. Two feeders of similar construction and exposure supply territories, one east, and one north of Elmwood Station. Of 13 cases of trouble in 2 years, 11 occurred in the east part, where the average ground resistance is 19.1 ohms. The average ground resistance in the other section was 65 ohms, and the number of transformers in the 2 areas is about equal. The average resistance of the driven grounds at locations where trouble occurred was, however, greater than the average for that area.

The practical benefit of counterpoises may be explained by an effective leveling of the earth strata from an electrical standpoint, as well as by the lowering of surge impedance or ground resistance.

R. D. Evans: (See p. 473.)

Corona Losses from Conductors of 1.4-In. Diameter

Discussion of a paper by Joseph S. Carroll, Bradley Cozzens, and Theo. M. Blakeslee, published in the December 1933 issue, p. 854–60, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934.

C. Francis Harding: Having made corona tests almost continuously at Purdue University since 1912, at which time our first paper on the subject was presented before the Institute, I am naturally very much interested in the results of the tests on cables of the large sizes and spacings reported in this paper.

Unfortunately the tests of various types of cables were not carried on throughout the same range of temperature, barometric pressure, humidity, and rain conditions, nor were they all comparable from the standpoint of the 3-phase vs. single-phase operation. It would be more appropriate, of course, to compare such cables under identical long term test conditions.

Figure 1 indicates the wide range of temperature, barometric pressure, and humidity which obtained during the various tests. Although the critical corona forming potential is not reached for cables of this size at the normal operating voltage specified for this line, such corona potentials will, no doubt, exist throughout some portions of such a long line as that contemplated, particularly at the higher altitudes through which it must pass.

Assuming the line to be operating at the critical corona potential under the *average* conditions of temperature and barometric pressure which obtained during these tests, it is found by calculation that the losses during the tests conducted at the higher temperatures are of the order of 4 kw per mile of 3-phase line, while the effect of the altitude of 3,500 ft at which a portion of the line is to operate will account for a loss of 29 kw per mile. In other words, the conditions due to temperature changes during the various tests and the variation in barometric pressures to which the actual line will be subjected will produce losses in all types of cables many times the variations due to differences of design, thereby making such latter variations a negligible quantity since the highest losses at normal operating potentials are shown to be of the order of from 1 to 1.5 kw per mile and the difference between individual cable losses only a small fraction of that value.

Although adequate data are not available for a complete humidity-loss curve, it is generally recognized that there is some considerable variation in critical corona-forming potential and in the resultant corona loss with changing humidity. The wide variation of humidity of from 20 to 62 per cent under which these cables of different designs and makes were compared would certainly affect the corona losses even with no change of design. Although at first it appeared that variation in humidity had little to do with corona losses, the following more recent quotation from the able work of the late F. W. Peek is significant.

"Greater loss should be expected in corona measurements during fog, due to charge and discharge of water particles. This causes loss at lower voltages and has the effect of decreasing the corona point. While humidity has no effect upon the starting point of corona, an effect might be expected on the loss after the discharge had already started."

It is probable that more recent tests will establish a relation between humidity and the starting point of corona as well, which will account for much of the variation in the losses during these tests. An earlier paper by some of the authors of this paper also indicates that corona losses are somewhat dependent upon humidity. ("Corona Loss Measurements on a 220-Kv 60-Cycle 3-Phase Experimental Line," by J. S. Carrol', L. H. Brown, and D. P. Dinapoli, A.I.E.E. Trans., v. 50, 1931, p. 36.)

Of course the comparative losses during rain and snow storms are of greater importance than the variation in fair weather losses resulting from the different designs of the cable surfaces. Although it was unfortunate that all cables could not have been tested under rain conditions in order that the more serious operating losses might have been determined, it is probable that those cables which have a completely closed tubular periphery such as Types *C* and *F*, as contrasted with the cables of stranded exterior, will tend to hold water longer after a storm and therefore maintain the higher storm loss for a longer period of time. Such cables have been shown to retain and gradually exude the necessary lubricating grease to a greater extent and thereby collect dirt upon their surfaces which will, no doubt, increase the corona losses with age. Relatively high storm losses have been found in the Purdue University tests as well as those reported in this paper.

Unfortunately, either the rather complicated methods of measurement, apparently not confirmed or calibrated elsewhere, were not precise enough to detect the variation in corona losses resulting from the various sizes of strands or else the other variables, as previously explained, caused such large variations in losses in the different tests as to neutralize the effect of varying strand sizes. It should be noted in this connection that in 2 tests the losses were practically the same with different sizes of strands: (See Types *D* and *E* of Fig. 12 and curves 2 and 3 of Fig. 13) while in another test the same size of strands provided different losses, since those of cable *E* (curve 4) are lower than those of cable *B* (curve 2) in Fig. 12.

With regard to the ratio of computation of 3-phase losses based upon single-phase tests which was used in some cases, it should be pointed out that with cables spaced as widely as 30 ft and supported only 30 ft above the ground, the neutral plane of the ground itself affects the losses between each individual cable and ground. The neutral point of the 3-phase circuit is shifted downward, therefore, by the nearby ground plane to such an extent as to introduce an error into the 3-phase vs. single-phase ratios which would be otherwise correct. It would be preferable to base such transfer calculations upon comparative 3-phase vs. single-phase empirical test data with the actual spacings to be used. Tests at Purdue University have indicated that with spacings of 30 ft and more, the corona losses due to the proximity of the ground plane were practically constant for a given potential and height of cable regardless of horizontal spacings.

Although much has been said about the variation of corona losses upon different types of cables, particularly under the unusually immune test conditions outlined in this paper which will not, of course, exist upon the actual line, it should be emphasized that corona loss is not an evil necessarily to be avoided. Such losses will, no doubt, exist upon portions of this line, at least at the high altitudes and/or under storm conditions and may prove to be a very valuable safety factor in the attenuation of surges. It has been shown by means of surge generator tests and cathode ray oscillograms at Purdue University and elsewhere that steep-wave-front surges, superimposed upon an energized 60-cycle power line, are attenuated much more rapidly than otherwise if the line is operating near the critical potential and the surge is of opposite polarity from the 60-cycle wave. It is probable, therefore, that the possibilities of corona formation upon this rather exposed line will provide an important protection against damage to insulation as well as to generating and receiving equipment during lightning storms.

Notwithstanding the general usage of the Peek corona formula, which was a most commendable contribution to the design of the early lower potential transmission lines, the subsequent test data which are being

gradually accumulated lead us annually farther away from his constants for extra high-potential large conductor specifications. Practically all of the tests carried on by the writer throughout the past 20 years have shown larger losses in the lower range of potentials than those calculated from the Peek formula, while the test losses are lower than those of the formula throughout the higher potential ranges. It should be noted that the formula proposed by W. S. Peterson (see "Development of a Corona Loss Formula," discussion, A.I.E.E. TRANS., v. 52, 1933, p. 62) recognizes increased losses due to higher humidity, but unfortunately interrelates humidity and surface irregularity factors which probably do not have any correlation whatsoever.

It is hoped that before there is a demand for another line above 220 kv, there will be available some more exhaustive tests of long duration involving daily readings over wide ranges of humidity as well as temperature, barometric pressure, cable sizes, and surface contour.

J. H. Foote: It is gratifying that the facilities at the Ryan Laboratory allow such full scale tests as the authors describe. The fact that the tests have been conducted with spacings, insulation, conductors, and span lengths similar to those to be used on the line, greatly enhances their interest and practical value.

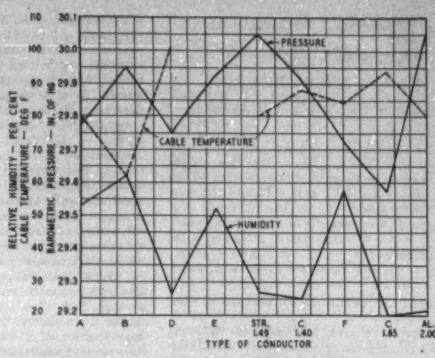
The paper shows that since all the conductors tested appear to have a critical voltage in excess of the operating voltage, the conductor diameter chosen (1.4 in.) is probably very ample indeed. In fact, the losses at the operating voltage with fair weather are so small that the differences registered by various surface conditions and conductor types are of almost negligible value.

The small actual corona loss to be expected is emphasized by comparison with the insulator loss. In a previous paper "Corona Loss Measurements on a 220-Kv 60-Cycle 3-Phase Experimental Line" the losses in a 13-unit insulator string ranged from $3^1/_2$ watts per string at 45-per cent humidity to 172 watts at 81-per cent humidity with 295 kv potential between lines. While these losses may appear negligible with fair weather, they assume appreciable magnitude during foul weather or high humidity. At 172 watts per string with 7 spans per mile they amount to 3.6 kw per circuit mile, and even at 5 watts per string in fair weather they will be $^1/_{10}$ kw per mile which approaches the losses of the most efficient conductor tested.

It would seem that, while the results are of interest in showing the losses of various constructions at potentials considerably above operating voltages, they also show that the operating corona losses of any of the conductors tested are relatively unimportant from an economic standpoint, and therefore with the diameter of the conductor fixed at 1.4 in., the corona loss characteristics do not here constitute an important factor in the selection of the conductor construction.

It is probable that similar tests conducted under abnormal atmospheric conditions would be of interest. Of course, it is difficult to make to order any desired weather conditions. The authors were fortunate in being able to make one test during a rain storm on the type *A* conductor. This test showed that the losses during the rain, at the particular voltage existing during the test, were 16 to 20 times as great as similar tested losses under fair weather conditions. It would seem that perhaps more consideration should be given to the comparative performance of the various types of conductors in stormy weather. It would be expected that the smoother segmented conductor designs would have lower losses during fair weather than would the stranded construction. Whether this would be true under less favorable weather conditions might be subject to argument.

Fig. 1. Range of temperature, barometric pressure, and humidity for the corona loss tests reported in the Carrol, Cozzens, and Blakeslee paper



In interpreting test results and using them in making a choice of materials or constructions, it is essential that the scope of the tests from which the results are obtained coincided with the expected operating conditions. Since the tested corona losses within the operating range are so small in magnitude and the variation in tested losses of the different constructions of even less significance within this operating range, it is assumed that the choice of conductor type was based upon other considerations. Tests on the mechanical properties of the various types of conductors probably were made and details of these would be of considerable interest.

Attenuation and Distortion of Waves

Discussion of a paper by L. V. Bewley published in the December 1933 issue, p. 876–84, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934.

A. R. Miller: Each new paper on traveling waves seems to add to the generality of our fundamental principles and methods. For some time certain discrepancies have occurred between the observed and calculated results, and have been variously explained—one might say guessed at; but Bewley coordinates to a greater extent some well known physical conditions of the problem and obtains solutions that bring calculated and observed values into much closer agreement. Thus, recognizing that corona changes the effective diameter of the conductor in so far as the electrostatic field is concerned and that the current distribution in the ground is quite different than is ordinarily assumed, very interesting phenomena are brought into light.

If 2 similar wires, spaced such that the distance between them is large compared to their radii, and are further assumed to be so located as to establish a system in themselves, the general solution requires 2 waves each of voltage and current traveling in opposite directions over the wires. Moreover, the ratio of the voltage to current wave traveling in one direction to those traveling in the other direction is the same in magnitude, but opposite in sign. The sign in this case simply indicates that the same electrostatic field traveling in one direction sets up a magnetic field in the opposite direction to that produced by the same field traveling in the opposite direction, which is in agreement with our fundamental notions of electromagnetic fields. This is the ideal case, in which the electrostatic and magnetic fields are orthogonal.

In the more practical case in which corona and ground conductivity are taken into consideration, and when one circuit is mutually related to another as in the case in Appendix I, there is found to be 4 waves required in the general solution, for both the current and the voltage. Thus, in one direction travels voltage (and current) waves of velocity v_1 and v_3. In the opposite direction are similar voltage and current waves of the same velocity. The more general solution is as follows:

Let the general voltage-current relationships be written as

$$\frac{\partial e_1}{\partial x} = Z_{11}\, i_1 + Z_{12}\, i_2 \qquad (1)$$

$$\frac{\partial e_2}{\partial x} = Z_{21}\, i_1 + Z_{22}\, i_2 \qquad (2)$$

$$\frac{\partial i_1}{\partial x} = Y_{11}\, e_1 + Y_{12}\, e_2 \qquad (3)$$

$$\frac{\partial i_2}{\partial x} = Y_{21}\, e_1 + Y_{22}\, e_2 \qquad (4)$$

where Z and Y are functions of p, in terms of the circuit constants.

Solving these equations simultaneously for e_1 (say) gives

$$e_1 \left\{ \frac{\partial^4}{\partial x^4} + (Z_{11}Y_{11} + Z_{12}Y_{11}) (Z_{12}Y_{12} + Z_{22}Y_{22}) \frac{\partial^2}{\partial x^2} + \left[(Z_{11}Y_{11} + Z_{12}Y_{11})(Z_{12}Y_{12} + Z_{22}Y_{22}) - (Z_{11}Y_{12} + Z_{12}Y_{12})(Z_{11}Y_{11} + Z_{22}Y_{11}) \right] \right\} = 0 \quad (5)$$

Exactly the same solution can be obtained for e_2, i_1, and i_2. Thus there is a quartic equation in the general case yielding 4 roots $-K_1$, $-K_2$, $+K_1$, and $+K_2$ and the solution for e_1 is

$$e_1 = A_1 e^{K_1 x} + B_1 e^{-K_1 x} + C_1 e^{K_2 x} + D_1 e^{-K_2 x} \quad (6)$$

and for e_2

$$e_2 = A_2 e^{K_1 x} + B_2 e^{-K_1 x} + C_2 e^{K_2 x} + D_2 e^{-K_2 x} \quad (7)$$

where the coefficients are functions of t but not of x.

By use of eqs 1, 2, 3, and 4 the following relationship can be obtained for corresponding coefficients in eqs 6 and 7.

$$e_2 = \frac{(Z_{11}Y_{11} + Z_{12}Y_{12})}{\frac{\partial x^2}{\partial^2} - (Z_{12}Y_{12} + Z_{22}Y_{22})} e_1 \quad (8)$$

Putting terms with "like" exponentials into eqs 1 and 2

$$A_1 K_1 e^{K_1 x} = Z_{11} i_1 + Z_{12} i_2 \quad (9)$$

$$A_2 K_1 e^{K_1 x} = Z_{12} i_1 + Z_{22} i_2 \quad (10)$$

Solved simultaneously,

$$i_1 = \frac{(A_1 K_1 Z_{22} - A_2 K_1 Z_{12})}{(Z_{11}Z_{22} - Z_{12}Z_{21})} e^{K_1 x} \quad (11)$$

$$i_2 = \frac{(A_2 K_1 Z_{11} - A_1 K_1 Z_{21})}{(Z_{11}Z_{22} - Z_{12}Z_{21})} e^{K_1 x} \quad (12)$$

These are the currents associated with the first voltage in eqs 6 and 7, respectively. It should be remembered that A_1 and A_2 are not independent in these expressions. Also, similar relationships hold for the B voltages in eqs 1 and 2 except for reversal of sign; the C and D voltages are related similarly.

In view of the foregoing, eqs 6, 7, and 8 may be written as

$$e_1 = f_1(x - v_1 t) + f_2(x - v_2 t) + f_3(x + v_1 t) + f_4(x + v_2 t) \quad (13)$$

$$e_2 = a_1 f_1(x - v_1 t) + a_2 f_2(x - v_2 t) + a_1 f_3(x + vt) + a_2 f_4(x + v_2 t) \quad (14)$$

for each voltage impressed upon the system. Current waves are obtained by eqs 11 and 12.

The equations developed in the paper assume only inductive and capacitive circuit constants. That is, resistance and "leakance" are neglected. The addition of the latter would not affect the number or velocity of the waves, but would complicate to a very great degree the interrelationships between them. In a particular case the voltages given in eqs 13 and 14 are related to each other through the terminal impedances by their reflection characteristics.

Joseph Slepian: Mr. Bewley has proposed a very bold and interesting method for explaining the observed manner of propagation of waves along systems of conductors parallel to a plane earth of finite resistivity in terms of component waves, which seems to have considerable success in a qualitative way. This success makes it seem likely that there is a correct or true element in Mr. Bewley's proposed method. On the other hand, I believe that there are incorrect elements in Mr. Bewley's method which lead to false conclusions.

For simplicity in discussion, I shall consider only a 2-conductor system, with zero resistance of the conductors, zero leakage between conductors (i. e., no corona) but with a resistive earth. It is necessary to ascribe finite resistance to the earth, for otherwise the zero-potential plane for the magnetic field necessarily would be in the surface of the earth; i. e., the actual earth currents would be confined to the earth's surface, contrary to the assumption of Mr. Bewley that it lies below the earth's surface. The departure of the effective velocity of propagation of the waves from that of light can come only from this earth resistivity, if we assume that the dielectric constant of the whole space including the earth is unity.

I think that the correct element in Mr. Bewley's method may be the following, perhaps true, theorem: Any wave system on the 2 conductors can be regarded as the superposition of 2 wave systems, with the following characteristics: For each wave system, the shape of the wave of potential is the same on each conductor, and therefore the shape of the wave of current is also the same on each conductor. The ratio of the amplitudes of potential waves on the 2 conductors is, however, different for the 2 wave systems. The ratio of the amplitude of the potential wave and current wave on one conductor is also different for the 2 wave systems. Each wave system, however, does not propagate according to ideal wave theory, with unchanging amplitude and shape as Mr. Bewley assumes, but each wave system undergoes attenuation and distortion, because of the resistance of the earth, at rates that are different for the 2 systems.

This theorem is certainly true when the 2 conductors are at the same height above the earth as is evident from symmetry considerations. Then, the 2 wave systems consist respectively of (1) potentials of equal magnitudes and like sign on the 2 conductors, and (2) of potentials of equal magnitude but opposite sign on the 2 conductors. Because of the smallness of the earth currents for the second system, the attenuation and rate of distortion for it will be small compared to the corresponding quantities for the first system.

If this theorem be true in general (and if it is new) then Mr. Bewley has made another very valuable contribution to the theory of propagation of waves on systems of parallel conductors. The resolution of an actual wave system into a sum of these special component wave systems should prove a tremendously valuable aid in the analysis of waves on conductor systems, even though I believe Mr. Bewley is wrong in concluding that these component systems each propagate with only small attenuation and distortion, and at definite velocities which are independent of the wave shape of the component waves.

I believe that Mr. Bewley makes a very fundamental error in writing eq 1 for waves which propagate at velocities other than the velocity of light. This error is made quite generally in textbooks dealing with waves on wires, where it is usually deduced from the differential equations:

$$L \frac{\partial i}{\partial t} = -\frac{\partial e}{\partial x} \qquad C \frac{\partial e}{\partial t} = -\frac{\partial i}{\partial x}$$

that waves travel with $\frac{1}{\sqrt{LC}}$, the velocity of light, instead of recognizing that the equations themselves cannot be written unless we first assume that we are dealing with waves that travel with the velocity of light. To make this clear, consider the second of these 2 equations. It is derived from the obvious relation that the time rate of change of the charge Δq on a given short element of line of length Δx is equal to the difference of the current flow into and out of the 2 respective ends of Δx.

$$\frac{\partial}{\partial t}(\Delta q) = -\frac{\partial i}{\partial x} \Delta x$$

Now, if C is the capacity per unit length of line, it is usually stated that $C\Delta x$ is the capacity of the short length Δx, so that $\Delta q = C\Delta x e$ giving the equation

$$C \frac{\partial e}{\partial t} = -\frac{\partial i}{\partial x}$$

But right there, the great mistake is made: The capacity of the short length of line Δx is not $C\Delta x$, unless the charge on Δx may be regarded as moving with the velocity of light. If the charge on Δx is at rest, for example, then the lines of electric force do not all lie in planes perpendicular to Δx, so that a proportionality between Δq and Δx is obtained; but some will reach out forward ahead of Δx, and some will reach out behind, so that the charge will be considerably larger than $C\Delta x e$ where e is the integral to infinity of the electric force taken in a plane perpendicular to Δx. This discrepancy will get relatively larger and larger, the smaller Δx is made. Clearly then the foregoing differential equation, which requires that Δx shall be made to approach zero, cannot be derived if the charge Δq is at rest. Incidentally, this shows that the wave equation cannot be correct at the end of a line, even for waves traveling with the velocity of light, because lines of force will reach out beyond the end, and will cause a loss of energy at a reflection there not predicted by the wave equation.

According to the usual Maxwell theory, the lines of electric force from a point charge at rest, reach out radially straight in all directions. However, if the charge moves, the lines of force are no longer straight, but while starting out radially in all directions, turn laterally into directions perpendicular to the direction of motion. As the velocity of the point charge increases, the lines of force turn out more sharply, until finally at the velocity of light they all lie entirely in the plane through the point charge perpendicular to the velocity. This is caused by the electric field induced by the magnetic field arising from the motion of the charge.

Now we may see that if the charge Δq on the element of line Δx is moving with the velocity of light, then the lines of electric force will all lie in planes perpendicular to Δx, Δq will equal $C\Delta x e$, and the differential equation of wave motion may be derived.

Similar discussion can be given for the first of the 2 wave equations. The inductance of an element of line cannot be taken as $L\Delta x$ where L is a constant, unless the current i there can be regarded as part of a wave traveling with the velocity of light. Only then will the magnetic field of the current element $i\Delta x$ be confined to the perpendicular slab of space including the element Δx. This is because the Maxwell displacement currents also contribute to the magnetic field.

These remarks all apply to Mr. Bewley's eqs 1. The equations can be derived only if we assume that they describe waves traveling with the velocity of light. Otherwise, they cannot be deduced.

As mentioned before, the confining of the lines of electric force of the moving element of charge to the perpendicular slab of space including the charge element is due to the electric field induced by the magnetic field, and the confining of the magnetic field of the current element to the perpendicular slab of space is due to the magnetic effects of the Maxwell displacement currents accompanying the electric field. The electric and magnetic fields are thus closely interrelated. Therefore, we may not make arbitrary independent assumptions as to the nature of the electric and magnetic fields. Mr. Bewley, therefore, must not assume arbitrarily that the electric field may have one plane of zero potential, and the magnetic field another plane of zero (vector) potential. If the electric and magnetic fields have everywhere the perpendicular slab distribution that is assumed in setting up eqs 1, then the zero-potential plane must be the same for both fields.

The 2-conductor system with resistive earth to which I have chosen to limit my discussion, may be expected to show the essential phenomena which Mr. Bewley has described and which he aims to explain. From the discussion which I already have given, it is clear that these phenomena must owe their origin to the lack of perfect conductivity of the earth. In fact, to produce currents in the earth parallel to the conductors, a parallel electric force is necessary. Hence the lines of electric force in space must have a component parallel to the conductors, and they will not lie everywhere in planes perpendicular to the conductors. Such waves as may be discerned therefore will travel with less than the velocity of light, but they will not be governed by Mr. Bewley's eq 1.

The existence of this parallel component of the electric field brings about the remarkable and at first sight paradoxical effect that a neighboring insulated wire has upon the propagation of waves in a given wire. The insulated wire can have an effect on the wave-bearing wire only if currents flow along it, for only with such currents can charges appear upon it; but if the electric field set up by the wave-bearing wire was perpendicular to the insulated wire wherever it encountered it, it is clear that no currents would be started in the insulated wire.

The existence of the parallel component of electric field makes clear in another way why Mr. Bewley's eqs 1 must be invalid. If the lines of electric force are not everywhere perpendicular to the conductors, then the potential at a point on one conductor is determined by the charge on the other conductor not at the same point, that is at the same value of x, but at some other point which will be ahead or behind depending on the inclination of the lines of electric force. Hence, eqs 1, which assume that the charge at any point of one wire is determined entirely by the potential there and the potential at the same point of the other wire, must be invalid.

It might be argued that with wave fronts of several thousand feet in length, and wire and ground separations of less than 50 ft, the parallel component of the electric field will be small compared to the perpendicular component and that therefore the wave equations have an approximate validity. However, we have just seen that the phenomena of attenuation and distortion which it is our business to explain owe their origin to the parallel component of field; therefore, it is difficult to see how we may hope to explain these phenomena by neglecting the very factor that brings them into being.

The criticism just given applies only to the eqs 1 which claim to govern the propagation of Bewley's component wave systems. The justifiability of the resolution into component systems of the type described, each traveling with its own velocity and manner of attenuation and distortion, seem to be plausible and apparently supported by experiment. The effective velocity of each component wave system, however, should be expected to depend on the wave shape, and should change during the propagation as distortion varies the wave shape, after the manner of waves on a single wire having finite resistivity.

R. D. Evans: Both of the papers dealing with surge propagation phenomena that have been presented today employ assumptions as to the equivalent depth of the earth return circuit. The calculation of the fundamental phenomena in a circuit with ground return assuming uniform resistivity of finite value is an extremely difficult problem. Much work has been done toward the determination of the steady state constants of these circuits by methods introduced by J. R. Carson. It seems to be of interest to consider what equivalent depth of earth return would be indicated by these methods for the resistivities of earth encountered in practice and for a frequency that might be considered comparable to lightning waves. The extensive work by the Joint Development and Research Subcommittee of the N.E.L.A. and Bell Telephone System has indicated that the resistivity of the earth varies between 1 and 10,000 meter ohms. Using an arbitrary high frequency, such as 1,000,000 cycles, the equivalent depths of return for conductors located 100 ft above the surface of the earth are indicated by these methods for (1) magnetic effects to vary between 215 and 460 ft and (2) for electric effects negligibly greater than 200 ft

Doctor Fortescue in his paper is concerned with application of the counterpoise to high resistance areas and assumes an equivalent depth of 400 ft. These calculations tend to support Doctor Fortescue's assumptions considering electromagnetic effects. While this method of getting at the depth of earth return may be criticized, as it is based on steady state rather than transient constants, yet it does seem pertinent to point out that the method gives values which check those indicated by the surge studies of Fortescue and Bewley.

It would appear for the front of the wave that the constants should be calculated on the basis of the same equivalent depth for both magnetic and electric effects, whereas for the tail of the wave greater depth should be assumed for magnetic effects than for electric effects. It seems unnecessary to assume, as Mr. Bewley has done, that the same equivalent depth should be used in computing constants applicable for both front and tail of the wave.

Power Limits of 220-Kv Transmission Lines

Discussion of a paper by Alex A. Kroneberg and Mabel Macfeman published in the November 1933 issue, p. 758–66, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934.

S. B. Crary: The authors have done a creditable piece of work in showing how the stability limits can be increased over that of the "simplest possible layout" with the expenditure of a relatively small additional investment. They have based their conclusions as to the benefits to be realized from each factor for improving stability on the gain in the transient stability limits as determined by the first swing of the machine rotors. Care must be taken in using the results of a transient stability analysis made in this manner as the stability limits of the subsequent swings or the steady state stability limits with the faulty line switched out may be below the limit as determined by the first swing. When the switching and relaying is fast, the maximum power that can be transferred through a disturbance may be determined by the steady state limits rather than the transient limit of the first swing. For example, the gain that the authors have credited to the series braking resistor over the base design cannot all be realized as the steady state stability limit with the faulty section switched out is probably in the neighborhood of 250,000 kw. This is below 300,000 kw, the transient limit obtained by the authors when the series braking resistor is used.

A further decrease in the practical gain to be realized by the use of series braking resistors is brought about by the fact that most systems are designed to have some margin between the steady state stability limit and the rated output of the station. For example, if the steady state stability limit is 250,000 kw and the rated output is 225,000 kw, which assumes only a margin of 10 per cent between the rated output and the steady state stability limit, it would seem unnecessary to provide equipment to raise the limit during the first swing to 300,000 kw when all the line normally will be expected to carry is 225,000 kw and all it can carry is 250,000 kw.

Consideration should be given also to the switching off of the braking resistors. Although the braking resistor will increase the power output of the generator, it will do so at a sacrifice of the synchronizing power between the generators and the receiving end system. This will increase the transient stability limits during the first swing, but will decrease the power limits of the subsequent swings as the machine groups oscillate about each other. The ideal arrangement, in order not to reduce the steady state limit or the limits of subsequent swings, would be to insert the resistors in the circuit only during the period when the fault is on or only during the first swing of the machine rotors.

However, even assuming that the braking resistors are used in this ideal manner so that it does not reduce the limit of subsequent swings, the steady state limitations

of a 280-mile 220-kv line are such that only a small practical gain can be realized by the use of series braking resistors when switching times of 0.2 sec or less are used. These features of the use of braking resistors will be found more fully discussed in the discussions of R. C. Bergvall's paper "Series Resistance Method of Increasing Transient Stability Limit," which was published in volume 50 of the A.I.E.E. TRANSACTIONS.

The authors' calculations of the power limits are simplified by assuming that the complements of the driving point and transfer impedance angles are small, and that $(P_1 - P_{11})$ is approximately equal to $(P_{22} - P_2)$. These assumptions, I believe, will lead to appreciable error in some cases and therefore cannot be applied generally to problems of this type.

The authors state by eq 13 that the change in kinetic energy of the rotor is proportional to the integral of the accelerating torque times the differential of the relative angular displacement, $d\delta$. This would be true if δ were the actual angular displacement with respect to some fixed axis in space rather than the relative angular displacement between the 2 rotors. The criterion developed by R. H Park for 2 machines and referred to by the authors is that the relative angular velocity of the rotors, $\frac{d\delta_{12}}{dt}$, is zero, not that the change in their kinetic energy is zero, when the following relation is satisfied

$$\int_{\delta_0}^{\delta}\left(\frac{T_{m1}}{H_1} - \frac{T_{m2}}{H_2}\right) d\delta_{12} = 0$$

This criterion generally is called the equal area criterion. Frequently it is explained loosely by means of the concept of change in kinetic energy while it should be understood to be the criterion which determines when the relative angular velocity between the rotors is zero, and not necessarily when the change in their kinetic energy is zero.

R. D. Evans: It is very gratifying to review the paper by Kroneberg and Macferran because it suggests the progress in stability that has been made in the last 10 years, during which time there have been presented many papers dealing with stability theory, laboratory tests, measures to improve stability, field tests, and operating experience; this paper is noteworthy because it gives economic comparisons of various system layouts which are analyzed from the stability point of view. The paper might be extended, however, to include evaluation of relative speeds of fault clearing. Since April 1932, when the paper was submitted to the A.I.E.E., there has been considerable progress in the development of circuit breakers and relays. The fault clearing time of 0.2 sec used in the paper is now viewed as conservative. This increased speed of fault clearing provides an additional factor that should be evaluated in relation to the other factors for stability improvement.

G. D. Floyd: The authors are to be commended for giving a very clear analysis of the factors influencing the power limit of 220-kv lines. In the past, the majority of the papers presented before this Institute have been concerned practically entirely with the technical features of the problem, without any data covering the costs of the various items. The reason for this was because the authors were probably not in a position to discuss this important feature.

Referring to Fig. 2 of the paper, I believe these curves illustrate a point that is of first significance, but which often is not fully appreciated. This is, that other things being equal, the power limit is a function of the synchronous capacity connected to the system, including transformer capacity. No intelligent or correct answer can be given to the question "What load can be carried on a given line?" unless the terminal conditions are specified.

I do not propose to criticize the data presented in this paper, which are no doubt correct for the conditions laid down. However, these data and the conclusions drawn from them may give a wrong impression. One would be led to believe that unless the special features analyzed in the paper are incorporated in the system, poor operating characteristics will result. This is not the case. If the transmission line is well designed, there will be, on the average, possibly 1 or 2 outages per year of a type equal to or greater than the authors set as a limit. The effect of these on the system as a whole may be tempered by a number of factors, 2 of which are:

1. The location of the fault, which may not be such as to produce the most severe oscillation.

2. The time of outage, which is quite likely to be at a time other than when the system is heavily loaded.

If these and other factors are considered, it does not seem that justification can be found for very much additional expenditure on equipment.

In the final analysis, it becomes a matter of judgment as to how far one would be justified in incurring additional expense in order to prevent an outage very likely to be of short duration, and with very little, if any, serious effect on system operation. The authors have not discussed this factor of probability, and it seems to me that the question of whether or not the system shall have special features incorporated in it cannot be decided unless this factor is considered. I believe members of the Institute would be interested to know which, if any, of the features of design considered by the authors actually have been incorporated in the system.

Nothing I have said will detract from the value of this paper. The authors set out a criterion for the stability limit of the system and analyzed it, showing the improvement to be expected from a stability standpoint, if various features were incorporated, giving also the increase in cost to obtain these features. I believe, however, that there is a place in this discussion for the points I have raised, and I hope they will be discussed further.

I would like to raise one other question: The authors have made no reference to the possibility of building a lightning-proof line. It has been stated more than once that such a line can be built. It may be possible to do it at equal or less cost than what would be incurred for the special features discussed in this paper. If such a line can be built economically, the stability limit then becomes the steady state limit, which as the authors have stated, is many times the lower or transient limit. All system faults, of course, are not caused by lightning; but if these latter are eliminated, the probability factor would make additional expenditure on account of instability unjustified, and therefore unnecessary.

W. W. Lewis: On page 761 of November 1933 issue of ELECTRICAL ENGINEERING, Kroneberg and Macferran discussed Petersen coils briefly and drew the following conclusion:

"Hence, it is safe to conclude that the possibility of using Petersen coils, at least in connection with 220-kv transmission, definitely should be rejected."

Probably what the authors intended to convey was the thought that in connection with their particular study, which pertained almost entirely to stability, Petersen coils did not show any advantage because their installation required 1 to 1 ratio isolating transformers and the reactance of these isolating transformers had the effect of reducing the stability limit. In addition, the cost of the Petersen coils and the isolating transformers had to be taken into account in evaluating the benefits of the Petersen coils. Where stability is not a factor, or under other circumstances, different conclusions may be justified and Petersen coils may be found to be applicable.

S. M. Zubair: One of the most significant features of the paper is the fact that transient stability power limits could be calculated directly by the integraph curves. The authors were able to avoid the step-by-step method of calculation by introducing the 2 approximations discussed in Appendix IV. The second approximation, however, is not necessary because if the last term of eq 9 is neglected (first approximation only) eq 8 gives:

$$\frac{E_1E_2}{Z_{12}}\cos\alpha_{12}\sin\delta - \frac{M_2(P_1 - P_{11}) + M_1(P_{22} - P_2)}{M_1 + M_2} = -\frac{M_1 M_2}{(M_1 + M_2)2\pi f}\frac{d^2\delta}{dt^2}$$

which readily becomes eq 24

$$\frac{d^2\delta}{d\tau^2} + \sin\delta = \frac{E}{B}$$

if

$$B = \frac{E_1E_2}{Z_{12}}\cos\alpha_{12}$$

$$E = \frac{M_2(P_1 - P_{11}) + M_1(P_{22} - P_2)}{M_1 + M_2}$$

and

$$\tau = t\sqrt{\frac{2\pi f\,(M_1 + M_2)\,B}{M_1 \times M_2}}$$

It is interesting to note, however, that the integraph solution can only be used if eq 24 does not contain a cos δ term. This necessitates the first approximation:

$$\frac{M_1 - M_2}{M_1 + M_2}\frac{E_1E_2}{Z_{12}}\cos\delta\sin\alpha_{12} = 0$$

or

$$\frac{M_1 - M_2}{M_1 + M_2}\sin\alpha_{12} = 0$$

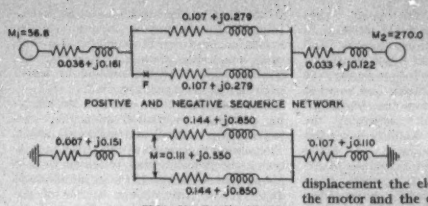


Fig. 2. Representation of a 110-kv system in which α_{12} is too high to be neglected

Theoretically this condition is obtainable only when either $\alpha_{12} = 0$ or $M_1 = M_2$. Since $\alpha_{12} = 90 - \tan^{-1}\frac{X_{12}}{R_{12}}$ where $R_{12} + jX_{12} = Z_{12}$, the transfer impedance, the value of α_{12} will decrease as the ratio of $\frac{X_{12}}{R_{12}}$ increases. In a 220-kv system where the ratio of reactance to resistance is high, the value of α_{12} may be negligible, but in a 110-kv system α_{12} may be too high to be neglected. This is illustrated in Fig. 2. For a 2-phase-to-ground fault at F, the equation of the relative angle of the 2 rotors is $0.83 \sin \delta - 0.19 \cos \delta - 0.317$

$$= -\frac{46.8}{2\pi f}\frac{d^2\delta}{dt^2}$$

where the $\cos \delta$ term could not be neglected and therefore the integraph curves cannot be applied.

Steady State Stability of Composite Systems

Discussion of a paper by S. B. Crary published in the November 1933 issue, p. 787–92, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934.

H. L. Hazen: See p. 477.

Power Limits of Synchronous Machines

Discussion of a paper by Edith Clarke and R. G. Lorraine published in the December 1933 issue, p. 780–7, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934.

S. B. Crary: The authors have presented in concise form for practical calculations criteria for determining the steady state power limits of 2, 3, 4, and 5 synchronous machines. The relative simplicity of these criteria was made possible by using a method of testing for stability which is different from that previously used and which, I believe, is worthy of more discussion than that given in their paper. They have chosen the criterion that stability exists if for a sustained increase in angular displacement the electrical power input to the motor and the electrical power output of the generator units of the system increase, constant system frequency being maintained. This criterion is different from that used by Wagner and Evans and presented in their paper "Steady State Stability" (A.I.E.E. Trans., v. 47, 1928, p. 94). Wagner and Evans used the criterion that the system is stable if it returns to its original assumed operating position after one of the rotors has been forcibly displaced from its original operating point. These 2 methods of analysis indicate different stability limits in certain regions of operation. The difference in the 2 methods can be demonstrated clearly by considering 2 machines operating at or near 90-deg relative angular displacement, the region where this difference exists.

Consider 2 synchronous machines, a generator and a motor, connected together by means of a line having resistance and reactance and operating with 90-deg angular displacement. Their torque angle characteristics will be as shown on Fig. 2 of the paper. The equal area criterion derived by R. H. Park (reference 4 of the paper), provides a method for analyzing the phenomena at this point. A diagram of the ratios of their accelerating torques to their respective inertias with constant mechanical torques plotted against relative angular displacement will appear as shown in Fig. 3(a) for a large generator inertia compared to the motor inertia, and as shown in Fig. 3(b) for a small generator inertia compared with the motor inertia. Referring to Fig. 3(a), it can be seen that if the angular displacement δ_{12} is increased suddenly, the motor will slow down more rapidly than the generator (the length ac is greater than ab and synchronism will be lost as there will be no restoring forces to bring the machines back to their normal operating position. If an increase in load is thrown on a motor operating at such a point, the accelerating torque per unit of inertia curve for the motor changes to that shown by the dotted line. This results, therefore, in a retarding torque acting on the rotor of the motor equal at the first instant to the increase in load (the distance $od \times H_2$) which causes the motor to slow down more rapidly than the generator, and the system is unstable. Therefore, for this case, both methods of testing for stability would find the system unstable for this particular condition.

Next consider the case when the motor inertia is large compared with the generator inertia as shown in Fig. 3(b). A momentary forcible increase in the angular displacement δ_{12} will result in the generator's slowing down more rapidly than the motor (the distance ac is greater than ab) thus returning the system to its original operating position. This method of testing for stability therefore indicates a stable operating point. Now consider a small increase in motor load with constant system speed. This will result in the slowing down of the motor at the first instant as is shown by the distance od. As the angular displacement between the motor and generator increases, the generator slows down more rapidly than the motor and the system returns to a new position of equilibrium, o'. However, at o' the new point of equilibrium, there is a retarding torque acting on both the motor and generator due to the increased load and line losses represented by the distance $o'd'$ which results in a reduction in the system frequency. As the governor of the generator attempts to bring the system frequency back to normal, the curve of T_{ai}/H_1 in effect moves upward and the point of equilibrium o' moves down until synchronism is lost. Therefore, for the case of series resistance and with a large motor inertia compared with the generator inertia, the system in this region of questionable stability can operate with a momentary increase in angular displacement, but cannot for a sustained increase in motor load. The first fact is of theoretical interest while the latter is of practical importance.

In a similar manner the 2 cases when the generator and motor are connected to a shunt impedance can be analyzed by Fig. 4. Figure 3 of the paper shows the shape of the

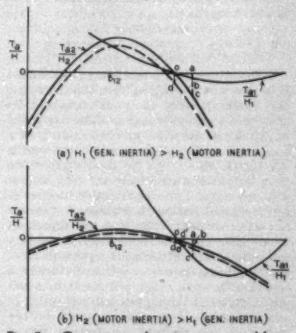


Fig. 3. Generator and motor connected by a series resistance

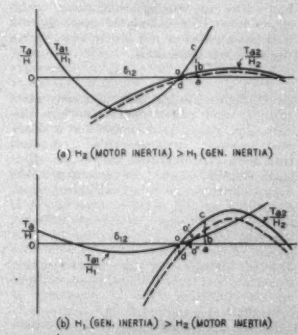


Fig. 4. Generator and motor connected by a shunt resistance

power angle characteristics for this case. Figure 4(a) of this discussion is for a small generator inertia compared to the motor inertia while Fig. 4(b) is for a large generator inertia compared to the motor inertia. The condition represented by Fig. 4(a) is unstable either for a momentary increase in angle or a sustained increase in load. The condition represented by Fig. 4(b), however, is stable for either type of load increase. In this case for a sustained increase in load on the motor, the generator and motor tend to reach a new point of equilibrium o' with constant governor input to the generator. Since this new point of equilibrium is above the line of zero accelerating torque, the system frequency increases. The governor on the prime mover of the generator decreases the mechanical input to the generator, which in effect moves the curve T_{a1}/H_1 down, until a new point of equilibrium o'' is reached with zero accelerating torques acting on both motor and generator. This case, Fig. 4(b), is the only case of the 4 which is stable for a sustained increase in load when one of the machines, in this case the generator, is operating with the slope of its power angle curve negative (negative synchronizing power coefficient).

The criterion for stability for this relatively simple case of 2 machines when machine 2 is subjected to a sustained small load increase is

$$-\frac{dP_2}{d\delta_{12}}\frac{1}{H_2} \quad \text{must be greater than} \quad -\frac{dP_1}{d\delta_{12}}\frac{1}{H_1}$$

When more than 2 machines are involved it becomes increasingly difficult to determine the exact stability limit for sustained increases in load in the region where one of the units has a negative synchronizing power coefficient. No simple relation such as the one given above can be used when more than 2 machines are involved. The answer depends not only on the relative inertias of the machines but on their rates of governor response as well. The authors, therefore, wisely have chosen the criterion for stability to be that each of the units have a positive synchronizing power coefficient. Such a criterion in some cases will result in pessimistic stability limits, but will not result in overly optimistic results as would be obtained if the method for testing was a momentary increase in angle or load. Consideration of the particular problem in hand after the synchronizing power coefficients have been calculated generally will indicate whether or not and to what degree the answer is pessimistic.

G. C. Dahl: The problem of steady state stability and power limits has been discussed in considerable detail for a dozen years or more. In spite of this fact it seems that no single criterion on the basis of which such stability should be determined has been definitely established and agreed upon. Surprising as this may be to some, it is nevertheless the case. Somewhat different schemes, all more or less justified by the nature of the problem, have been used by different investigators. It seems fortunate, therefore, that this question again is brought up for discussion with the possibility of settlement once and for all.

Besides depending upon (1) the electrical characteristics of machines and circuits, the ability of a system to operate stably in the steady state is influenced by (2) prime mover characteristics, and (3) inertia. In determining steady state stability and power limits, however, the 2 last-mentioned factors seldom are taken into account. To what extent this is justifiable and to what extent the various factors are important from the standpoint of influencing the problem of steady state stability never has been completely investigated. It would indeed be valuable to secure additional experimental results and to compare these with calculations based on different premises.

In the paper "Static Stability Limits and the Intermediate Condenser Station" by Evans and Wagner (A.I.E.E. TRANS., 1928) it is shown that under fixed shaft-load conditions (an assumption that eliminates any effect of prime mover characteristics) the steady state stability is influenced by inertia. In order to find the angle between the various machines at which the system may be operated stably, the inertia should be included in the calculations. With reference to a 2-machine system consisting of a generator, an impedance line, and a synchronous motor, this means that stable operation, theoretically at least, may take place when the machines are farther apart than the impedance angle of the connecting circuit (the latter including the impedance of the machines themselves). A power circle indicates the existence of 2 values of maximum power, one for the generator, and one for the motor. The latter is the smaller and hence usually the value of interest, i. e., it represents what ordinarily is termed the *power limit of the system*. If the generator inertia is infinite, the angular displacement at this value of power represents the limiting stability angle. If, on the other hand, the motor inertia is infinite, the angular displacement may be increased to that corresponding to maximum power of the generator. For finite values of inertia, operation is practicable over a part of the zone between these 2 limiting angles. It is evident that operation beyond the angle corresponding to maximum motor power can be established only by increasing the prime mover input to the generator. It cannot be established by any slow load application to the motor shaft, although it is conceivable that the system might settle in this region after a suitable transient application of load to the latter machine.

It is evident that since in a system, stability must be available when load is applied to any arbitrary machine, the region beyond the maximum power of the motor in the above case is of no great significance. Operation always will take place at an angle smaller than that corresponding to this power limit. In this region the question of stability can be settled without reference to inertia or prime mover characteristics, and the power limit can be determined without introducing the use of these factors.

It seems therefore that for a 2-machine system, stability and power-limit calculations can be performed in practice without consideration of prime mover characteristics and inertia. To what extent this is permissible with a multimachine system has not as yet been demonstrated. However, on the assumption that it may be done also here, I agree that the criterion by which each machine should be tested is that considered in the paper by Clark and Lorraine involving an infinitesimal load application to the shaft of the machine and the examining as to whether or not the requisite synchronizing power is available. I wish to raise a question, however, regarding the detailed aspects of the method by which such stability tests are executed.

The analysis is to be based on the following premises: constant frequency (i. e., no prime mover action) and no inertia effect. The assumption made in the paper in analyzing the multimachine system is that in giving one of the machines an infinitesimal displacement with respect to one of the others, the power outputs of the rest of the machines remain constant. This assumption is evidently contrary to fact except when the second machine involved is made to assume the entire load increment by automatic frequency control of the governor. This can only take place after the elapse of a certain time interval. It seems to me that since we are here considering an *incipient tendency* of one machine to become displaced due to the application of an infinitesimal additional shaft load, all other machines should be considered fixed in phase with respect to each other. This, in my opinion, gives a more logical basis in obtaining the power distribution between the other machines and the effect of this group with respect to the machine being tested, especially when the coupling between the single machine and the group is relatively loose. This, for instance, would be the case where a remotely located hydroelectric station supplies power to a metropolitan system over a long transmission circuit.

In conclusion I wish to say that I am glad that the question of criteria for steady state stability has been taken up again for discussion. It is of some importance to get complete agreement on these matters. As already stated, however, I believe that before this can be done, further experimental results and also analyses will have to be presented so that the effect of the various factors may be appreciated better. We have under way now at the Massachusetts Institute of Technology some work along these lines. We hope to secure a series of test results in our machine transients laboratory, and shall use these to check analyses based on different premises.

R. D. Evans: Clarke and Lorraine, under the heading of "Test for Stability," discuss operation at angles greater than α, the angle which corresponds to maximum power for the end which first encounters it. Maintenance of stability at greater operating angles was indicated by Wagner and Evans in their paper in 1927. Clarke and Lorraine do not disagree with this, but make a distinction between an arbitrary slight increase in angle and an arbitrary slight increase in load. They point out that for increase in load, equilibrium under initial conditions including frequency cannot be regained for operating angles greater than α. It is suggested that the 2 statements are not in conflict, but that each is correct for the conditions assumed. However, it may be observed that operation for angles greater than α may be not only of theoretical interest, but also of practical importance, if equilibrium can be secured at reduced frequency. In such cases normal frequency may be regained by redistribution of load without an interruption to

service, and such a system may be operated closer to the steady state power limit with the same margin of safety.

In Appendix III of this paper are given 3 separate cases for replacing a load end network by an equivalent network with an equivalent voltage and equivalent series impedance. The first 2 of these may be viewed as special cases of a more general method of using equivalent circuits applicable to systems in which synchronous machines maintain their internal voltages at constant value and definite relative phase position. This method may be illustrated by considering its application to 3 machines with voltages E_a, E_b and E_c feeding through three impedances Z_{ax}, Z_{bx}, and Z_{cx} between the internal voltages and the junction point x. The equivalent impedances and equivalent voltages are defined by the eqs 1 and 3.

$$\frac{1}{Z_{xq}} = \frac{1}{Z_{ax}} + \frac{1}{Z_{bx}} + \frac{1}{Z_{cx}} \tag{1}$$

$$I_x = \frac{E_{xq}}{Z_{xq}} \tag{2}$$

$$= \frac{E_a}{Z_{ax}} + \frac{E_b}{Z_{bx}} + \frac{E_c}{Z_{cx}} \tag{3}$$

Additional machines can readily be handled by adding additional terms to eqs 1 and 3. A shunt load may be taken into account by setting the voltage of that branch equal to zero.

The series impedance branches may be replaced by a complex network with lumped or distributed constants. The proof for this generalized method was published in 1926 (A.I.E.E. Trans., v. 45, 1926, p. 75).

H. L. Hazen: In the study of the steady state stability of an n-machine system by power increment methods, the problem of distributing a load increment applied to one machine, for example, the kth, among the remaining $(n - 1)$ machines arises. This distribution can be made on the basis of any one, or of a combination of the following assumptions: (1) that the relative rotor positions of the $(n - 1)$ machines remain unchanged, but that the group position changes with respect to that of the kth rotor; (2) that the prime mover inherent speed regulation at constant gate or throttle is effective in determining the frequency-load characteristic of each unit and hence the division of load increment; (3) that the governors determine the frequency-load characteristics, the assumption made in Crary's paper ("Steady State Stability of Composite Systems," Elec. Engg., v. 52, Nov. 1933, p. 787–92); and (4) that the governor characteristics are readjusted in response to the load increment by automatic frequency controllers. In the paper by Clarke and Lorraine it is assumed that one machine is equipped with automatic frequency control.

The first of these assumptions, that the relative angular positions of the $(n - 1)$ machines are not changed, has been used by several investigators. This assumption would certainly be a fair approximation to the truth when the coupling of the kth machine to any of the $(n - 1)$ machines is relatively loose compared to the couplings of the $(n - 1)$ machines with each other. In this case, although the division of an increment of load applied to the group may vary widely due to the fact that one of the other assumptions is more nearly valid than the constant relative angle assumption, the changes in relative angles within the group would be so small in comparison with the change in angle between any one of these and the kth machine as to be quite negligible in their effect on the stability of the kth machine. Since computations resulting from this assumption are readily made, it is very useful when applicable. That this assumption represents an accurate formulation of the physical relations significant in determining steady state stability in the more general case, in which the coupling between machines is more nearly equal, is, I believe, an hypothesis as yet lacking adequate experimental verification. In fact, since the relative angles among the $(n - 1)$ machines are constant only during a short time interval after any increment of load is added, it would appear that this assumption is probably not basicly applicable to steady state analysis. However, it may be very useful, practically.

The second assumption, that the load increment taken by any of the $(n - 1)$ machines is proportional to the machine rating and inversely proportional to the per-unit regulation at the given operating point of the prime mover at constant gate or throttle, represents a condition that will exist if the various rotors reach mechanical equilibrium before the governors have time to act. This assumption probably represents actual conditions rather well during a considerable period of time in the case of hydroelectric units in which the time for the prime mover torque correction through governor action may be relatively large compared to the period of the electromechanical rotor oscillations. In the case of turbine alternators, in which the response to governor action is substantially complete within a half second after a load change, this assumption probably does not represent the facts accurately at any time following an appreciable load change. However, in steady state stability analysis we are interested in very small load changes, in which the frequency change is very small. Even the most sensitive governor has a small but finite range, determined by friction and backlash, over which the speed may vary without causing the governor to respond. For variations of load that do not change the speed of the prime mover, by virtue of its inherent speed regulation, enough to cause governor action, this second assumption would appear to be reasonably in accord with the facts for a sufficient period during a slow system-load change to make it significant in steady state stability analysis. The mechanics of calculation on the basis of this assumption are identical with those given by Crary except that the governor per-unit regulation is replaced by the prime mover inherent regulation at constant throttle or gate.

The third assumption, that made by Crary, may very likely be the most appropriate for a practical case in which governors have a very small insensitive speed range and a relatively rapid response, and in which the load increments are applied at a finite though perhaps very small rate.

The fourth assumption, that automatic frequency controllers have the opportunity to act before conditions critical in steady state stability are reached, probably is useful as the authors state, not because it gives an accurate picture of the physical mechanism of steady state instability, but because when used with judgment it yields useful results with relatively simple analysis.

It is generally recognized, I believe, that even steady state stability is fundamentally a dynamic problem and that therefore the basic criterion for stable operation is that the various machines included in a system shall remain in synchronism after any change, such as a slow application of load, has been made. In view of this fact the various assumptions stated in this discussion apply only to the approximate, but practically the most useful, analyses in which inertia is neglected.

Power Limit of a Transmission System

Discussion of a paper by W. S. Peterson published in the August 1933 issue, p. 569–72, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934.

Edith Clarke: Under "Fundamental Principles," Mr. Peterson states "A transmission system is essentially 2 groups of synchronous machinery, electrically connected together by a transmission line, . . ."; and, in the closing paragraph, "The method outlined in this article is one that enables an engineer without much special training in handling stability problems to obtain reasonably quickly solutions for the simple system which are quite accurate for all types of single location short circuits."

For the benefit of those "without much special training in handling stability problems," I would point out that the synchronous machines of transmission systems do not always swing in 2 groups during disturbances. In fact, they may swing in 3 or more groups depending upon the type of system and character and location of the disturbance.

When power is supplied from a generating station over long transmission lines to a load center which is also fed from nearby generators, or is equipped with synchronous condensers and a fault occurs on one of the transmission lines, the machines in the generating station probably will swing in one group and those in the load area in another group. If this be true, the system can be represented by 2 equivalent machines. This is the type of system shown in Fig. 2 of Mr. Peterson's paper and is the type of system and character of disturbance to which his method is applicable. However, should a fault occur between machines in the load area, the synchronizing torque between them might be so reduced that they would lose synchronism with each other, or one machine might lose synchronism with the others in the area. In this case, although the machines at the distant generating station would swing together, those at the load would not and the system could not be represented by 2 equivalent machines.

Two-machine methods are essentially time savers and are valuable as such. For any disturbance for which the machines of a system swing in 2 well defined groups, the error in replacing the system by 2 equivalent

machines is slight. Experience in stability calculations is an aid in predetermining the machines which will swing together. When such experience is lacking, it may be advisable to calculate the time-angle curves for the important machines or machine groups of the system for a typical operating condition and disturbance. Then, if the machines of the system swing in 2 groups, it reasonably can be assumed that they will swing in 2 groups for similar operating conditions and disturbances that are comparable.

A somewhat different method of applying the equal area criterion to short-circuit problems when the effect of resistance is taken into consideration is given in "Calculation of Two Machine Transient Stability With Resistance," by S. R. Pritchard, Jr., and myself. This article will appear in the February, 1934, issue of the *General Electric Review*. The angle between the machines at which the fault must be switched off in order for stability to be maintained is determined graphically. Then the time corresponding to this angle is determined by means of one time-angle calculation.

Cross Potential of a 4-Arm Network

Discussion of a paper by Anatoli C. Seletzky published in the December 1933 issue, p. 961–7, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934.

W. B. Kouwenhoven: Seletzky presents a very simple and ingenious method of applying Schenkel's equations for the determination of the loci of the potential across the detector arm of a 4-arm bridge circuit. Seletzky, however, illustrates the application of his method with a bridge that is not commonly used in measurement work. In the bridge that he has used the center of the circle lies on a line connecting the e'_0 and e'_∞ vectors. This is not the case for all 4-arm a-c bridges. Here e'_0 is the value of the potential across the detector arm when the variable factor is taken as zero and e'_∞ the potential for the variable equal to infinity.

I have determined the loci of the potential across the galvanometer for both the series resistance and the Schering bridges. These 2 bridges give results that are similar in many respects; therefore I will present the data for only one of them.

Consider for example one of the commercial series resistance bridges shown in schematic form in Fig. 1. Here R_3 and R_4 are the ratio arms of 5,000 ohms each. The specimen under test is represented by its equivalent circuit, namely, the capacitor C_1 with its series resistance R_1. Assume that C_1 is 500 $\mu\mu f$ and that R_1 is 1,000 ohms. The variable arm contains the air capacitor C_2 and the resistance R_2. Since the bridge ratio is 1 to 1, $C_2 = 500$ $\mu\mu f$ and $R_2 = 1{,}000$ ohms at balance.

Operating this bridge at 1,000 cycles holding C_2 constant at 500 $\mu\mu f$ and varying R_2 from zero to infinity, I find that the vector potential across the detector circuit for R_2 equal to zero is $e'_0 = 7.85 \times 10^{-4} \angle -90°$. When R_2 becomes infinity $e'_\infty = 0.5 \angle 0°$. At balance the galvanometer potential vector $e'_{bal.}$ is zero. These 3 points determine the circular loci of the potential across the galvanometer whose center, for R_2 variable, lies on the line connecting the e'_0 and e'_∞ points, as pointed out by Seletzky.

When R_2 is held constant at 1,000 ohms and C_2 is varied from zero to infinity, the e'_0 vector is found to be $0.5 \angle 0°$ and the $e'_\infty = 0.5 \angle 179°+$. Here as before the potential at balance is zero and it is evident that the vectors lie practically on the same straight line. The radius of the circle is very large in this case and its center does not lie on the line connecting the e'_0 and e'_∞ vectors.

It is evident from this analysis that in the series resistance bridge the vector potential across the detector produced by variations in the resistances is displaced 90 deg from that caused by changes in capacitance. It is also clear that over the normal operating range of bridge values of resistance and capacitance, not only are these vectors 90 deg apart, but also they are fixed in space. Therefore, it is possible to use a separately excited a-c galvanometer as a detecting instrument and to adjust the phase of its field excitation so that it will respond to a variation in either resistance alone or capacitance alone. This conclusion is borne out by experimental proof (see "A High Sensitivity Power Factor Bridge," W. B. Kouwenhoven and A. Banos, Jr., A.I.E.E. TRANS., v. 51, 1932, p. 202–10).

The determination of the points for the loci of the detector circuit potential also brings out another interesting fact concerning the relative sensitivities of the 2 balance operations. For example, the change in the resistance R_2 from zero to its balance value of 1,000 ohms produces a change in the potential across the galvanometer of only 7.85×10^{-4} volt per volt applied to the bridge; whereas the change in capacitance C_2 from zero to balance at 500$\mu\mu f$ causes a change in galvanometer potential of 0.5 volt per volt.

Portable Schering Bridge for Field Tests

Discussion of a paper by C. F. Hill, T. R. Watts, and G. A. Burr published in the January 1934 issue, p. 176–82, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934.

J. C. Balsbaugh: I think this paper gives a very interesting application of the Schering bridge. I should like to ask the particular reasons for using the inverted type of Schering bridge inasmuch as the more general type also would be applicable. The more general type of Schering bridge may be used with one of the bridge arms at ground potential and then balancing the shield-to-ground potential. The advantages of this method would be that it would maintain the measuring and balancing resistances and capacitances at close to ground potential. Furthermore, in this case the lead from the

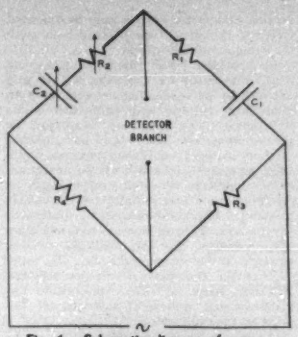


Fig. 1. Schematic diagram of a commercial series resistance bridge

bushing being tested to a disconnecting switch will be at a point common to the 2 halves of the bridge and therefore will not introduce difficulties in the bridge measurements similarly to the case of the inverted Schering bridge where this lead from a bushing is connected to one of the bridge arms, and therefore electrostatic pick-up in this lead being included in the bridge measurements.

I should also like to obtain the sensitivity of the bridge expressed as that change in power factor from balance which will give, say, 1 mm deflection of the galvanometer for certain specified bridge constants and applied voltage.

With respect to the use of power factor as a criterion of the condition of insulation in general, I think it would be better to use some value that would be directly proportional to the in-phase component of current and would be independent of capacitance. This method would give a more accurate indication of the condition of an insulation and would be more applicable for direct comparative purposes. In general, of course, power factor is not in independent of a change in capacitance and furthermore is not directly proportional to the in-phase component of current when the power factor exceeds 0.05 to 0.10.

Eugene D. Eby: The measurement of power factor constitutes one means of comparing insulating materials of dissimilar character and also the effects of varying conditions upon the same or similar classes of insulations. Power factor measurements on apparatus in service may add materially to the sum total of our knowledge of the various insulating materials, as well as disclose the effects of service conditions upon such materials commonly employed in electrical equipment.

It is generally recognized that the absolute value of the measured power factor of a particular insulating material, as compared with similar measurements of other materials, constitutes in itself no basis for comparing its suitability for its use in a particular field to the suitability of other insulations in their respective fields. In other words, the absolute value of the power factor means very little, since different insulations

vary widely in power factor while performing their functions with equal success. In fact, a value of power factor that would be considered entirely normal for one material could be accepted as sufficient evidence of unreliability for another. For example, a certain filling material for bushings having a normal power factor at 25 deg C of 0.001 would be immediately condemned at a power factor of 0.02 which is the normal value for certain grades of resin treated paper.

It becomes apparent, therefore, that with widely varying values of power factor for different insulating materials a composite structure employing several such materials will show a power factor intermediate of the maximum and minimum values represented and dependent upon the relative amounts and disposition of the various materials employed. Thus, a bushing the insulating material in which is largely resin treated paper will have an over-all power factor approaching the value for this material, whereas, a bushing employing low power factor oil to a large degree will naturally have an over-all power factor much lower than the paper bushing. For these reasons, each type of bushing, and even each size of a given type (for the proportions of widely different materials vary appreciably) will have a normal characteristic power factor of its own. An intelligent use of power factor measurements must recognize these varying normal values.

The effect of service conditions upon the power factors of different insulating materials may be widely different also. This fact even may obscure the presence of danger in a composite structure, as, for example, when a sparingly used material, which contributes very little to the over-all power factor of the composite structure, experiences a serious increase in its own power factor without appreciably affecting the whole.

The best guide for determining the significance of a power factor measurement is a comparison with previous measurements under the same conditions or with known standards. For this reason, complete records of all measurements should be placed on file for future reference and for comparison with new readings as obtained.

Because of the great variation in bushing design, and in the characteristics of the materials employed, as well as the varying effects of service conditions upon these different designs and materials, a great amount of data will be required before any strict limits can be set for power factor values beyond which operating reliability is definitely impaired. It is likely that such limits will vary widely for different types of bushings. For example, bushings using only solid materials, some of which have their electrical properties greatly affected by moisture, may require a comparatively low limit of power factor beyond which they should be removed from service; on the other hand, it may be found that bushings employing a liquid filler which allows moisture to settle out in time, or causes it to rise to the surface can be given a higher limit, since with continued operation their condition would tend to improve.

Because of the widely varying effect of temperature upon Power Factor values, any established limits must be related to a definite temperature or be expressed in the form of temperature vs. power factor curves. The effect of temperature varies widely with different materials as illustrated in Fig. 2.

Consequently, the temperature—power factor characteristics of different types of bushings will be different, depending upon the materials of which they are composed. This is illustrated in Fig. 3.

The effect of change in the testing voltage upon the power factor value is also different with different materials, and consequently, with different combinations of materials. While dry type bushings generally have a rising characteristic, bushings of the liquid filled type may have a falling characteristic as illustrated in Fig. 4. Fortunately, experience indicates that for field purposes a test potential of from 10,000 to 20,000 volts is adequate for indicating the general condition of a bushing.

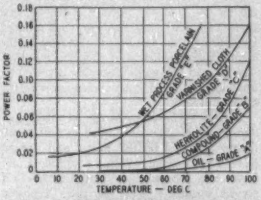


Fig. 2. Variation of power factor with temperature, for representative bushing materials

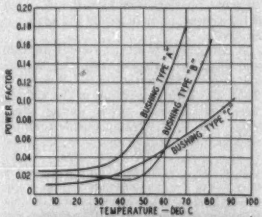


Fig. 3. Variation of power factor with temperature, for several types of bushings

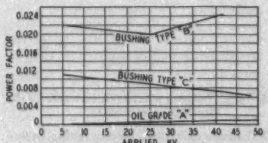


Fig. 4. Variation of power factor with voltage, for 2 types of bushings using liquid fillers

Everett S. Lee: The very interesting paper by Hill, Watts, and Burr and the admirable papers by Gross and Turner, published in the January 13 and January 20 issues of *Electrical World* on "Testing Bushings and Insulation by Power-Factor Method" in which results of field tests on some 10,000 bushings are reported, bring before us the time-honored subject of the determination of the quality of electrical insulation. That this is not a new subject, the oldest ones among the readers will attest. I know from the literature that it started long before my time and I know from experience that it is not yet solved.

Some 9 years ago there was delivered from this platform a paper ("Testing High-Tension Impregnated Paper-Insulated Lead-Covered Cable," by Everett S. Lee, A.I.E.E. TRANS., v. 44, 1925, p. 104) on the testing of cables which, with the ensuing discussion, included almost every ramification of the subject known at that time; and a year later the classic papers of Roper and Halperin ("The Quality Rating of High-Tension Cable With Impregnated-Paper Insulation," A.I.E.E. TRANS., v. 44, 1926, p. 528) and Farmer ("Tests of Paper Insulated High-Tension Cable," A.I.E.E. TRANS. v. 45, 1936, p. 553) were presented at Madison, Wis., suggesting ways in which the quality of insulation might be definitely evaluated. It was brought out at this time that our knowledge of the mechanism of the breakdown of insulation had not been brought to a point allowing definite evaluation to be carried on with certainty.

The subject has since been consistently studied for all classes of apparatus and all kinds of insulation, but the answer today is much the same.

From all of our experience certain empirical tests applied in this way or in that way have served to show that new insulation was in such condition that the apparatus could be used safely and the life to be expected therefrom under known operating conditions would be satisfactory. In each case there is a safety factor sufficient to provide for obtaining the desired result. As insulation is used and becomes subjected to not only usual but sometimes unusual operation conditions, the same tests are generally applicable although the limiting values may change.

So it is with bushings. It is generally accepted that measurements of insulation resistance and power factor obtained by any accepted means, of which there are several give data that allow of discussion relative to the quality of the insulation at the time of the measurement. In general, insulation resistance is the most sensitive test for detecting the presence of moisture; but for the various forms in which deterioration is manifest, I believe it is generally felt that power factor results are of the greater usefulness. As time goes on the measurement of other properties may be found appropriate; but it is the interpretation of the measured values into terms of quality of insulation which is the most difficult part of the whole problem and the one which presents the greatest uncertainty. The more data that are obtained under the same general conditions, the greater the certainty of the interpretation; but it is still true that with our present knowledge the limiting values that may be set, although helpful, are not all-conclusive nor certain to such a degree that the job can be considered wholly perfect.

It is not a difficult matter to measure the power factor of a bushing in the field either by a bridge method, such as described by Hill, Watts, and Burr, or by the wattmeter-voltmeter-ammeter method described by Gross and Turner. The real difficulty comes in assigning limiting values representative of

quality conditions and to do it with certainty. The more of this work that is done, however, the greater will be our ability to use whatever information we have for good.

F. L. Moser and H. B. Wolf: The paper by Hill, Watts, and Burr is of especial interest to operating men responsible for the maintenance of apparatus and continuity of power service.

The management of the company (Duke Power Company) with which we are associated has considered the development of equipment suitable for testing bushings to be of great importance. We therefore have long been experimenting with various devices. Early in 1930 after many tests the equipment that we now use proved satisfactory. As our experience indicates the great value of bushing testing in reducing failures, with consequent reduction in interruption to power service, we are presenting herewith a brief description of our equipment with a summary of results obtained.

In making this test we apply an a-c potential of 33 kv to the bushing under test and read the current flow through the combined capacitance and resistance of the bushing. The equipment used consists of a motor-driven 100-watt 110-volt single-phase alternator for supplying a fixed wave shape and voltage to the step-up transformer, which has a ratio of 110 to 30,000 volts, a milliameter with current transformer, and an a-c voltmeter, together with necessary

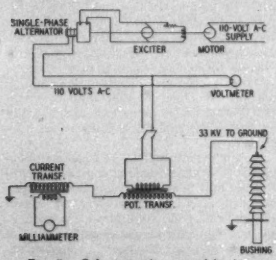


Fig. 5. Schematic diagram of bushing testing equipment in use by Duke Power Company

Table I—Summary of Tests on Oil Circuit Breaker Bushings

Year	Rated Kv	No. of Breakers	No. of Tests Made
1930	100	214	2,556
	44	8	60
1931	100	233	4,344
	44	40	264
1932	100	241	2,886
	44	48	546
1933	100	209	2,334
	44	40	426
Total bushing tests, 100 kv			12,120
		44 kv	1,296
Grand total			13,416

leads, etc. (See Figs. 5, 6, and 7.) The milliampere reading is recorded as well as the temperature at the time of test. If the reading obtained is above the known average for the type and voltage of the bushing under test, and if the reading is not reduced by cleaning, the bushing is removed to the shop, dismantled, and, if possible, repaired. The lift rod and guide assembly is tested by applying potential to the bushings with the breaker closed.

Defects in bushings of the oil filled, condenser, and compound filled types manufactured in the United States and abroad have been located by this equipment and have been successfully repaired locally. A service record is kept of these repaired bushings and only one has failed from August 1932, to date. Table I shows a summary of tests made.

In the year 1933, 68 100-kv and 10 44-kv defective bushings were located and all but 2 100-kv were repaired locally and again put in service.

A comparison of service records for 1930 and 1933, that is before and after the development of this method of test, is shown in Table II. Lightning storms in this vicinity were not unusually severe during either year. The U. S. Weather Bureau recorded 45 storm days in 1930 and 57 in 1933; the 10-yr average is 51.8 storm days. As the voltage (33 kv) impressed on the bushing is over half of the line to ground voltage of the 100-kv bushings and somewhat over the line to ground voltage of the 44-kv bushings, the readings give a very positive indication of the condition of the bushings.

Approximately 2 months is required to make a routine test of the 250 breakers normally tested. Two men travelling in a light coupe are used; the equipment is compact and light enough to be carried in the rear compartment of the car. Approximately

Fig. 6 (left). Making a field test on a 100-kv oil circuit breaker bushing

Fig. 7 (below). Complete bushing testing equipment used by Duke Power Company

Table II—Failures of Oil Circuit Breaker Bushings During 1930 and 1933

	1930	1933
100-kv bushings in service	1,446	1,470
100-kv bushing failures in %	1.73	0.61
44-kv bushings in service	1,260	1,260
44-kv bushing failures in %	2.22	0.40
Total bushings in service	2,706	2,730
Total bushing failures in %	1.96	0.67

4,000 miles are travelled in making a routine test.

We agree with the authors that the majority of bushing troubles are due to moisture entering the bushing. It is not uncommon for 1 lb of water to be evaporated from a 100-kv bushing which has been in service several years. Due to the improvement in design and construction, the newer type bushings do not absorb moisture to the extent of the older types; however, a number of the newer type have been found defective.

A limited number of transformer bushings have been tested. As the percentage of transformer bushing failures is small compared to oil circuit breaker bushing failures, the improvement resulting from transformer bushing tests cannot be expected to yield as noticeable results as in the case of breaker bushing tests. However, these tests are well worthwhile where the service from transformers is of vital importance or where service records indicate deterioration of bushings.

H. H. Spencer: The maintenance of apparatus bushings, particularly oil circuit bushings, has been a problem that has long occupied the attention of operating engineers. In The New England Power System we have made use of the megger for 15 years as an aid to determining when bushings should be removed from service. This instrument has been used with increasing success as experience has improved the technique of the operating personnel.

In 1928 the New England Power System commenced studying the conditions of bushings by means of field measurements of dielectric loss. The method used was devised by the Doble Engineering Company and was a modification of their equipment which previously had been used in testing pin type insulators. The test equipment consists of direct reading voltmeters, ammeters, and wattmeters measuring the total current and power in the bushings being tested under an applied voltage of 10,000 volts, rms, 60 cycles.

Our success with this type of test has been much better than with the 1,000-volt megger; but the success of this method or any other method which depends upon the measurement of resistance, leakage current, or dielectric loss rests entirely upon the experience of the operator in making the tests and the judgment of the engineers in interpreting the results. The fundamental characteristics that the bridge presented by the authors of this paper, or the apparatus we have used, detects, is change. Inherently a bridge probably can detect smaller changes in power loss than the wattmeter can. Practically, the casual differences in testing technique due to leads, etc., may introduce greater errors than the inherent difference in

precision between the bridge and the wattmeter. In any case the major problem is for the engineer to decide how much change he can tolerate in the dielectric loss or power factor of a particular bushing before it is necessary to remove it from service.

There can be no question as to what constitutes a desirable specification for an oil circuit breaker bushing. Its external flashover voltage should be less than the internal flashover or puncture voltages, and it should be greater than the discharge voltage of adjacent protective devices such as spillway sections of transmission lines, coördinating gaps, or lightning arresters. During the past few years, the characteristics of insulators have been studied with increasing care and the suggestion has been made that station and line insulation be coördinated within fairly close tolerances.

However easy it may be to install new apparatus so that the insulation will be properly coördinated, there exists at present only one means of determining whether insulation that has been in service for some time is still coördinated properly—the high potential test both at normal frequency and under impulse. Such tests are difficult to perform in the field; but even more important is the fact that so many bushings would be severely damaged by the high potential testing that the replacement cost would be prohibitive. It appears that a station design using fairly wide tolerances of insulation coördination, plus a testing technique involving indirect measurements backed up by experience and comprehensive test records on each individual bushing, will have to be the ultimate answer to this problem.

Heavy Surge Currents—Generation and Measurement

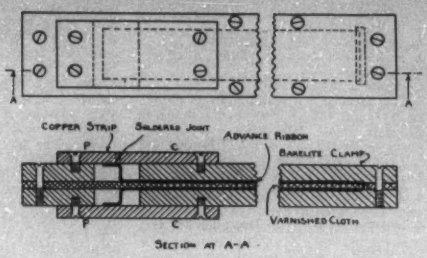
Discussion of a paper by P. L. Bellaschi published in the January 1934 issue, p. 86–94, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934.

Theodore Brownlee: Means for producing and measuring heavy surge currents have been developed in the lightning arrester research laboratory of the General Electric Company in Pittsfield along much the same lines as outlined in Mr. Bellaschi's paper, and we are in general agreement concerning the precautions and requirements necessary to obtain good results.

Except for the sake of economy, an impulse generator built for millions of volts is not adapted for heavy current work. The spacings used for clearance between individual capacitor tanks, and between the tanks and ground, add unnecessary inductance to the circuit. As stated by Mr. Bellaschi, low impedances are needed throughout, meaning a large capacitance and low inductance and resistance. The capacitors should be carefully designed, and if roll wound, many taps brought out to secure low internal resistance and inductance. Usually it is necessary to use the same capacitors for high voltage and high current work, so that low voltage high capacitance units are not available. At any rate, the available capacitors should be connected all in parallel with tanks as close together as possible. A convenient arrangement is to mount 2 rows of capacitors, one above the other, with the upper row upside down so that all may be connected to 2 parallel busses mounted on the capacitor bushings. Busses of large copper tubing minimize the inductance. The load should be connected to the midpoints of the 2 parallel busses. If a very large number of capacitors is to be used with a minimum of inductance, several double rows should be spread out from the load much the same as the elements of shunt B in Fig. 11 of the author's paper.

Fig. 8. Low inductance shunt for impulse measurements

Current clips at C-C
Potential clips at P-P



The methods outlined in the preceding paragraph are for obtaining the highest possible current from a given number of capacitors. Such effects as the fusing of conductors depend only upon the energy available, and it is immaterial whether there is considerable inductance in the circuit or not, since in a series circuit all the energy must be dissipated in the resistance load.

It is convenient when making an experimental study of the heating effects of impulses to have aperiodic waves, as the analysis of the oscillograms is much simpler. To secure such waves less additional resistance is required with low inductances. Thyrite is admirably adapted to render high current waves nonoscillatory, for it has low resistance at high currents and increased resistance at low currents. Hence, with a given capacitance voltage and inductance, a higher and more symmetrical aperiodic current wave can be obtained by using thyrite. Examples of such waves were shown about 2 years ago in an article on the blowing of fuses by impulses. ("Impulse Characteristics of Fuse Links," E. M. Duvoisin and T. Brownlee, *General Electric Review*, May 1932, p. 260–6.)

The study of high currents is almost of necessity tied up with the study of more moderate currents of very short duration, for in both, shunts of very small time constants, L_s/R_s, are required. At the time of the fuse-blowing tests, the problem of producing reliable shunts of low time constants was attacked both experimentally and by calculation. The best arrangement found is illustrated in Fig. 8 where an extremely thin ribbon of advance of manganin metal is doubled back and tightly clamped together with a very thin layer of insulation between. In this manner the outgoing and incoming current paths nearly coincide, and the inductance, while calculable, is almost impossible to detect by experiment. In Fig. 9 is reproduced Fig. 3C of the fuse-blowing article previously mentioned, showing one of the faster waves recorded by this type of shunt.

A shunt was made up similar to a single element of the shunts shown by the author in Fig. 11 and having the same resistance as our shunt of 0.474 ohm. A 20-in. length of No. 20 B. & S. gauge manganin wire was used making a twisted loop 10 in. long.

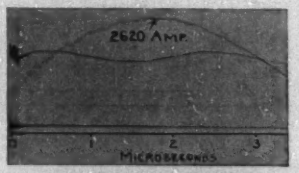


Fig. 9. Cathode ray oscillogram of a 4.8-μ sec wave (16.8 amp² sec) recorded by means of a shunt of the type shown in Fig. 1

The insulation thickness was about 0.002 in. giving 0.036 in. between centers and 0.032 in. conductor diameter. Copper leads were soldered on and brought out at right angles to the shunt element and the manganin wires carried on noninductively for about 2 in. where they were connected to our customary shunt cable.

The inductance was assumed to be the same as for 2 parallel conductors and calculated by the well known formula:

$$L = 0.004l\left[2.303\log_{10}\frac{2D}{d} - \frac{D}{l} + \frac{\mu}{4}\right]$$

where

L = inductance in microhenries
l = length of each wire in cm
D = distance between centers in cm
d = diameter of wires in cm

The calculated inductance is 0.107 μh giving a time constant L_s/R_s = 0.226 μsec.

Our 0.474-ohm shunt was made of 23 in. of advance ribbon 0.25 x 0.004 in., doubled back with one layer of varnished tape 0.01 in. thick for insulation.

The inductance is calculated by the formula:

$$L = 0.00921[(d^2/b^2)\log d + 0.5(1 - d^2/b^2)\log(b^2 + d^2) + 0.8686\, d/b\tan^{-1} b/d - \log b]$$

where

d = distance between centers of tapes in centimeters

l = length of loop in centimeters = $^1/_3$ length of tape
b = breadth of tape in centimeters
L = self-inductance of shunt in microhenries
Common logarithms used.

This formula is a combination of formulas 117 and 132 of Bureau of Standards *Scientific Paper 169*, (Rosa and Grover, Formulas for the Calculation of Mutual and Self-Inductance, *Bulletin* of the U.S. Bureau of Stds., v. 8, No. 1, Jan. 1911).

If we let $b/d = x$ there is obtained:

$$L = 0.00921l\left[\left(\frac{x^2-1}{2x^2}\right)\log(1+x^2) + \frac{0.8686}{x}\tan^{-1}x - \log x\right]$$

showing that the inductance depends only on the length and the ratio $X = b/d$.

Also it is found for the cases where the ribbon width is large compared to the thickness of the ribbon or insulation, that the inductance is very nearly proportional to the parameter ld/b, so that for a given thickness of ribbon and insulation, the inductance and resistance are proportional, and the time constant L_s/R_s is fixed. Hence, the length and width of ribbon required for a particular shunt is determined by temperature considerations. The change in resistance of "advance" materials is less than $^1/_3$ of 1 per cent for all temperatures up to 400 deg C.

For the 0.474-ohm "advance" shunt the calculated inductance is 0.0194 μh giving a time constant of 0.041 μsec.

In order to show the distortion produced by these 2 shunts, the dotted lines of Fig. 10 give the shunt voltage that would be produced on each with the passage of the 2,620-amp current surge shown in Fig. 2. These are to be compared with the solid line which is based on a shunt of no inductance. It is very evident that the lower inductance ribbon shunt gives a much more faithful representation of the true current wave shape. However, the discrepancy is more a change in phase than of magnitude, and unless very extended time scales are used on the oscillograms, it is difficult to detect the errors by simple oscillographic comparison of current-time waves.

One good method to detect the inductance of any particular type of shunt is to construct a counterpart using copper wire in which the inductance voltage will predominate because of the greatly lowered resistance. A simpler method and the one we use to judge our shunts is to record the volt-ampere curve of a noninductive resistance such as a short thick water column or stack of thyrite. Then, unless the recorded voltage and current are in absolute phase, a loop will appear in the characteristic. Figure 11 shows 2 volt-ampere curves taken on the same stack of thyrite disks using the same impulse circuit and the 2 0.474-ohm shunts. The impulse used was slightly slower than shown in Fig. 10, rising to a crest of 3,800 amp in 3.0μsec and dropping to half value in 6.8μsec. In spite of this fact, the loop is very pronounced with the twisted wire shunt and imperceptible with the ribbon shunt. The physical explanation of the superiority of the ribbon shunt in this particular case is the fact that the outgoing and returning current paths are closer together. If, instead of a single element of No. 20 wire, a large number of elements of fine wire were put in parallel, the time constant would be reduced, but at the expense of making a rather intricate and delicate shunt.

The conclusions to be gathered from the foregoing paragraphs are applicable to the measurement of as high currents as can be produced. It is only necessary to use wider ribbon and perhaps, spread a few elements in parallel as is done by the author. Shunts of somewhat smaller time constants than 0.0194 μsec can be made by using thinner ribbon and very thin mica insulation. The use of higher resistance alloys, such as nichrome, decreases the time constant, but nichrome is difficult to solder to the current leads, and has a considerably higher temperature coefficient than advance or manganin.

A method for compensating for the inductance of 4 terminal resistances has been described by F. B. Silsbee ("Notes on the Design of 4 Terminal Resistance Standards for Alternating Currents," Bureau of Standards *Journal of Research Paper No. 133*, v. 4, No. 1, Jan. 1930) but such refinements seem hardly necessary for the fastest laboratory waves now used. The same paper also shows some experimental data by which the skin effect of ribbon shunts may be calculated at low frequencies. There seems to be few available data concerning skin effect for conductors at close spacings and high frequencies. If we assume the low frequency formulas are approximately correct at high frequencies, it is found that skin effect can be disregarded in both types of shunts and all of our experience substantiates this conclusion. The capacitance between the shunt conductors with either type of shunt is entirely negligible. For instance with the 0.474-ohm ribbon shunt the total capacitance between ribbons is (assuming K = 4) 214$\mu\mu f$ giving a time constant R_sC, of about 0.0001 μsec.

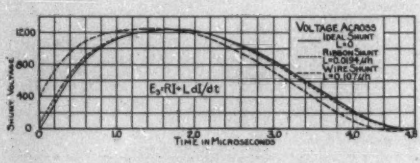


Fig. 10. Calculated effect of inductance in 0.474-ohm shunts

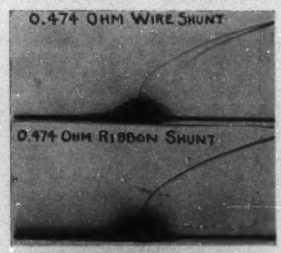


Fig. 11. Volt-ampere characteristic of a stack of thyrite disks measured with 0.474-ohm wire shunt (above) and 0.474-ohm ribbon shunt (below)

J. L. Thomason: In Appendix III of his paper, Mr. Bellaschi gives the derivation for the current required to fuse copper wire with an applied exponential wave. It is interesting to note that similar calculations were made by Mr. Peek about 4 years ago in his 1930 paper "Lightning" (A.I.E.E. TRANS. v. 50, p. 1077–89).

Bellaschi based his calculations on an exponential current wave specified in terms of the time T to 50 per cent of crest current, that is

$$i_1 = I\epsilon^{-0.69t/T}$$

The energy associated with this wave is

$$H_1 = r\int_0^\infty i_1^2\,dt = \frac{r\,I^2\,T}{1.38}$$

Peek based his calculations on an exponential current wave specified in terms of the time T_1 to 5 per cent of crest current,

$$i_2 = I\epsilon^{-3t/T_1}$$

And the energy associated with this wave is

$$H_2 = r\int_0^\infty i_2^2\,dt = \frac{r\,I^2\,T_1}{6}$$

Therefore for waves of equal crest and energy $H_1 = H_2$ or

$$T = \frac{1.38}{6}T_1 = 0.23\,T_1$$

Consequently, expressing Bellaschi's current equation in terms of T_1 instead of T, there is

$$I = 320{,}000\frac{A}{\sqrt{T}} = 660{,}000\frac{A}{\sqrt{T_1}}$$

as compared with

$$I = 510{,}000\frac{A}{\sqrt{T_1}}$$

from Peek's curves. The constant terms are at least of the same order of magnitude.

I should like to ask Mr. Bellaschi what specifically was learned about lightning phenomena by these high current tests? How was the current distributed in the cross section of the arc? This point may have an essential bearing on the calculation of the inductance and surge impedance of a lightning stroke. How long did the path remain ionized? This point may have an important bearing on the question of repeated strokes.

Simultaneous Control of Voltage and Power Factor

Discussion of a paper by L. F. Blume and F. L. Woods published in the December 1933 issue, p. 884–9, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934.

A. Boyajian: During the past few years, I have been very much impressed by the strong tendency in the electrical industry to give preference to static equipment as exemplified in the rapid growth of power rectifier installations in competition with synchronous converters. The static equipment generally is far more efficient, very quiet, requires minimum maintenance, and lends itself most conveniently to automatic operation with remote control. Now, L. F. Blume and F. L. Woods call attention to another field in which static equipment may come to play an equally prominent part, extending into fields dominated in the past by the synchronous condenser.

I have had the privilege of discussing this paper with the authors previously and have found out that their major proposition is not so much the replacement of one kind of equipment by another as it is the proposition that power factor correction and voltage control should not be considered as separate problems and treated by different specialists; they should be treated and solved as one problem with proper regard to both aspects of the problem. In the past, when power factor was the major consideration, capacitor engineers generally solved the problem. In general there was some improvement in voltage regulation also, but this was only incidental and not very satisfactory. When voltage regulation has been the major thought, either synchronous condensers or tap changers have been utilized in the circuits of higher power. Here again, the power factor is unaffected or, if affected, it is incidental and subservient, and best results can never be obtained. The thesis of the authors' present paper is that by proper combination of equipment for both voltage regulation and power factor correction, each part of the equipment is utilized for the type of service and in the range in which it is most effective, and the resulting benefits are maximum.

In line with the foregoing, the authors also believe that there may be suitable applications for the synchronous-condenser-tap-changer combination as well as the capacitor-tap-changer combination. Whatever may be the cost comparison between the static equipment and the rotating equipment at the present moment, it is a significant fact that capacitor cost curves, even after correction for the changes in the industrial price level, have been sloping downward for several years, and one may venture to predict that this will continue for some time to come, making the static equipment for simultaneous control of voltage and power factor increasingly more attractive.

L. M. Olmsted: This paper presents an extremely interesting and convenient method for solving the various problems arising in connection with the application of shunt capacitors or synchronous condensers to regulate voltage. Also, the scheme by which the effective shunt capacity in the combined equipment is varied seems most ingenious, and reduces the equipment to a minimum.

The device has limitations, however, which may seriously restrict its application on power systems. In order to control voltage most effectively by improving the load power factor it is necessary to locate the capacitors at the load center so that the voltage drop in the supply system may be reduced by the neutralization of reactive current. On distribution feeders, for example, which are commonly regulated by means of individual regulators at the substation, it seems probable that locating such regulating equipments at the several load centers would prove undesirable. The most likely application would seem to be for bus regulation in substations, where it might replace the present regulating equipment.

Wide acceptance of such a device depends, of course, upon economic justification. The paper suggests this and presents a comparison of relative losses. A valid comparison can be secured, however, only by analysis of the investment involved for the several equipments, the operating expense, and the losses properly evaluated to include charges for the supply system. Such a comparison indicates that the addition of capacitors usually will not reduce the cost of regulating distribution feeders and suggests that even for substation bus regulators there will be many situations where the capacitors cannot be justified.

It is recommended that the analysis begun in the paper be extended to disclose for the guidance of the industry the conditions for which the combination of voltage and power factor control can be justified.

Effects of Rectifiers on System Wave Shape

Discussion of paper by P. W. Blye and H. E. Kent published in the January 1934 issue, p. 54–63, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934.

J. J. Smith: This paper by P. W. Blye and H. E. Kent gives a useful method of estimating the effect on the wave shape when a rectifier is operated on an a-c system. The data given show that their formula has been checked with calculation in several cases, and the agreement generally is within ±20 per cent which is sufficient for such calculations. The authors also give a brief review of the results that may be expected from the resulting harmonics in the wave shape.

Their method consists in assuming that the valve action of the rectifier in cutting off the current in successive anodes can be replaced by an equivalent harmonic voltage in the circuit. In a paper by H. D. Brown and J. J. Smith (TRANS., A.I.E.E., v. 52, Sept.-Dec. 1933, p. 973) we approached the problem from the other point of view, namely that of determining the effect of the inductance of the circuit in modifying the currents under load. We have used both types of calculation in a number of cases and it may be of interest to state that on the average they agree within better than 20 per cent. In one isolated case the difference between the results was 75 per cent, but no opportunity was available to test which method gave the better practical result since the installation was only a projected one. The impedance diagram of the system in the latter case was a very complicated one with several resonance points.

In calculating any given installation there are 2 points at which discrepancies may arise: (1) in the estimate of the impedance of the system; (2) in the use of the authors' formula. I should like to get an idea of the authors' experience as to the relative magnitude of the per cent error which might be expected due to these 2 causes; that is, given the measured impedance, what accuracy can we expect and how much additional error may be introduced when we have to estimate the system impedance.

Usually it is more important that the result of calculation be correct for the case when the rectifier is fully loaded than for the case when the rectifier is lightly loaded. Can we assume roughly in connection with the curves in the authors' Fig. 3 that the lower values correspond to full load approximately?

I should like to suggest in connection with the authors' Fig. 10 that if actual values for a typical case were added it would materially enhance the paper since it would enable any one working a problem to check his method of calculation on a standard case. Possibly the authors could add such a diagram in the discussion.

Under the heading "Power System Factors Affecting Wave Shape" on page 61 (ELEC. ENGG., Jan. 1934), reference is made to the effects to be expected on large systems and in cases where high voltage supply lines are used. It is important to remember that the distortion in voltage is a function of the impedance of the system. If we connect a rectifier to a large system through a considerable amount of reactance, the resulting distortion at the terminals of the rectifier may be as large as if it were operated from a small system. Thus some of these statements, while in general correct, might lead to errors if they are taken too literally.

On page 61 the reader is referred to the Report of the Joint D. & R. Subcommittee of the E.E.I. and Bell System for other coordinative measures. In those reports the various measures are scattered through several volumes. I believe that a paper before the Institute describing these methods and giving an outline of the effects to be expected from them would be a valuable contribution to the literature and would be of considerable assistance in practical studies.

R. F. Davis: In the usual field case involving a consideration of the inductive coordination of telephone circuits and a-c feeders supplying rectifiers, preliminary calculations of the order of magnitude of the noise to be expected serve as a valuable guide. While such noise computations are not an adequate substitute for actual measurements, often it is not practicable to make sufficient measurements in the early stages of the project to determine accurately what the noise will be. In such cases, the

results of computations made during the planning stage of the project permit an orderly program of study of those cases where the calculations indicate a potential noise problem. Prominent in such a preliminary review is the consideration of rearrangements which might readily be made in the two services and which would materially reduce the likelihood of excessive noise. Also consideration may be given to the other methods of coördination referred to by the authors.

The noise estimates require data not only regarding the power system characteristics, but also with respect to the coupling and telephone plant, so that it is evident that a high degree of accuracy in the calculations is unlikely. Since the methods of computing one of the factors described by P. W. Blye and H. E. Kent materially narrow the range of error involved, their value in the over-all noise calculations and in inductive coördination work is evident.

Equivalent Reactance of Synchronous Machines

Discussion of a paper by S. B. Crary, L. A. March, and L. P. Shildneck, published in the January 1934 issue, p. 124–32, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934.

J. W. Butler: In reading this paper one gets the idea that this proposed equivalent reactance would be a very difficult one to use. There are given 3 equations (5, 6, 7), for the equivalent reactance of a cylindrical rotor machine, and 2 equations (9, 10), for the salient pole machine. These equations refer to the value of equivalent reactance to use under different operating conditions such as power factor and voltage. Also Figs. 8 and 11 are given showing the equivalent reactance of the machine as a function of the external impedance. These figures show a very wide range of reactance. For instance, Fig. 8 varies from 0.4 to 1.2 for a cylindrical rotor machine and Fig. 11 varies from 0.41 to 0.95 for a salient pole machine. Thus it appears without further study that the value of equivalent reactance is very critical to power factor, voltage, and the external impedance connected.

Fortunately, this picture is not as bad as it seems. Referring to Fig. 11, it is seen that the equivalent reactance of a salient pole machine for all values of external impedance, having a ratio of resistance to reactance of from 0 to 0.75, varies only 10 per cent. This range of the rating of resistance to reactance is certainly much greater than will be met in practice. Thus for a salient pole machine, operating under a constant voltage back of leakage reactance (constant flux loading) the equivalent reactance is found to be substantially constant and is not affected much by the power factor, terminal voltage, or the connected external impedance.

This enables a test to be made for the equivalent reactance of the salient pole machine under a condition other than that under which it is to be operated, but with

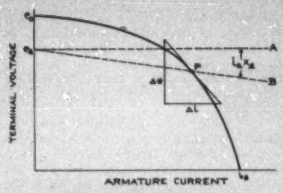


Fig. 1. Voltampere characteristic of a synchronous machine with constant field current at zero power factor

the same flux loading. For the salient pole machine the zero power factor test is the only one that can be simply made for the determination of the equivalent reactance. From this test, the equivalent reactance is obtained in accordance with eq 18. Consequently, if the test is made with the machine at zero power factor and the equivalent reactance measured at the point of the voltampere characteristic where the voltage back of leakage reactance is the same as it is when the machine is operating under normal operating conditions with the same field current, a reactance is obtained that corresponds very closely to the value under normal conditions.

The voltampere characteristic of a synchronous machine with constant field current at zero power factor has the general shape shown by the curve Fig. 1 of this discussion. This curve is easily obtained from test as follows: The point of zero current is obtained by reading the open circuit voltage e_0 with normal field current, and the point of zero voltage is obtained by reading the short circuit current i_0 with normal field current. Intermediate values are determined by operating the machine as a synchronous condenser from a power source in which the voltage may be varied. The field current is held at a constant value for the entire range corresponding to normal full load field current. The determination of the location of point P in Fig. 1, which is the point at which we are to measure the slope for determining the equivalent reactance is as follows:

Line A is drawn from the calculated value of e_l (voltage back of leakage reactance) for the full load normal operating condition, the internal drop from e_l to the terminal voltage is $i_a x_l$. Hence line B is drawn having a displacement from e_l equal to $i_a x_l$. Thus, the intersection of B with the voltampere curve at P gives a point at which the zero power factor machine is operating with the same internal voltage (or flux loading) as it would under normal conditions, and the equivalent reactance is

$$X_{d(eq)} = \frac{\Delta e}{\Delta i}$$

The equivalent reactance as determined by this method could be used in calculations as well as forming a basis for the comparison of various machines.

In the near future, the equivalent reactance probably will be used as a basis of comparison for various machines under steady state operating conditions just as the transient reactance is used today for transient conditions. If this be the case a standardized method of measuring this reactance will have to be adopted. In analyzing the saturation problem, the leakage reactance is here taken as the one that is not affected by saturation and the rest of the synchronous reactance is taken as the saturated part. The Potier reactance certainly should not be taken as the unaffected part because it actually does vary over a wide range (200 or 300 per cent) with saturation. At present there is not a standardized definition of leakage reactance. Hence, in order to cope with this saturation problem correctly and to form a sound basis for future contributions to the art along this line, I would suggest that the standardizing committee of the A.I.E.E. look into, or at least consider, the possibility of arriving at a definition of leakage reactance for general use and thus among other advantages place the comparison of machines on a rational basis.

H. B. Dwight: The paper by Crary, Shildneck, and March shows that, for steady state loads at voltages involving saturation of synchronous machines, values of synchronous reactance, if used, should be considerably smaller than the "unsaturated" value obtained from a test by short circuit at the terminals. It is gratifying that their conclusion, while different in method, is similar to that described in my paper which they quote as Ref. 4. An advantage of their method is that the effects of pole leakage flux and load power factor on synchronous reactance are taken into account. Their method has been compared with tests, as stated in their paper. A very satisfying test for the over-all accuracy of this method of calculation is to show maximum power in kilowatts, by test and by calculation, and it would be of interest if the authors would give such an example. The details of such a sample calculation would also be of assistance to those who wish to make practical calculations according to this method. It is to be noted that a special value of voltage, E_{eq}, is found and used with the special synchronous reactance, in calculating power, and so the values of synchronous reactance in this and other papers are not directly comparable.

Another practical problem is that of natural frequency of rotatory oscillation of a synchronous machine. Some careful measurements of this have been made at the Massachusetts Institute of Technology, and the writer hopes to present them in the near future, together with corresponding calculations by adjusted synchronous reactance.

To the list of references that have described the need of special values of synchronous reactance, there might be added the paper by E. B. Shand (A.I.E.E. Trans., 1924, p. 59; discussion p. 96) in which steady-state maximum power is correctly calculated by families of curves. The statement is made in Mr. Shand's discussion on p. 97 that the method of synchronous impedance "will prove inaccurate unless great care is used in the choice of synchronous impedance to represent a given machine."

E. H. Freiburghouse: Crary, Shildneck, and March have developed an ingenious graphical and mathematical method for determining, more accurately than heretofore the steady state power limit; also the

synchronizing power coefficient at any operating load on a synchronous machine.

They have accomplished this by developing from differential equations and point coefficients approximate, and also accurate, equations for obtaining equivalent synchronous reactances which are employed in the usual manner, instead of the unsaturated synchronous reactance. It should not be overlooked that with saturation there is a different equivalent synchronous reactance for every different load condition also an equivalent excitation voltage e_{eq} and displacement angle δ_{eq}.

It seems from the data indicated in the authors' Figs. 5, 6, and 7 that machines having very low short circuit ratios and high values of leakage reactance and excitation voltage e_d should have relatively greater values of k, more saturation, larger ratios a/b, and therefore lower ratios of equivalent reactance x_{eq} to unsaturated reactance x_d. This indicates that the steady state synchronizing power coefficient of low short circuit ratio machines may not be as poor relatively as the short circuit ratio indicates.

Comparing curves in the authors' Figs. 9 and 12 for the synchronizing power coefficients of cylindrical rotor and salient pole generators the conclusion may be reached that the influence of saturation is of greater magnitude in the case of cylindrical rotor machines, however the salient pole generator for which these curves were calculated may not necessarily be representative of salient pole machines.

In applying the equations given in the paper care should be taken to ascertain whether the coefficients k and a/b, given in the authors' Figs. 5, 6, and 7, are applicable to the machine in question.

In the authors' Appendix E, eq 6-E was obtained by substituting $k = 1$, $a/b = 0$, and $x_d = x_{eq}$ in the differential equation 2-E. The general equation (6-E) for x_{eq} also could have been obtained by differentiating equation

$$e_{eq} = \sqrt{e_t^2 + i^2 x^2_{eq} - 2e_t i x_{eq} \cos(90 + \theta)}$$

obtaining

$$\frac{de_{eq}}{di} = \left[e^2_t + i^2 x^2_{eq} + e_t i x_{eq} \sin\theta\right]^{-1/2} \times \left[e_t \frac{de_t}{di} + i x^2_{eq} + \left(e_t + i\frac{de_t}{di}\right) x_{eq} \sin\theta\right]$$

Now if excitation e_{et} and θ are assumed to be constant it follows that

$$e_t \frac{de_t}{di} + i x^2_{eq} + e_t x_{eq} \sin\theta + i x_{eq} \sin\theta \frac{de_t}{di} = 0$$

Hence

$$x_{eq} = -\left(\frac{de_t}{di} + \frac{e_t}{i}\right)\frac{\sin\theta}{2} + \sqrt{\left(\frac{e_t}{i} + \frac{de_t}{di}\right)^2 \frac{\sin^2\theta}{2} - \frac{e_t}{i}\frac{de_t}{di}}$$

and when $\theta = 0$ and power factor equals unity

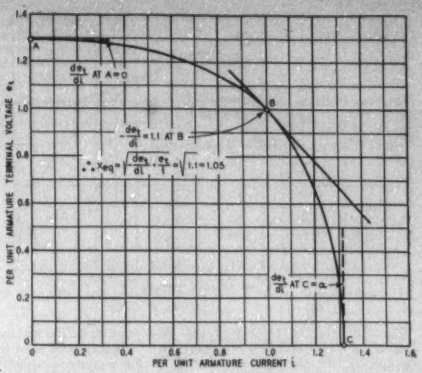
$$x_{eq} = \sqrt{-\frac{e_t}{i}\frac{de_t}{di}}$$

or when power factor is zero $\theta = 90$ deg

$$x_{eq} = -\frac{de_t}{di}$$

Fig. 2. For generator No. 1

Cylindrical rotor characteristic for field current corresponding to rated armature terminal voltage and current at unity power factor. Points A, B, and C determined by test



Others of the authors' equations (15, 16, 17) show that the equivalent synchronous reactance of cylindrical rotor type machines when operated at any particular field excitation, terminal voltage, and constant power factor can be obtained quickly by means of the voltampere characteristic. Or conversely, these relations can be used in determining the shape of the voltampere characteristic.

For zero power factor, the equivalent synchronous reactance x_{eq} is simply the negative per unit slope of the voltampere curve at the particular operating voltage. The zero power factor voltampere curve must approach and then coincide with a straight line having a slope numerically equal to the per unit unsaturated synchronous reactance, x_d, as the terminal voltage approaches zero. That is, the equivalent reactance at low voltage must be the unsaturated synchronous reactance, x_d, as no appreciable saturation exists in the machine at these low voltages. Since the 3 points A, B, and C of Fig. 4 of this discussion may be determined from test data, the voltampere curve at zero power factor may be drawn in quite accurately by making the curve coincide at B and C with the straight lines through B and C, the slope of the straight line through point B being determined by the authors' eq 4-E and that through C having a slope equal to the unsaturated synchronous reactance.

Also at unity power factor, for a given voltage and a particular excitation, the slope $-\frac{de_t}{di}$ of the voltampere curve may be estimated by means of the authors' eq 3-E. Or, if the slope of the voltampere curve is determined from test, the equivalent synchronous reactance at the given voltage may be obtained by means of the equation $\sqrt{-\frac{de_t}{di} \times \frac{e_t}{i}}$. The curves in Figs. 2, 3, and 4 of this discussion were made to pass through points A, B, and C which were determined by tests and drawn tangent to lines having slopes conforming to the authors' eq 3-E. At unity power factor the voltampere curve has an infinite slope at zero voltage and a zero slope at zero current. This result is obtained directly from the authors' eq 5-E for unity power factor, $\theta = 0$.

In a similar manner, voltampere curves may be readily drawn for any power factor and excitation by making use of 3 test points, by estimating the slope at the given voltage by means of the authors' eq 2-E and by determining the slope at zero voltage by means of the authors' eq 5-E (which, for $e_t = 0$ and $x_{eq} = x_d$, yields $\frac{de_t}{di} = -\left(\frac{x_d}{\sin\theta}\right)$). These relationships should prove to be useful guides in determining the voltampere characteristics, or if the voltampere characteristic is known, the equivalent synchronous reactance for the conditions corresponding to the voltampere characteristic may be determined accurately (authors' eq 6-E).

Table I—Data for Determination of Equivalent Synchronous Reactance

Generator	No. 1	No. 2	No. 3
e_t (test)	1.0	1.0	1.0
i (test)	1.0	1.0	0.98
Power factor	1.0	1.0	0
θ	0	0	90°
e_d (test)	1.705	1.315	2.31
e_{et} when $i = 0$ (test)	1.293	1.105	1.385
i when $e_{et} = 0$ (test)	1.315	1.78	2.04
x_d (test)	1.293	0.742	1.135
x_l (calc.)	0.133	0.106	0.17
e_l (calc.)	1.009	1.006	1.167
k (calc.)	1.058	1.065	1.20
e_d (calc.)	1.675	1.305	2.34
k (calc.)	50.7	34.2	0
a/b (calc.)	0.327	0.313	1.115
$-\frac{de_t}{di}$ (calc. for $e_t = 1.0$)*	1.1	0.418	0.533
x_{eq} (calc. equations 16 and 17)	1.05	0.646	0.533
e_{eq} (calc.)	1.455	1.193	1.52
δ_{eq} (calc.)	46.6	33.0	0
P (equation 13)	1.0	1.0	0
$dP/d\delta_{eq}$ (equation 14)	0.954	1.55	2.85
x_{eq}/x_d	0.812	0.87	0.47
δ_{eq}/δ	0.917	0.965	.....

*Calculated by authors' eq 3-E for unity power factor and authors' eq 4-E for zero power factor.

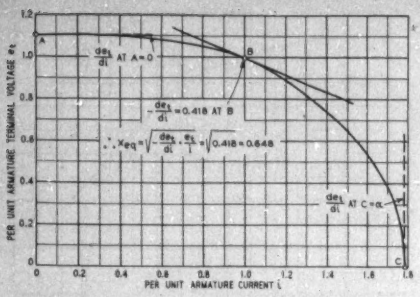


Fig. 3. For generator No. 2

Cylindrical type rotor characteristic for field current corresponding to rated current and voltage at unity power factor Points A, B, and C determined by test

Data are given in Table I of this discussion by means of which the equivalent synchronous reactances were obtained for the 3 generators having voltampere curves presented in Figs. 2, 3, and 4. Data also are given in the table showing relative

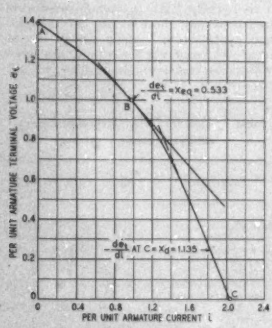


Fig. 4. For generator No. 4

Armature terminal voltage and current for field current corresponding to 0.98 rated current at rated voltage and zero power factor. Cylindrical type rotor overexcited. Points A, B, and C determined by test

values of excitation, displacement angle δ, and synchronous reactance for the saturated and equivalent unsaturated cylindrical type rotor generators of both high and low short circuit ratios.

Sterling Beckwith: The authors' analysis of the effect of saturation on synchronous reactance is most interesting. I have gone over it in considerable detail, but its completeness and exactness leave little to add.

The problem solved is of considerable importance in the design of the Metropolitan Water District's line for transmitting power from Boulder Dam to the pumping plants along the Colorado River Aqueduct. This is for the reason that the simplicity of the system and the relative unimportance of transient stability will allow normal operation to be much closer to the steady state stability limit than in most other comparable systems. Since the reactance that determines the steady state limit will be largely synchronous reactance, the effect of saturation will be important. The District consequently made its own determination of the effect of saturation, and although the method used was more approximate than that used by Crary, Shildneck, and March, it gave results which were easier to use, and which were found to be sufficiently exact for the intended application. The original derivation will not be given here, but the same results will be obtained from the equations of the authors' Appendix C, as the simplification of the results may be of some interest.

If it be assumed that no saturation exists in the quadrature axis, i. e., that the vector $(K_1 - 1)e_t$ in the authors' Fig. 3 of the paper is parallel to the direct axis, e_d, then the effect of saturation on synchronous reactance does not depend on conditions external to the machine itself.

To illustrate, take equation (C-9) and assume that the armature saturation is zero and that the direct axis armature saturation is included in K_1. Then

$$X_{d(eq)} = X_l + (X_d - X_l)\frac{1}{K_1\left(1 + \frac{a_1}{b_1}\right)}$$

which is independent of external conditions. Further simplification of this equation gives:

$$= X_l + (X_d - X_l)\frac{b_1}{K_1(b_1 + a_1)}$$

$$= X_l \ (X_d - X_l)\frac{TR}{K_1(TR + RO)}$$

See authors' Fig. 2

$$= X_l + (X_d - X_l)\frac{TR/TP}{\frac{TP}{TL}(TO)/TP}$$

Since $K_1 = \frac{TP}{TL}$ and $(TR + RO) = TO$

$$= X_l + (X_d - X_l)\frac{\text{slope of sat. curve}}{\text{slope of air gap line}}$$

since $\frac{TR}{TP}$ = slope of sat. curve

and $\frac{TO}{TL}$ = slope of air gap line

The saturation curve to be used is that including only direct axis saturation. Crary, Shildneck, and March plot this as e_t against Ke_t, but as only the ratio of 2 slopes is need, it can be plotted in any terms desired. I have found it more convenient to use e_{td} as the ordinate and ampere turns as the abscissa, as the curve then becomes identically the no load saturation curve when $e_t = e_d$. If e_t does not equal e_d, the curve is altered only because the field form of the machine is altered by the demagnetizing ampere turns. I have found that the correction for this distortion is small, and that it is almost as accurate, and more convenient to correct the voltage at which the slope of the saturation curve is taken than it is to change the saturation curve, as this allows the no load saturation curve to be used for all operating conditions.

To show for an average saturation curve, how the voltage e_{td} varies with operating conditions, the curve of Fig. 5 of this discussion was drawn. To illustrate: If the machine operates with a field current of 3, and with a load that gives a terminal voltage of 0.92 and a power factor of 0.80, then the saturation is the same as that at the no load voltage 1.2 (obtained by following the

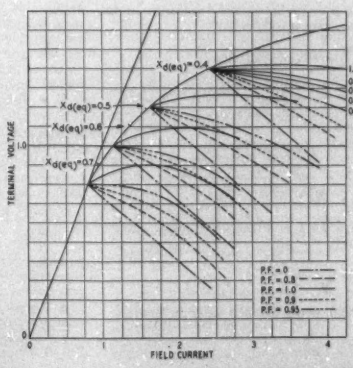


Fig. 5. Lines of constant direct-axis components of internal voltages—from vector diagrams for a wound-rotor machine with $X_d = 4X_l$

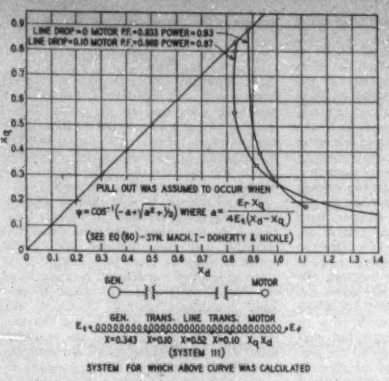


Fig. 6. Maximum values of x_q and x_d of motors with power transmitted over the system shown in the sketch —line capacitance = 0; system losses = 0

line for 0.8 power factor back to the no load saturation curve) and the saturated reactance is equal to the leakage reactance plus the demagnetizing reactance times the ratio of the slope of the no load saturation curve at this voltage of 1.2 to the slope of the air gap line. A correction for the difference between the flux form at no load and at the operating point could have been made if desired, by correcting the voltage 1.2 by a suitable amount.

To show that the effect of the above assumption of no quadrature axis saturation does not materially affect the steady state stability calculations, the curve of Fig. 6 of this discussion was drawn. This curve was obtained using the equivalent system and power limit equations shown on it, and shows that power limit is dependent almost entirely on X_d for X_q greater than half of X_d.

One thing I would like to ask the authors is whether the salient pole generator they chose for numerical calculations was a representative one. About 75 per cent of the saturation under no load conditions (i. e., $e_t = e_{td} = e_i$) appears to exist in the armature, whereas it was my opinion that 25 per cent was a more usual figure at normal voltage, and that this figure should decrease due to field leakage as the voltage increased, instead of increasing as shown.

R. D. Evans: The paper by Crary, Shildneck, and March discusses methods for determining the effects of saturation in modifying the values of machine reactances used for various purposes, particularly for steady state stability calculations. From a technical viewpoint, it is desirable to provide a more rational basis than has heretofore been available in evaluating effects of saturation on the machine reactances and the paper is valuable from this standpoint.

Certain parts of the paper, particularly Figs. 8 and 11 may give the impression that the effects of saturation have heretofore been neglected in determining machine reactance to be used for stability calculation. From this standpoint, these figures would have been more useful if they had compared the results of the proposed method with the empirical methods in use. One of these methods, which has been used in stability work for ten years, is based on the determination of the excitation of the machines for the load conditions assumed by any conventional method. Then for the value of excitation so determined the machine reactance is taken as corresponding to the difference in voltage between the no load and the zero per cent power factor saturation curve. In general, this method has given very satisfactory results for ordinary conditions of operation, where steady state stability would be of interest, which conditions include operation near unity power factor on the generator and with considerable impedance in the external system. Figs. 8 and 11 relate the appropriate value of machine reactance to the external impedance instead of the excitation of the machine field. Therefore, the figures tend to conceal the effect of variation in field current on the appropriate value of machine reactance.

From a practical standpoint it seems desirable to express the opinion that these equivalent reactances for computing steady state stability limits of generators supplying power systems will not supplant the values in common use, namely, short circuit ratio as a general index for measuring the sizes of machines and transient reactance for determining the transient stability characteristics. The conventional methods of figuring steady state stability appear to be sufficiently accurate for the ordinary cases. Where steady state limits may become of importance voltage regulators will be used and for such cases the stability limits will not be determined by the reactances described in the paper. Furthermore, steady state stability is rarely the actual stability limit of a system since this is normally determined by transient conditions arising principally from system faults.

The paper is viewed as an important contribution in rationalizing effects of saturation but is reassuring that present methods of calculations will not, for the present at least, be greatly effected.

L. A. Kilgore: The authors present in this paper a new method of calculating an equivalent synchronous reactance for use in steady state stability calculations. The method proposed is less empirical than the conventional method referred to in the (accompanying) discussion by R. D. Evans, but far more complicated. Even the approximate method suggested for salient pole machines (eq 10) involves separate curves for stator and rotor saturation and armature and field leakage constants. These factors cannot be tested for separately and can only be calculated by the designer of the machines, and the more accurate formulas (eqs D-7 and D-8) are very complicated indeed. These things make the method of little value as a practical method of calculation.

The chief value of this paper is apparently in its contribution to the theoretical analysis of the effects of saturation, for an accurate method of dealing with saturation is valuable as a means of checking the simpler empirical methods. The authors have carried their analysis out quite thoroughly, but they still neglect certain factors which appreciably affect the saturation.

The authors assume that the stator saturation is a function only of the vector sum of the terminal voltage and leakage reactance drop. However, consideration of the actual flux distribution in the air gap shows that under load the maximum gap density increases more than the fundamental density, hence the tooth saturation may be much higher than calculated on this assumption. The effect of the pole tip

Table II—Comparison of Methods on Salient Pole Machines

% Kva load	173	125	100	142	178
% Power factor	90	96.8	98	100	100
% Direct synch. react. (X_d)	89	83	85	102	83
% Quad. synch. react. (X_q)	65	58	62	75	58
% Sat. at no load in % of air gap	19	15	19	23	15
% Leakage reactance (X)	8	6	8	8	6
% Potier's reactance (X_p)	17	13.5	16	17.5	13.5
Calculated Field Current in % of Test Value					
Using authors' assumptions	99.0	95.5	98.5	98	96.0
Using direct axis projection of B_p	98.0	95	98	97.5	96.5
From no load and 0.0.p.f. sat. curves	102	102	100.5	101.5	103
Using Potier's react. voltage (E_p)	102.5	102	101.5	103	104.5
No saturation considered	83.5	86	86	87	83
Calculated Equivalent Reactance X_{deq}					
Author's approximate method	37	50	46	58	50
Potier's reactance method (E_{pd})	40	54	46.5	60	54
From no load and 0.0.p.f. sat. curves	37.5	46	40	47	46

saturation is not included, but consideration of the actual densities in pole tip under other than zero power factor load shows appreciable increase in saturation for many machines.

These effects show up in the comparison with tested field currents shown in Table II of this discussion. Field current calculations based on the authors' assumption checked quite well at zero power factor and fairly well at 0.8 p.f., but at 0.9 to 1.0, the calculated currents as shown by the table are consistently low, the average being 97.5 per cent of the tested field current. The comparison was also carried out for the other methods, and it is interesting to note that the standard A.I.E.E. method of using tested no load and zero power factor curves is consistently high, averaging 1.8 per cent high for these machines.

A third method of calculating the equivalent reactance has been suggested (in an accompanying discussion) by Sterling Beckwith. This method assumes that the saturation is a function of the direct axis projection of the voltage behind Potier's reactance (E_{pd}), and on this basis, it can be demonstrated that the equivalent reactance is

$$X_{deq} = X_p + \frac{(X_d - X_p)}{S_{pd}}$$

where S_{pd} is the ratio of the slope of the no load saturation curve at the voltage E_{pd} to the slope of the air gap line.

This method, while not based on quite as accurate assumptions as those used by the authors, is far more usable. It is nearly as simple as the conventional method referred to by Evans and has the advantage in that it is less empirical and gives a reactance value which is higher than the actual value rather than too low, and when used in stability calculations, gives results which are on the safe side.

Protecting Machines From Line Surges

Discussion of a paper by J. F. Calvert published in the January 1934 issue, p. 139–46, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934.

Edward Beck: J. F. Calvert has presented data that will make practical a close coordination of rotating machines and protective devices because in his paper appears a method of calculating the permissible rate of rise of surge voltage at the machine terminals. The machine designer should now be able to furnish the protective engineer with specifications for the permissible crest and rate of rise of voltage at the machine, and the protective scheme can be designed accordingly. In general, the protective schemes that already have been proposed, have sufficient margin to protect the usual machines; but, in such cases as large high voltage machines for instance, exact data on the permissible rate of rise of voltage no doubt will not only give greater security, but will permit use of the most economical protective equipment.

Particular attention should be drawn to Appendix II of the paper in which the effect of reflections between a capacitor at the machine and an arrester on the line at some distance is discussed. In any such scheme, as proposed in references 8 and 13 of the paper's bibliography, these reflections enter into the picture because they very strongly influence the rate of rise across the capacitor.

What happens is that at first the voltage that travels toward the capacitor is the voltage that passes the line arrester, with which is associated a certain current depending on the surge impedance of the line between them. When this voltage reaches the capacitor, the capacitor reduces the voltage, sending back toward the arrester a reflected wave of opposite polarity. When this wave reaches the arrester it tries to reduce the voltage at the arrester, but usually the original lightning surge on the line will have sufficient energy and duration to keep the voltage up to the arrester terminal voltage. Consequently the line from the arrester to the capacitor must draw more current than it did before; in effect current is transferred from the arrester to the line and into the capacitor, which consequently must charge at a higher rate than it did before. These changes in the charging rate of the capacitor will occur at intervals of the time it takes the surge to travel from the capacitor to the arrester and back again. If the distance between them is 2,000 ft the time interval is 4 μ sec. It is likely that the lightning disturbance causing the surge will be of greater duration than this. Therefore, it is likely that reflections between the arrester and the capacitor will occur. These will, for the first few reflections, increase the charging rate of the capacitor, and the steepness of the wave front applied to the machine.

In the paper presented a year ago by Rudge, Wieseman, and Lewis ("Protection of Rotating A-C Machines Against Traveling Wave Voltages Due to Lightning," A.I.E.E. TRANS., v. 52, June 1933, p. 434) there are curves showing the calculated rate of rise of voltage across the capacitor in the scheme also shown by Calvert's Fig. 16. These are based upon the application of arrester voltage only to the capacitor, with no reflection between the capacitor and the outer arrester. A closer approach to the actual conditions would show steps of increasing rate of rise at 4 and 8 μ sec, and further modifications of positive or negative influence thereafter.

In other words, the charging rate of the capacitor is determined not only by the arrester voltage and the surge impedance of the line between them, but by the distance between them as well, as was pointed out in the article by Calvert, Monteith, and Beck, published in the *Electric Journal* of March 1933. They are caused by an increase in current into the capacitor, or they may be looked at as caused by successive decreases in the resultant surge impedance of the line as the reflection takes place. They are calculated by the methods outlined by Calvert in his paper. These reflections between the line arrester and the capacitor are of greater importance than reflection from the machine neutral since the machine neutral is removed from the capacitor in microseconds several times the interval between the capacitor and the arrester.

A. C. Monteith: The protection of rotating machines directly connected to exposed lines has been developed to the point that a scheme now can be selected with a knowledge of its limitations. J. F. Calvert's latest contribution presents a method of analysis which will simplify the application of protective devices to rotating machines.

It is of interest to note that all schemes utilize lightning arresters in various locations. In the case of the delta connected machine and star-connected free-neutral machine arresters have been suggested at the mid-point of the delta to ground and at the neutral to ground respectively to prevent reflections, thereby reducing the amount of capacity necessary at the terminals of the machine. If the machine acted as a transmission line, even with the arrester, a voltage of short duration in excess of the arrester voltage should appear. It is of interest to note that Figs. 3 and 5 of Calvert's paper collaborates the results of other tests showing that in the case of rotating machinery this voltage does not appear. This fact allows a more economical protective scheme than if arresters could not be used at these points and further eliminates the necessity of making assumptions as to the length of the incoming surge.

An Experimental Ignitron Rectifier

Discussion of a paper by L. R. Ludwig, F. A. Maxfield, and A. H. Toepfer published in the January 1934 issue, p. 75–8, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934.

C. C. Herskind: A comparison between a new piece of apparatus and an old one of similar size or rating always is of interest. It helps us to distinguish those factors that are new and to determine what has been gained. Several years ago an experimental polyphase rectifier of about the same size as the polyphase ignitron described in the paper was tested in Schenectady. This rectifier had an inside diameter of approximately 16 in. and was 16 in. high. I believe the polyphase ignitron shown in the author's Fig. 2 is about 13 in. in inside diameter and 3 in. high. The rectifier that was tested at Schenectady was of conventional design and had 3 anodes. It carried loads of from 300 to 350 amp at 750 volts. It also operated at 1,500 and 3,000 volts.

From these data the 2 rectifiers seem to have approximately the same current rating, although the conventional rectifier was operated at a higher voltage than the ignitron. An important difference between the 2 rectifiers is found in a comparison of the losses. The data presented in this paper indicate that the arc drop of the ignitron rectifier is considerably lower than that measured in the conventional rectifier.

If operating experience in actual service proves the reliability of the igniter and the other new features in the ignitron rectifier, this reduction in arc drop will be an important step forward in rectifier development.

I would like to ask the authors of this paper whether they believe that rectifiers using the igniter principle can be built for higher voltages, higher current loading, and higher vapor pressures.

One of the ignitrons described in the paper shows a cooling coil in the cathode pool. Have tests indicated that any appreciable reduction in arc drop might be obtained by this means?

Selby Haar: It appears from the authors' Fig. 2, that the anodes are mounted on relatively long rods secured at the upper ends. Has observation showed any tendency for these rods to vibrate transversely, particularly with pulsating currents? This vibration if of large magnitude would cause a short circuit.

An Economic Study of Suburban Distribution

A. H. Sweetnam and C. A. Corney, January 1934 issue, p. 97–102.

Radial Versus Primary Network Distribution

H. E. Wulfing, January 1934 Issue, p. 38–42.

Fundamentals of Design of Electric Energy Delivery Systems

J. Allen Johnson and R. T. Henry, December 1933 Issue, p. 831–8.

Joint Use of Poles With 6,900-Volt Lines

W. R. Bullard and D. H. Keyes, December 1933 Issue, p. 890–8.

Discussion of a group of papers presented for oral discussion at the session on power distribution of the winter convention, New York, N. Y., Jan. 25, 1934.

C. T. Sinclair: The committee on power transmission and distribution, through its subcommittee on distribution, has been arranging for the presentation of a number of papers dealing with the economics of distribution systems. The papers presented at this session are the first of the series. It is expected that other papers now in various stages of preparation will be made available for later meetings.

There seems to be an opinion prevailing in certain quarters that the overhead distribution system merely is an assemblage of poles, wire, and fixtures, and, on this basis, certain cost estimates have been disseminated which easily may lead to erroneous conclusions. Also there seems to be an opinion prevailing that the distribution system is the much abused stepchild who has been all but ignored in the family circle.

The papers, together with others that may follow, were arranged to present to the membership ample evidence that neither of these conclusions necessarily is true. Even a casual reading of the papers will result in the conclusion that the type of system is of fundamental importance, and that the authors and their associates have given much thought and intensive study to the problem. It is believed that a study of these papers will result in the conclusion that the distribution system is something more than poles, wires, and fixtures.

While it is true that the engineering thought given to the distribution system has not in all cases been as extensive as perhaps warranted, we know that analyses such as are described in these papers have been and are being made all over the country.

We observe that the authors in certain instances have not come to the same conclusion as to the type of system best suited to their local situation. These differences are to be expected. Local conditions and limitations play an important part in the economic choice of a type of distribution system. Some of the factors are:

1. The Existing System. The type of system existing has a definite bearing on the method used for expanding the system. In most cases we must live with the existing system and expand it. It is the exceptional case where we can start with a clean slate and build from the ground up.

2. Local Restrictions and Ordinances. Almost every locality has some form of local restriction which affects the design principles and costs. Certain streets are underground by ordinance, overhead conductors may not be run across streets, transformers may not be located on certain streets, etc.

3. Topographic Conditions. Some localities are favored with straight and uniform streets and a level area. Others have crooked streets, intersecting at angles, and not continuous, with ravines and hills which result in difficulties in construction and may render one type of system more economical than another.

4. Local Conditions. There are many local conditions, usually of minor importance, which when taken collectively often affect the principles of design. For example, many cities have alleys which effectively can be used for pole lines. In the case where such an alley is adjacent to and parallels a street underground by ordinance, an appreciable saving in cost will result as overhead lines may be run in the alleys. Another local factor usually of minor importance but which may be of major importance is that of large city estates, scattered throughout a normal residential area. Circuitous pole routes result in some cases; larger copper is necessary.

These factors must necessarily result in certain differences in the types of systems. The paper by Messrs. Sweetnam and Corney arrives at one conclusion, and the paper by Messrs. Johnson and Henry arrives at another. Mr. Wulfing has still another solution. Messrs. Bullard and Keyes have presented a different phase of the distribution problem—the utilization of a higher voltage for distribution purposes.

While the solution of Messrs. Sweetnam and Corney differs materially from that of Messrs. Johnson and Henry, they may not be as divergent as might appear. There seems to be one important factor which is common to both—the use of relatively small transformation units. Because of space limitations, it is not possible for the authors to describe but little more than the high spots and conclusions of their study. The discussion will undoubtedly bring forth certain questions of engineering interest. We do not believe that it is the thought of any of the authors that their particular conclusion is the universal answer, and that their solution and only their solution applies to all areas. We may differ with any or all of the authors' opinions, but we must conclude that they have thoroughly studied their own problem and have come to a conclusion that will result in an efficient system of electric distribution for their community.

D. K. Blake: "Circumstances alter cases" is a maxim that certainly is true in the realm of distribution economics, as evidenced by the 4 papers presented at the winter convention session devoted to that subject. Several generalizations can be made from these papers and from more than 20 different studies I have made or reviewed, covering as many actual different circumstances.

1. No one system of distribution is so economical or universal as to exclude all the others from consideration.

2. Circumstances do occur that have a pronounced effect in favor of one system and against others.

3. High voltage radial systems, low voltage radial systems, overhead secondary networks, aerial cable systems, and primary network systems have places of economic superiority in the industry.

4. The existing system usually has the most influence as a circumstance favorable to one system and unfavorable to the others.

5. All factors and circumstances combine to present a complicated problem that requires intensive study and much labor.

6. The very complexity of the problem makes it quite easy for anyone to overlook the particular circumstances that make one system a better solution than others.

7. Studies based on uniform ideal conditions can do no more than show the relative importance of the factors influencing the total cost but they are valuable for that purpose.

8. Studies based on actual conditions are not conclusive until the circumstances favorable to one system and unfavorable to others have been carefully analyzed and shown to be real and not artificial, resulting in misapplication of the systems appearing to be unfavorable.

9. All new schemes make a greater use of transmission voltage and provide for load growth in smaller increments with varying degrees.

The term "primary network system" was coined to convey the idea of a primary distribution system having the same fundamental technical features and fundamental economic principles as the well known secondary network system. Now, in the secondary network system, circumstances do occur in practice where it is more economical to place two or more transformers (supplied from as many high voltage feeders) in the same vault connected together on the secondary side to a common bus. This bus may be tied into a street network or any number of such vault installations might exist without any secondary interconnection between the vaults whatsoever. No matter which it

is, all cases are commonly referred to in literature and in conversation as a secondary network system for the reason that the same equipment, features, and principles are employed that are inherent in a network supplying a uniformly distributed load. Of course, it is certainly true that those cases having no interconnected secondaries between vaults are radial secondary substations. Hence, we have, in loose language, networks that are radial systems and radial systems that are networks.

In the early years of the secondary network system, it was necessary to do a considerable amount of educational work to show that the system was flexible, permitting the same equipment, features and principles to be used in those cases where the circumstances made it economical to use the radial bus instead of the network grid.

Now, it is also true of the primary system that circumstances do occur where the cost of primary radial feeders is low, because of short distance or overhead construction that will make it more economical to feed from one location instead of several. The very first installation of so-called primary network equipment in South Boston was just such a case, where one unit with 2 transformers and 3 short 2.3-kv feeders was more economical. In Brookline and Pittsfield, a 4-unit grid was more economical. In Malden, Massachusetts, 2 units; and in Altoona, Pa., 1 unit, are operating as simple 1 transformer and 4 feeder radial substations, ready to be used in a network grid when the load develops. Also, the Sweetnam-Corney paper shows that the radial connection in Fig. 5 of that paper is more economical for the initial installation than a 3- or 4-unit network grid.

The Johnson-Henry paper, likewise, shows that there are circumstances in Buffalo that make it of decided economy to place 3 of their standard units at one location with 9 short radial feeders instead of forming a network with 1,500-kva units. Reference to Figs. 2 and 3 of that paper will show clearly that these substations are the exact equivalent of 3 2500-kva primary network units and, therefore, employ the same equipment, technical features, and economic principles as the primary network systems in Pittsburgh, Boston, Pittsfield, Altoona, and Malden. Anyone could call the Buffalo radial system a primary network system with the same reasonableness that they would the secondary radial system in the Chrysler Building in New York a secondary network system. It is obvious that equipment could be standardized by manufacturers to be used either way, with substantial savings to the industry.

Mr. Wulfing's paper presents in a commendable manner an analysis that shows the primary network, in the form of a grid, costs somewhat more than their standard automatic radial substation system. Everything favorable to the primary network system seems to have been taken into consideration, although I do feel that 6 network units instead of 10 would be ample in view of the overload capacity of the transformer for emergency operation. If advantage were taken of this, the network would show up favorably.

Perhaps Mr. Wulfing will present some figures, showing the saving, even though his company may not care to operate in that manner, even if an actual saving did occur in favor of the network. It would also be of benefit to the industry if he would present a comparison with three network units on one lot, connected similar to the Buffalo system. Two cases should be studied, one using two three unit substations and the other three three unit substations. Another circumstance of importance in the Chicago case is that a large number of underground network ties are used which surely make it almost impossible to justify a network arrangement, unless the same underground ties would have to be there in the radial system as well.

Now, I would like to present a comparison between the network system as a grid and the identical units connected as a radial system. This will permit us to see clearly just what the circumstances are that would permit us to expect the grid arrangement to be the most economical. Space, however, precludes this, so it will have to be reserved for a future paper.

Such an analysis will show that there are 2 requirements in order for the network system to have a substantial economy over the equivalent radial system. First, the circumstances must be such that the network will actually save 4-kv cable and underground construction. Second, that for large areas, permitting a common network over the entire area—or, what is the same thing, a smaller area of higher density, permitting a large number of units interconnected into a common network—the network not only will save money on cable and conduit, but also will save money on substations and even transmission cable, if the distance between the area and the generating station is substantial. Any attempt to apply a network to circumstances other than these is very apt to show a greater cost for the network.

W. R. Bullard: The papers by Messrs. Johnson and Henry, H. E. Wulfing, and Sweetnam and Corney are timely and of fundamental importance in view of the attention now focused on ways and means of reducing distribution costs. It seems surprising, however, that in making cost comparisons of various types of distribution systems for application to the individual local situations, not 1 of the 3 papers includes consideration of the simplest and usually the most economical of all overhead distribution systems. Perhaps this is due to the nature of the existing systems in the cities involved and to impracticability of changing the present basic system plans in considering future development; or perhaps other local conditions rule the simpler system out.

The type of system which the writer refers to as being simple and economical is the radial system utilizing the "subtransmission" voltages (6.6, 11, and 13.2 kv) directly as the primary voltage and eliminating the distribution substation. By this the writer does not mean the more expensive types of such systems, such as those employing aerial cable for the primary circuits, but rather, the most simple and inexpensive form of open wire construction.

In the paper by Messrs. Johnson and Henry, mention is made of the higher voltage primaries in connection with high load density distribution and low voltage a-c networks, but the implication seems to be that such a system is not applicable to overhead distribution involving light load densities. The system is not mentioned at all in the other 2 papers. The writer realizes that in the case of Buffalo, the subtransmiss on voltage of 22 kv would be somewhat more difficult to use as a primary voltage, than those of the other 2 cities, but even a voltage of this order of magnitude is not entirely impracticable.

The direct radial high voltage system has been used for a number of years in urban, suburban, and rural situations by several operating companies with the practices of which the writer is familiar, and to those who have used the system, the economic advantages of eliminating the distribution substation are obvious. Furthermore, the difficulties of construction and operation, popularly supposed in the past to accompany the use of this system, have been found to be partly imaginary and by no means insurmountable; and service requirements have been fully met.

In the conventional low voltage primary system the distribution substation represents an appreciable portion of the over-all investment. Various expedients are being used to minimize the cost of the substation and some of these are described in these papers. All efforts in this direction are highly commendable and these papers give evidence of substantial progress. The writer feels, however, that the time is fast approaching when distribution engineers generally will no longer be satisfied with the intermediate steps of cost reduction but will take the larger step involving the complete elimination of the distribution substation, and the adoption of the subtransmission voltage as the primary voltage. Where service requirements can be met by radial circuits, the radial system will be used. But this may be combined with the *low voltage* network principle to provide exceptionally high grade service in those districts or individual locations where such service is necessary.

John S. Parsons: The writer has been very much interested in reviewing the 3 papers dealing with the economics of distribution systems for 3 actual areas, especially in view of the more theoretical general economic comparisons we have made of various types of systems employing overhead distribution circuits. When the wide difference in load densities in the 3 areas, differences in the existing distribution plant, and other conditions are taken into account it is not surprising that a different system was found economic in each case.

Apparently in all of these studies the transmission circuits are all underground cables in duct. The primary network system particularly is adapted to the use of underground main transmission runs with aerial cable taps to the network units. Usually this will result in materially decreasing the system cost as compared with all underground transmission, and in the case of the Chicago study, where the costs of the 2 systems studied were very nearly the same, might have changed the conclusions; especially if advantage is taken of air-blast on the network units to provide emergency capacity when a transmission circuit is out of service.

While the conclusions reached in the Buffalo and Somerville studies are different

there is one point of similarity which is of particular interest. That is, in both cases the distribution substations used in the systems found to be the most economical are relatively small bus regulated sections without any high voltage bus or automatic switchgear on the high side of the transformers. Based upon our own work and a number of other economic studies which I have had an opportunity to review, it is my opinion that complete analyses of overhead load areas will in a very large number of cases show that the most economic system is one employing this type of substation.

These small bus regulated substations are essentially of a unit type of construction and may be made up of from 1 to about 5 units. Each unit consists of a 3-phase transformer, usually of from 1,000 to 3,000 kva capacity, a high voltage disconnecting switch, regulating equipment, low voltage breaker, secondary bus, probably 2 to 4 distribution feeder breakers, and a bus sectionalizing breaker for tieing together the busses of adjacent units. Standardizing on a few such factory-built units I feel would be a definite step forward in the reduction of distribution system costs and warrants serious consideration. Such standardization would not prove a handicap to the flexibility so necessary in distribution system design to meet the large number of conditions encountered. The units could be used either in a radial or primary network system as the case required. And it should be possible to construct in most cases the necessary radial station by assembling a number of units of the proper capacity. The adoption of more or less standardized units somewhat along the lines I have suggested would mean that the distribution engineers of the power companies would not have to spend so much time on the details of substation design, and would thus have more time to devote to the distribution system as a whole. This should help to reduce the delivered cost of electric energy by more effectively attacking that portion of the electric power system which offers the greatest possibilities for cost reduction.

Our studies of distribution systems for overhead areas lead me to believe that there are sections of overhead load areas which can be supplied most economically by the overhead secondary network system which employs but a single voltage transformation in going from the subtransmission to the utilization voltage instead of 2 transformations as is usually the case. The adoption of such a system may make joint use of poles at relatively high voltage, that is voltages of 11 or 13 kv, extremely desirable. I have, therefore, read Messrs. Bullard and Keyes paper with much interest and would like very much to get their reactions to the possibilities of joint use in those cases where the power circuits are 13,000 volts open wire construction.

E. W. Oesterreich: In analyzing the papers it was found that it was practically impossible to reconcile the apparent discrepancies in the basic conclusions, due to the absence of supporting cost data, or to the different basis of cost determination.

We can readily understand why topographical conditions may have a great influence on the relative unit capacity costs of the various distributing systems between the substation and the point of customer utilization. However, in these papers the outstanding difference for the cost per kva of firm for capacity distribution substations. Take, for example, the substation cost estimates when compared to the equivalent network unit estimates as presented by Messrs. Johnson and Henry, and Messrs. Sweetnam and Corney. The Johnson-Henry paper shows the network unit installations as being approximately 75 per cent higher in capital investment cost than the equivalent substation installations. Messrs. Sweetnam and Corney indicate the opposite of this condition in that their network unit installation costs are approximately 42 per cent below the corresponding substation investment requirements. In another study recently completed by a company, which study involved an area of 11 square miles and a 1931 peak load demand of 32,000 kva, the analysis showed that for a distribution substation which incorporates the most recently proposed practices in economical substation design, the estimated investment cost could be lowered to a point where the total investment for the substation capacity would be approximately equal to the investment required for the network unit installations.

This wide spread in substation investment cost data would indicate not only a decided difference of opinion as to operating and engineering design requirements for a presupposed similar service requirement, but a large differential in the installation costs of the equipment.

Mr. Wulfing shows in his paper in Table IX that in the network plan the transformer units are installed as the load growth within the area under consideration and, in the surrounding station area, requires the additional capacity, while existing substation capacity is utilized to its fullest extent for the maximum period of time. In the radial feeder plan, the initial installation of the new substation appears immediately to release to the surrounding area, substation capacity of 4,000 kva in excess of that released, or rather unloaded, in the network plan. According to the table this additional released capacity amounts to a total of 14,500 kva in the first 6 years considered or, roughly, an average capacity of 2,500 kva for 6 years. To make the annual cost comparison applicable, it would appear that the annual cost of the equipment released, which is not used or useful in supplying capacity for the growth in load in the surrounding area, should be charged to the plan creating the idle investment condition. Or, if all of the surrounding station capacity made available by the radial plan is necessary to supply immediate load requirements of the surrounding area, then it would seem more equitable if the cost of the difference in the amounts of this capacity used under the 2 plans should be charged to the network plan.

Messrs. Johnson and Henry present a worthwhile contribution to the industry by clarifying the fundamentals involved in the problem of economic design of distribution systems. Unfortunately, their presentation of comparative capital costs as shown in Table II is of such a general nature that the lack of data relative to items of the subdivisions prohibits comparisons with conditions as they exist on other properties.

A system composed of small increments of capacity, installed at or near the concentrated loads when needed, and feeding into a distribution system which does not require frequent, costly circuit revision work adequately to serve the increasing demands brought about by normal growth of load and the addition of new circuits, presents economic advantages which are apparent. But local conditions, construction practices, operating, and service standards may impose such restrictions that the ideal condition cannot be obtained. The papers presented force us to recognize the engineering, economic, and operating phases of distribution as a problem which cannot effectively be subdivided into component parts such as transmission, substation, and distribution. For each of the related phases and for the composite system there is a solution which results in the lowest annual costs over a reasonable period of time. It is this solution which we must strive for regardless of precedents, and existing functional jurisdictions.

The officers and contributing authors of the power transmission and distribution committee are to be congratulated on their courage in presenting a symposium on a subject so controversial in nature as this one. The importance of the effect of differences in operating requirements and engineering design practices on distribution costs has been emphasized in the presentations. It is to be hoped for that this session will provide the necessary stimulus to distribution engineers so that the attendants at future Institute conventions will be able to derive the benefits of further thought and analysis of this problem.

Joint Use of Poles With 6,900-Volt Lines

Discussion of a paper by W. R. Bullard and D. H. Keyes published in the December 1933 issue, p. 890–8, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., Jan. 25, 1934.

P. H. Chase: The adoption of joint use at 6,900 volts in the Staten Island area recognizes the economic advantage of this arrangement in that particular case, and also shows a highly commendable attitude of cooperation by the power and telephone interests. It is through trial in particular situations such as this that experience can be gained with which to meet the ultimate requirements of both systems occupying the same territory in the safest, most economic arrangement. The study was concerned mainly with the economics and relative safety of certain phases of power and telephone distribution. The economics of this particular situation shows a substantial saving in investment to the electric company, and therefore this was a major consideration. From the standpoint of hazard to telephone plant, the coördinative measures adopted in the power system are such as to impose practically no higher voltage than is the case with the more usual practice of joint use.

The paper brings out that a limiting feature in joint use at the higher voltages is the

development of telephone fuses which will operate satisfactorily at these voltages. Granting this, it is to be hoped that suitable fuses may be developed in the near future.

The evaluation of the hazard factor in studying higher voltage joint use is a most difficult problem. Both the effects when contacts occur, and the frequency of these contacts need to be carefully studied. The former has been well covered in this analysis, but the latter has not been particularly emphasized. The frequency of contacts probably is as large a factor in the solution adopted as the effects of the contact. Higher voltage joint use generally would involve higher insulation, greater clearances, faster relaying, etc., all of which work toward a lower frequency of contacts. It is quite possible that the reduction in frequency of contact may offset the effects due to increase in voltage magnitude, and thus make joint use at higher voltages as acceptable as with the lower voltages.

Satisfactory practical experience extending over about 12 years in Philadelphia with approximately 3,000 poles of joint use with open wire 13-kv lines, and both open wire and cabled telephone circuits without modifications to the plant of each because of such joint use, strongly substantiates the foregoing. The writer is inclined to feel that theoretical considerations to a great extent overemphasize the year-in-year-out hazard to telephone plant when the probable frequency of occurrence is omitted.

The writer understands there are several other areas in which there has been long-time experience with joint use involving voltages of the order of 13 kv.

It would seem particularly appropriate now to undertake detail study of such areas, in order to parallel and balance with operating results the existing theoretical and development investigations. As often happens in many branches of engineering and other human activities, quite possibly it may be found that certain greatly-feared hazards are of such infrequent occurrence as to be of infinitesimal operating importance, unusual conditions may be cleared up in unexpected ways or with negligible damage, and additional expenditures for some of the additional safeguards may be found unnecessary. The writer makes these statements without in any way minimizing the value and importance of thorough-going study of all the contingencies, but, however, urging the need for more data from operating experience.

Radial Versus Primary Network Distribution

Discussion of a paper by H. E. Wulfing published in the January 1934 issue, p. 38–42, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., Jan. 25, 1934.

C. A. Corney: Table V of the paper gives approximately $510,000 as the present value of 10 years' annual costs of developing the 4-kv radial system. Table VIII gives approximately $550,000 as the present value of 10 years' annual costs of providing for load growth by means of a 4-kv network system. Thus, the 10-year present value of network costs is 8 per cent greater than for the radial system. It will be observed that the radial system calls for a total new investment over the 10-year period of approximately $842,000, of which about $500,000, or 60 per cent, is needed the first year. The network system calls for a total new investment over the 10-year period of approximately $1,060,000, of which only $360,000, or 34 per cent, is needed the first year.

In the Boston study, it was believed that due to the unknown effect of future occurrences on the outcome of present plans, assumptions would be progressively less accurate for the later years. In making any choice, therefore, between various plans, the later years should be given less weight than the earlier years. This factor is taken into consideration in the same manner as by the summation of annual costs discounted at 7 per cent per year, except that a factor of 15 per cent per year, compounded annually, is used, 7 per cent of which is for interest and 8 per cent for relative inaccuracy. If this method is applied to the Chicago study, the radial system gives approximately $383,000 as the present value of 10 years' annual costs, while the network system gives approximately $400,000 for the same value. Thus, the 10-year present value of network costs is reduced to a value only $4^1/_2$ per cent greater than for the radial system.

When differences between systems are reduced to 5 per cent, or below, they may be considered negligible and for all practical purposes the costs equal. The choice should then be made on the basis of other considerations such as character of service rendered with respect to continuity and regulation, flexibility in meeting load conditions and operating efficiency.

Concerning continuity, it should be recognized that faults in single radial feeders of large capacity such as 2,000 to 2,500 kva will interrupt more load than would be served from a single network main. Furthermore, 4-kv bus faults in network units do not interrupt any load, whereas bus faults in radial substations will interrupt several complete feeders until they can be switched to other busses or feeders.

Concerning regulation, it may be said that the network inherently provides a more uniform voltage condition throughout an area than can be maintained by separate radial feeders. The network bus voltage can readily be made to compensate for drop in mains, distribution transformers and their secondaries, as is being done in the Boston network, which has been in successful operation for 2 years.

The flexibility of a network system is evident as capacity may be added in small increments when and where it is required by loading conditions. This gives the network a distinct advantage in minimizing cumulative carrying charges and in closely following changes in area load centers.

Factory built network units are ideal subjects for standardization and quantity production and should always reflect this fact in their cost in comparison with substation equipment assembled and erected locally. Also it should be borne in mind that radial substation capacity rarely is used to the full, as pointed out in a recent article ("Pertinent Facts in Primary Distribution," by D. K. Blake, *Electrical World*, April 22, 1933, p. 508–12).

It is interesting to note that Mr. Wulfing's study shows lower energy losses by 35 per cent for the network than for the radial system.

F. M. Starr: Mr. H. E. Wulfing has given a very clear-cut summary setting forth the comparative costs and carrying charges for both a primary network and a radial distribution system to care for a load growth in a typical area over a period of 10 years. The results of his analysis show that the radial distribution system is somewhat less costly than the primary network although the difference is not large.

Although the scope of Mr. Wulfing's paper has not permitted a complete discussion of the various detail design factors of the 2 respective systems (i. e., primary network and radial system), it is, nevertheless, evident that he has made a very thorough study, and we may assume that, at least for this particular area, Mr. Wulfing's conclusions undoubtedly are correct.

However, I should like to point out that the conditions requiring the particular network development as described in this paper cannot be considered typical of conditions existing in the average load area of this type, and the conclusions arrived at here cannot be interpreted as having general significance.

Figure 1 shows the predicted load growth over a period of 10 years in the area under consideration. In addition, the growth in firm capacities of the proposed network and radial systems are shown, the dotted line referring to the network and the solid line referring to the radial system.

The firm capacity of the radial system is determined by assuming 1 transformer bank out of service and a permissible overload of 50 per cent on the remaining bank or banks. To this capacity is added the capacity of external feeders serving the area as noted in Table IX of the paper. For example, the initial firm capacity of the radial system is 5,000 kva (1 bank) plus 2,500 kva permissible overload plus 3,000-kva radial feeder capacity from outside the area.

The firm capacity of the network is determined by assuming 1 transmission feeder out of service and a permissible load of 2,800 kva on each network unit remaining in service. This figure is determined by allowing 25 per cent emergency overload plus 300 kva for 10 deg C ambient in addition to the 2,000-kva continuous forced-air-cooled rating of the standard network unit, and is somewhat more conservative than the 50 per cent emergency overload permitted on the radial substation.

It may be noted in this case that the firm capacities of both the radial and network systems substantially are greater than the predicted load throughout the 10-year period. Such a condition always is necessary with a radial system since the initial installed capacity must necessarily be large and succeeding increments in capacity must likewise be large. However, in most cases, it will be found that the network can follow the load curve much more closely than was found to be permissible in the present case. For example, in many cases similar to this one, the 2 initial units would have been easily adequate up to 1934, 4 units would

have been adequate from 1934 to 1937, 6 units would have been adequate up to 1939, and 8 units would have been adequate through 1941.

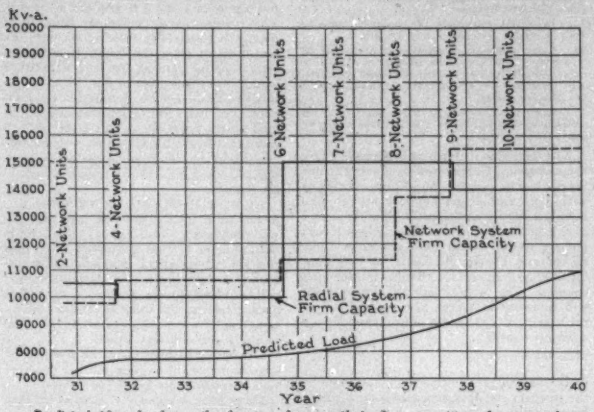
Thus, Mr. Wulfing might easily have found in making this study that—with identically the same assumed load growth, but with a somewhat different layout of existing equipment—the ultimate network would have consisted of 8 units instead of 10, and 2 transmission lines instead of 3, and the carrying charges would have been considerably reduced owing to the delayed installation of the 8 network units. These combined savings would show the network economically to be considerably more attractive than the radial system.

An alternative layout might have been adapted permitting still greater savings in some cases. For example, the third transmission line might have been installed in 1937 or 1938 instead of 1939. The 6 initial units could be fed from these 3 lines (2 per line) giving a network firm capacity of 11,200 kva (in addition to any external feeder capacity which may still exist in the area), which is adequate to care for the total load throughout the 10-year period. Although, in Mr. Wulfing's particular case, 10 units were necessary, it is evident certainly that in many cases 6 units would have been adequate for a similar load area.

In regard to distribution system economics, I should like to emphasize one further factor which may result in considerable savings for the network but which cannot be evaluated in an estimate.

Referring to the load curve again, suppose that the radial system had been adopted and developed as planned up to 1935. At this time the third transformer bank will just have been installed. Even though the load should grow as rapidly as predicted, this third bank will constitute unused capacity for several years to come. But suppose the load should stop growing or fall off at this time—an occurrence which experience has shown may very well happen. In this event a heavy and unnecessary investment in substation capacity must be carried.

Had the network been adopted, it would have developed in small increments and its expansion could have been curtailed at any time the load stopped growing thereby obviating unnecessary capital expenditures.



Predicted 10-yr load growth, showing also growth in firm capacities of proposed network and radial systems

I am bringing up these points merely to emphasize the fact that generalized conclusions in regard to distribution system economics certainly cannot be drawn from the results of an isolated study.

Fundamentals of Design of Electric Energy Delivery Systems

Discussion of a paper by J. Allen Johnson and R. T. Henry published in the December 1933 issue, p. 831–8, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., Jan. 25, 1934.

C. A. Corney: We are indebted to Messrs. Johnson and Henry for their valuable suggestions for the standardization of terms, to be used when dealing with supply systems generally. Much of benefit would result if these or similar terms should be generally used.

The first part of this paper is concerned with what may be referred to as the "fundamental principles" which any distribution system should adhere to in order that it may satisfy the requirements of a proper economic balance. With these principles the writer believes we can all agree. The latter part of the paper describes the radial system adopted in Buffalo after comparison with a primary network system. One of the authors in the *Electrical World* article mentioned in the paper gave a more detailed description of the radial system adopted and expressed doubt as to the suitability of the network system, as developed at that time, with reference to regulation, instability between units, and relaying. It was stated also that the cost of the network system was found at the time of their study to be at least 10 per cent greater than the radial system adopted. The present paper indicates that a network for this area would be 36 per cent greater in cost than the radial system adopted. It would be of interest to have the reasons for this rather wide difference in estimates more fully explained.

Since the Buffalo system was completed, the Boston Edison Company has put into successful operation a primary network using standardized factory built units. Regulation is entirely satisfactory; instability is prevented by reversed reactance connections on line drop compensators and a rising voltage characteristic is readily obtained to overcome drop in mains, distribution transformers, and their secondaries. Relay operation has been very satisfactory, experience having been gained with faults on both the transmission system and on the distribution mains. In all cases relay operation has been correct.

In the matter of cost, it would seem that, for Buffalo conditions where densities run up to 5,000-kva per square mile, the selection of network units as small as 1,500-kva capacity was not well advised as it would appear that 3,000-kva units would have been more suitable. The writer knows of no reasons why network transformers cannot be standardized in larger capacities, also using the same switching unit as at present developed. The cost of a single 3,000-kva network unit would on this basis only be about 16 per cent greater than for a 1,500-kva unit.

Had such larger units been considered, it would appear from a brief study of Table II of the paper that with the fewer units required and the less mileage of subtransmission cable needed the cost comparison would have been much more favorable to the network, if indeed the network might not have cost less than the radial system.

The writer feels that the costs of the Buffalo radial system must have reflected the savings attendant upon quantity purchase and installation of so many units of the same type at the same time and using but one set of drawings. In the usual case a radial system is expanded piecemeal with attendant higher costs.

The authors refer in the paper to 2 particular difficulties which they found in attempting to apply the primary network scheme, one being the unfavorable effect on firm rating factor of the network caused by irregularities in the area such as parks, waterways, railroads, etc., and the other, of obtaining uniform loading of network units on account of the impedance in the network. Concerning the question of the effect of irregularities in the area, it is difficult for one unfamiliar with local conditions to see how the network need suffer in that respect in comparison with the radial system. It is not always necessary to have network mains supported at both ends, so that long stretches of mains crossing park or other territory in which there is no load are uncalled for. In the Boston network there are

numerous radial branches from network mains and several cases where short radial feeders run directly from network switches without being tied in to another network unit at the far end.

Concerning the uniform loading of units, we have had absolutely no trouble in this respect, being able by adjustments of the line drop compensators to divide kva load very satisfactorily. Mr. T. H. Haines will later present test data on this feature.

It is of course to be expected that with non-uniform and variable loading conditions in an area, network transformers will not be loaded exactly alike at all times, anymore than it would be possible to load the various stations in a radial system with exactly equal amounts of load.

The authors refer to the facility with which load can be transferred from one station to another. In order for this to be done readily an overloaded station must have an underloaded one adjacent. As adjacent stations are on the average about a mile apart and as network units would be much closer together than this, such a condition of loading in a network system automatically would adjust itself by nearby units picking up load from units which tended to become overloaded. In neither system can spare capacity at a distance from an overloaded section readily be made use of. Additional capacity must usually be added in either case at or near the heavily loaded or overloaded area.

In the cited case of uniform load growth over the entire area it seems to me that in the radial system transformer units and additional feeders would have to be added throughout the area in exactly the same manner as additional network units and mains would be needed throughout the area. I see no advantage of the radial over the network system in a case of this kind.

A very excellent analytical study of the question of load division and regulation in large and small networks under various loading conditions both normal and abnormal was made by Mr. F. M. Starr of the General Electric Company and reported in his paper presented at the Chicago A.I.E.E. Convention in June 1933, (Theory of Primary Networks, Trans. A.I.E.E., Sep.-Dec., 1933, p. 934–42). The analytical studies were checked by tests on actual networks and by the use of the calculating table. This paper concludes in one place that "the loss of a transmission feeder in a network of fairly large size need never impose an excessive overload on any transformer." The paper further indicates that satisfactory emergency loading conditions may be obtained without the necessity of interleaving transmission feeders.

Messrs. Johnson and Henry go into some deatil to describe desirable features of their system without stating clearly that many of these also are possessed by the primary network in some cases to a greater degree.

Some of the more important points claimed for the radial system which are common to the network are as follows:

1. Uses small substations closely spaced.
2. Has short distribution feeders and eliminates the need for carrying main feeders to load centers and providing radial branches from there.
3. Utilizes bus regulation.
4. Develops low short circuit currents.
5. Provides freedom in the choice of location on account of small size.
6. Has no high voltage bus or switching equipment.
7. Provides simple compensation for line drop.
8. Faults in subtransmission, transformers, or regulators are isolated without interruption.
9. Secondary network units also may be supplied from the same transmission circuits.
10. Industrial and lighting loads may be served from the same feeders.
11. Industrial customers of moderate capacity may be served by separate 4-kv feeders.
12. Large industrial customers may be served direct from subtransmission circuits, or substation or network units installed on customers' premises. This later plan has been carried out in one case on the Boston system.
13. Load may be shifted from heavily loaded subtransmission circuits to a lightly loaded nearby group.

The foregoing features are all possessed by the network. In the opinion of one who has been able to observe operating conditions with both radial and network service, the network provides inherently a higher degree of continuity, better regulation, lower losses, greater ability to start motor loads without flicker and greater flexibility in providing for load growth and for changes in area load centers. The writer believes the network will in many instances also prove itself in the matter of cost per kw of load carried over a period of years.

T. H. Haines: Soon after the installation of the primary network supplied from 3 transformer units on the Boston Edison System, a series of tests was made to determine the division of load between the 3 units. It was found that under light load conditions when the network was taking about 1,150 kw of load, unit 1 carried 30.2 per cent of the load, unit 2 carried 35.3 per cent of the load, and unit 3 carried 34.5 per cent of the load. Similar tests made under full load conditions of 2,850 kw showed that unit 1 carried 33.5 per cent of the load, unit 2 carried 32.7 per cent of the load, and unit 3 carried 33.8 per cent of the load. A complete description of the Boston network layout was given in an article by Mr. A. H. Sweetnam (4-Kv Network Saves 20 Per Cent, *Electrical World*, March 14, 1931, p. 500–3). It should be noted when referring to the article that the Boylston Street unit 4 is not yet in service.

A very good indication of the manner in which the load divides between the 3 network units is given by Table I which gives the total kilowatthours delivered to the network for the year ending January 2, 1934.

Table I

	Kilowatthours			
Unit	Aϕ	Bϕ	Cϕ	Total
1	1,172,800	1,185,000	1,330,200	3,688,000
2	1,439,600	1,413,800	1,316,700	4,170,100
3	1,231,500	1,258,800	1,234,200	3,724,500

This shows that unit 1 supplied 31.8 per cent of the total kilowatthours, unit 2 supplied 36.0 per cent and unit 3 supplied 32.2 per cent. These figures show that unit 2 carried a slightly higher percentage of the total load than the other 2 units. This is explained by the fact that unit 2 supplies a radial circuit directly from the bus in addition to the network ties to the other 2 vaults.

The kva likewise is controlled easily by the line drop compensators so that all the units will operate at very nearly the same power factor.

A few months after the network had been in operation, a case of system trouble developed which caused the transmission lines feeding units 1 and 3 to trip out of service. The reverse energy relays at these units operated successfully clearing the network transformers from the faulty transmission lines thereby causing the entire network load to be thrown on to unit 2. As it so happened, this trouble occurred in the forenoon when there was only about 2,000 kw of load on the network, so unit 2 was able to carry this load with very little drop in voltage as may be seen from the following readings obtained from the recording meters in the 3 units.

At about 9:45 a.m., the recording ammeters at all 3 units went off scale, and immediately units 1 and 3 dropped out, while the ammeter at unit 2 dropped back to a position indicating the total load of the network at that time. Simultaneously, the voltage on all 3 units dropped to zero from approximately 120 volts and immediately came back to 112 volts at unit 1, 118 volts at unit 2, and 116 volts at unit 3.

The network operated in this manner for approximately a half-hour until it was possible to return units 1 and 3 to service.

There have been only 2 cases of breaker operations on the 4-kv network mains since their installation, and in both instances the relays operated successfully to clear the fault.

The first operation was caused by 2 primary wires being down in an overhead section of one of the network mains causing 1 breaker operation, and upon reclosure the circuit stayed in for 5 minutes; then another breaker operation occurred and upon this reclosure the circuit stayed in until it was taken out for repairs.

The second operation was caused by the breakdown of an overhead sectionalizing oil switch. In this case the circuit breakers at each end of the affected main reclosed 3 times and then locked out. The effect of the total of 6 reclosures was rather disastrous to the switch. We have since reduced the number of reclosures possible.

In conclusion, therefore, it may be stated that all relay operations have been entirely correct to date, as all troubles, both on the 13.8-kv and on the 4-kv systems have been successfully cleared.

G. O. Eaton: In 1931 the Malden Electric Company installed 2 medium voltage network units in Medford. These have since been operating as radial substations and have proved satisfactory in all respects.

This installation has demonstrated the adaptability of the net work plan for meeting changing load conditions. When the existing 2 units were installed the load was growing rapidly and the installation of 2 additional units was planned for the next year. The expected load growth did not materialize and the original units still are able to take care of the situation.

If, in 1931, a conventional radial substation had been built rather than to install network units a comparatively large initial investment in land, building, and transformers would have been made during the

following years of unexpected restricted growth would have been but little utilized. It is estimated that the initial substation investment would have amounted to about twice as much as was spent on the network system. It will be seen, therefore, that substantial savings in capital costs have been made.

C. M. Gilt: Messrs. Johnson and Henry are very fortunate in having had the opportunity to design and install a new 60-cycle distribution system and are to be complimented on the very complete analysis they have made of the whole problem. All too frequently our electrical systems grow by piecemeal additions based upon piecemeal analyses. No doubt we would often save money in the long run, and provide better over-all service by adopting and then following a consistent plan of development as a result of a complete analytical study rather than adopting what appears to be the best expedient for each move.

It is interesting that Messrs. Johnson and Henry have arrived at the same general conclusions and therefore somewhat confirm the conclusions at which we arrived in Brooklyn in studying our distribution problem, which are that secondary networks best meet the needs in high load density areas, and the radial system best satisfies the lighter areas. We can go one step further and say that for the types of loads and load densities we have studied, the low voltage network not only gives the best service but is the cheapest installation wherever the distribution system must be underground. Of course, a secondary underground network cannot compete in cost with an overhead radial system. The underground network gives better continuity than the radial system, yet the continuity of a good radial system is such that in general one cannot justify very much more money for improved service to the average consumer. Our records over the past 7 years indicate that the average radial customer may expect one outage every $2^1/_2$ years which will last about an hour. The average network customer may expect an outage once every 500 years but it will last nearly 3 hours.

When we redesigned our electrical system in 1922, we did not have equipment available for a low voltage a-c network, the latter having infiltrated and replaced our radial system over the past 7 years. While we omitted from our substations high tension breakers, sectionalized our 4-kv busses and used automatic reclosing feeder breakers, the Buffalo design has gone further in reducing costs and probably has improved service by shortening the 4-kv feeders. I am confident that were we to redesign our radial system in light of our experience and present day equipment we would construct smaller and simpler substations, much as is done in Buffalo. A review of our substation records indicates very few failures within the station and that failures resulting from equipment installed to secure flexibility and continuity may be as embarrassing as failures which would have occurred had there been somewhat less equipment and flexibility.

Certainly we have lost nothing but initial cost and continuing maintenance costs by connecting transformers directly to "subtransmission" cables without circuit breakers. There is no reason why several substation transformers cannot be so connected to one high tension cable. It is common practice to connect many network transformers in this way and we are connecting network units onto our substation feeders without any real detriment.

In discussing generating station switching Mr. Eales advocated a principle of physically separating circuit breakers from the equipment they are to protect, and so applied it to distribution systems and network units in particular that it might well receive some comment at this session. The writer agrees with the principle as an ideal but in application must temper the ideal by the costs it would involve and the results of experience. To separate our network switches from our network transformers by a wall as installed in our manholes, would increase the size of the manholes and cost of installation by over 15 per cent, and sacrifice some of the advantages of a complete factory built unit. In Brooklyn there are over 1,000 3-phase units in operation with the network switch mounted in a box on the transformer tank. Most of these have been in service for 2 years, and some of them for 7 years. During this period we have had 11 failures of transformers or high tension potheads, none of which involved the network switch, and 4 network switch failures that destroyed the switch, none of which involved the transformer. Should a transformer failure involve the network switch, the result would be a secondary short circuit, a condition which we must expect from other causes as well and must be prepared to meet. Therefore we could hardly justify the extra cost were we to follow out this principle in the case of manhole transformers. The condition is somewhat different in the case of transformer installations in vaults in customers' buildings. Here space arrangements and handling facilities commonly dictate single phase transformers with separate network switches and the isolation usually can be obtained at little or no extra cost. The advantages may be slightly greater also, as a short circuit of the network switch may be a failure on the customer's service cables and interrupt service to him rather than a short circuit on the general street network.

A. H. Kidder: The method for discounting the expenses incurred in different years to their "present value" (as used by Messrs. Sweetnam and Corney, and by Mr. Wulfing) is particularly commendable in that it is a device which recognizes logically the important difference between the value of a dollar in hand and the value of a dollar to be saved at some future date. The writer believes this is the first time that economic perspective has been introduced in such papers to allow for the above difference and to allow for progressively increasing uncertainties in estimates of future savings. This is true particularly in the Sweetnam-Corney paper where the values have been discounted at 15 per cent compound interest. During the past few years the writer has found this device to be practically indispensable for summarizing estimated year by year expenses in comparisons between plans which involve varying amounts of changeover expense and different construction schedules.

The Sweetnam-Corney paper also illustrates the way in which some important local considerations may affect an economic comparison which deals with plans for supplementing existing facilities. Two such factors which apparently were beyond the control of the engineers in this instance are given in the following:

1. Take for example the Christmas-stocking shape of the Somerville area and the present substation location over half a mile from the load center. These local factors place the plan for enlarging the present substation under a considerable economic handicap.

2. Also, for instance, a large part of the approximately $100,000 investment difference between the least expensive primary network plan (No. 7) and the plan for enlarging the existing substation (No. 1) may be due to the fact that the substation is modernized under plan No. 1, and is not modernized under any other plan. The decision that the substation need not be modernized under the network plan may or may not have depended to a considerable extent upon judgment. In any event, this factor might be responsible for a large part of the economy shown by the network plan. In the interest of accuracy, the writer believes some credit should have been given to plan No. 1 for the fact that alone it provides for rebuilding the substation, although it is doubted that this increased accuracy would have any important effect upon the conclusion reached.

The writer is becoming more than ever convinced that no distribution system yet developed holds sufficient promise to justify abandoning intensive search for a system in which the cost per unit inherently lies in a much lower order of magnitude than is being found in the systems analyzed to date, where the margin of economy is narrow. It is important to realize, however, that such a system, if discovered, probably would be installed more or less piecemeal as required by load growth and its effect upon primary distribution system costs as a whole might not become impressive for 10 or 15 years after adoption of the plan.

Opportunities for economy in present systems must not be overlooked in the search for new methods. This is true particularly since such economies might be appreciable and probably few years would be required to realize their maximum benefits. For instance, it is very probable that present substation and distribution facilities can be operated safely at loads considerably higher than at present.

Under normal loading conditions, with all the capacity in service, the loading of the substation and distribution facilities may be increased very appreciably without allowing operating temperatures to exceed present conventional limits.

Emergency outage of one unit at the time of the peak in the year when the peak would be comparable to the total capacity installed is, on the average, a very remote contingency indeed. At its worst this would involve only a few hours' operation at unconventional temperatures. It is probable, however, that most of the facilities now used can be subjected to such an emergency condition as often as 1 to 5 times during their useful life, without noticeable effect upon their life, and with negligible effect upon appropriations to reserves for renewals and replacements. From the service point of view, such an emergency probably would have no more serious consequence than perhaps the delivery of voltage slightly below normal during the 1 or 2 hours duration of the most severe condition.

If some such schemes are found to be practical, their benefits will accrue almost immediately and may add measurably to the difficulty of finding more economical, new methods for primary distribution.

News
Of Institute and Related Activities

Many Sections and Branches to Celebrate the Institute's 50th Anniversary in May

SECTIONS of the Institute throughout the country as well as many Student Branches are now actively formulating plans for the celebration of the Institute's 50th anniversary during May 1934. Many of these celebrations will be held jointly between Sections and Student Branches.

To assist those who may not already have formulated definite plans, the following summary of what many Sections and Branches are doing is given. Although many of these plans were still in the formative state at the time this issue went to press, the ideas contained herein may prove valuable. The following paragraphs are taken directly from the plans submitted by the different Sections and Branches, and are, of course, subject to revision.

University of Alabama Branch. Plans to observe the 50th anniversary by holding a joint meeting of the Birmingham Section and the Student Branches of Alabama Polytechnic Institute and Mississippi State College. A feature of this meeting is expected to be an address from the oldest Institute member available in the District.

Baltimore Section. A dinner meeting in May has been tentatively decided upon, to which appropriate speakers will be invited. The arrangements for this meeting have been assigned to an entertainment committee which is now active.

Chicago Section. A celebration meeting during May is contemplated. It has been the custom of this Section to have a smoker each year, usually during the spring season, and at which a larger percentage of the members is in attendance than at any other meeting during the year. It is planned to combine the celebration meeting and the smoker in 1934 in the hope of getting out as many of the members as possible, especially those who have a knowledge of the early history of the Institute. It is hoped that through this arrangement appropriate celebration ceremonies can be conducted.

Cleveland Section. The annual meeting customarily held by this Section in May is being extended this year to make a fitting 50th anniversary celebration. The meeting has been arranged so that Doctor Whitehead may be present as the speaker. It is intended to invite representatives of other engineering societies to attend, and the Section also hopes to coöperate with the Branch at Case School of Applied Science.

University of Denver Branch. A program in honor of this celebration is expected to be included in the May meeting. It is expected that the history of the Institute will be reviewed with special attention to the outstanding men who have been responsible for its continued success, and also that there will be presented a history of the progress of the electrical industry through this period, showing the relation of the Institute to this progress.

Erie Section. Provided that more elaborate ceremonies for celebration of the 50th anniversary are not arranged, it is possible that some special anniversary features will be incorporated in the special ladies' night which is scheduled for May 15.

University of Idaho Branch. As May is the regular month and year in which the biennial engineering show is held, every effort is being made to have the Student Branch take an unusually active part in this show and emphasize in its display the fact that this is the 50th anniversary of the Institute. Although plans have not yet been crystallized, a large enthusiastic student meeting has been held and some 30 different projects are under way. The fact that this is the 50th anniversary will be made an emphatic idea of the show.

Indianapolis-Lafayette Section. The anniversary meeting will take place in the latter part of May and is planned as a social meeting to celebrate the Institute's 50th anniversary and to close the season's activities for this Section. A golf tournament and other outdoor activities are planned for the afternoon, followed by a dinner at which a speaker of prominence will give a history of the Institute and the men who have been active in it since its organization.

University of Kansas Branch. A combined meeting is being held with the Kansas City Section to celebrate the Institute's 50th anniversary. The program for this meeting is in the hands of the Section's program committee. Engineers who were in active practice during the early days of the Institute will probably be secured as speakers.

University of Louisville Branch. A joint meeting of the Louisville Section and the University of Louisville Branch is being planned. The students will present papers pertinent to the occasion, and special demonstrations will be given.

Lynn Section. A banquet will be held in Boston, Mass., on April 7, at which mention of the 50th anniversary will be made. An effort will be made to have as many of the charter members of the Institute as is possible attend this banquet.

Minnesota Section. The meetings and papers committee of this Section has scheduled a discussion of the matter of celebrating the 50th anniversary, and definite plans will be made. It is felt that the anniversary should be recognized in some appropriate way and the Section plans to exert great effort in trying to make this event an outstanding one in the history of the Minnesota Section.

Mississippi State College Branch. This Student Branch plans to join with the Student Branches of the University of Alabama and Alabama Polytechnic Institute in a joint celebration with the Birmingham Section.

Montana Section. The Montana Section and the Montana State College Branch are planning to hold a joint meeting in Bozeman, this meeting to include a lecture and banquet.

University of Notre Dame Branch. Tentative plans at present include the holding of an open meeting of this Branch to which the entire university and the public will be invited. At this meeting some outstanding electrical demonstration will be presented, probably in conjunction with the research laboratory of an industrial organization. Other plans will be formulated later.

Ohio State University Branch. Although plans of this Branch for the 50th anniversary celebration have not yet been definitely formulated, it seems most probable that the Branch will join with the Columbus Section in this enterprise.

Oklahoma City Section. It has been decided to have a one day joint meeting of the Oklahoma City Section and the Student Branches of the Oklahoma Agricultural and Mechanical College and Oklahoma University. The technical part of the program will consist of papers by students from the 2 colleges and members of the Section. The meeting will be concluded with a banquet in the evening at which it is expected a speaker who is a nationally prominent Institute member will be present, and who will give an appropriate address. The details of the meeting are being worked out by the meetings and papers committee of the Section.

Oklahoma Agricultural and Mechanical College Branch. It has been the custom for this Branch to have a joint meeting with the Student Branch of the University of Oklahoma in May, under the sponsorship of the Oklahoma City Section. Although this meeting has taken place alternately on the 2 campuses, it has been decided for this year to merge the joint meeting with the anniversary program and to hold the meeting in Oklahoma City in order that a larger portion of practicing engineers might attend. The student sessions will be held in the morning, at which a paper presented by a representative of each of the 2 participating schools will be presented. This will be followed by a luncheon at which visiting electrical engineering students of both colleges

will be guests. At the Section meeting in the afternoon, 2 papers are to be presented. This will be followed in the evening by a dinner meeting. It is likely that the meeting will take place during the first half of May.

Pittsfield Section. An anniversary banquet is being planned for May. Details are now being arranged.

Providence Section. The program committee of this Section has made tentative plans for an outing to take place in May. This will be held on a Saturday afternoon and evening, the afternoon being given over to sports with a dinner in the evening, with an appropriate speaker. In this way it is hoped not only to celebrate the Institute's 50th anniversary but also to create a feeling of better fellowship among the individual members of the Section.

Rose Polytechnic Institute Branch. A combined meeting of the Branches of Purdue University, University of Illinois, and Rose Polytechnic Institute, and the Indianapolis-Lafayette Section is being planned for either April 14 or April 21 at Rose Polytechnic Institute. The program is to consist of papers during the morning, with a luncheon program, followed by inspection trips in the afternoon.

Rutgers University Branch. The Student Branch is planning a joint meeting with the Newark Institute of Technology Branch, which will be held at Rutgers University. It is hoped to have one of Mr. Edison's laboratory assistants present some of his experiences in connection with the early developments of electricity.

San Francisco Section. As the 50th anniversary of the founding of the Institute is the 30th anniversary of the founding of the San Francisco Section, it has been proposed that these 2 events be celebrated at the same meeting. A possible feature of the program is a dramatic sketch portraying the founding of the Institute, featuring as characters several charter members of this Section. The selection of an appropriate paper from one of the early A.I.E.E. TRANSACTIONS also is being considered, this paper to be read and discussed by different members of the Section, who will play the parts of the original author and discussors. It has been suggested that a Student meeting be arranged for the afternoon, with the anniversary meeting in the evening.

University of South Carolina Branch. It is planned to celebrate the Institute's 50th anniversary with a banquet in May. The speaker is to be Prof. Thomas F. Ball, counselor of the Branch, and his speech will center around the founding of the Institute and its history. The banquet will be arranged in every way to bring out the main theme of the anniversary. If funds permit a large cake with 50 candles will grace the center of the banquet table.

Semiannual Meeting of The A.S.M.E. The semiannual meeting of The American Society of Mechanical Engineers will be held in Denver, Colo., June 25–28, 1934, at the Cosmopolitan Hotel. The tentative program, which has been provided by the Colorado Section of the society, contains technical sessions covering machinery and management developments. Papers are promised on recent mechanical engineering developments in mining, fuel utilization, sugar refining, humidity, and management. A group of inspection trips to plants and mines is being arranged.

North Eastern District Meeting to Be Held in May

The meeting of the Institute's North Eastern District, No. 1, will be held this year in Worcester, Mass., May 16–18, 1934. In addition to arranging satisfactory technical sessions, considerable attention is being paid to student participation in the meeting. In arranging sessions and inspection trips, the interests of both groups, namely, active members and Students, are being considered.

The papers being arranged for discussion at the Worcester meeting are to be based largely upon papers recently published in ELECTRICAL ENGINEERING, supplemented by special subjects and items of local interest.

1934 Yearbook Now Available

The Institute's Yearbook, not published since 1931, is again being published this year and contains a complete listing arranged both alphabetically and geographically of names and addresses of all members (correct to January 31, 1934), a copy of the by-laws and constitution, a list of Institute officers and committees, as well as other information of interest in Institute activities. This Yearbook is now available for distribution.

It is the definite policy of the Institute to protect its members against the promotional activities of those who might use the Yearbook for commercial advantage. The earnest coöperation of all members is therefore requested to prevent the use of this Yearbook for advertising or circularizing purposes. Any such action must be considered as outside of its field of application, and as absolutely prohibited.

Large Electrical Equipment Orders Placed

Following announcement that the electrification of the lines of the Pennsylvania Railroad from Wilmington, Del., to Washington, D. C., will be completed, contracts aggregating over $1,250,000 for major electrical equipment were let by the Safe Harbor Water Power Corporation and the Pennsylvania Water and Power Company. Power for the electrification from the Susquehanna River to Washington will be supplied by these 2 companies and by the Consolidated Gas Electric Light and Power Company of Baltimore, known as the Aldred group.

These equipment contracts were divided between the General Electric Company, the Westinghouse Electric and Manufacturing Company, and others. The equipment will be ready for delivery of power before the end of 1934.

The orders call for the delivery of the largest single-phase waterwheel generator ever built in this country. This generator which will have a capacity of about 31,700 kw, will be especially designed for railroad supply, and will be installed in the hydro-

Glareless Lights for St. Paul Airport

LIGHTING especially designed to eliminate stray vertical light which acts to obstruct an aviator's vision and impair his view of the landing field has been installed at Holman Field, the airport at St. Paul, Minn. The 3,000-watt floodlights used have 45 and 25 deg lenses. Three banks of 2 floodlights mounted on 28-ft platforms supported by pipe standards comprise the major part of the runway lighting. Two obstacle markers are mounted above each bank as a warning to low flying aircraft. Also, the hangar apron is lighted by 250-watt floodlights. The floodlighted apron is shown in this view, the lighted runway being in the distance. This equipment was manufactured by the Westinghouse Electric and Manufacturing Company.

electric plant at Safe Harbor. Included also in the contract is a frequency changer of approximately 26,000-kw rating. Transformers, substations, and transmission lines will be constructed by the power companies, and later, an additional power supply requiring an outlay of upwards of $1,000,000 will be provided by the Consolidated Gas Electric Light and Power Company. Exclusive of the contracts for electrical equipment recently placed, expenditures of the 3 power companies in connection with this electrification will be upwards of $4,000-000.

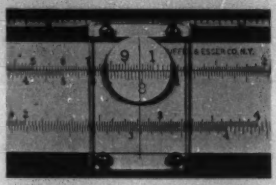
Future AIEE Meetings

North Eastern District meeting,
Worcester, Mass., May 16–18, 1934

Summer convention,
Hot Springs, Va., June 25–29, 1934

Pacific Coast convention,
Salt Lake City, Utah, Sept., 1934

New Slide Rule Magnifier



A small slide rule magnifier which incorporates certain advantages not available in other slide rule magnifiers has been patented by H. P. Clausen (A'03, M'03). This magnifier, being spherical in shape, with a flat bottom, magnifies the scale quite evenly and brightly in all directions. As there is very little distortion the magnifier does not need to be centered on the hair line. The magnifier is attached to the glass runner of the slide rule by suction and can be changed in position when desired. As it covers only one scale at a time, the other scale is left free for ordinary work. It magnifies the scale to about twice actual size. Further information can be obtained from R. D. Wadia, 15 Charlton Street, New York, N. Y.

Reports of Committee Meetings Held During Winter Convention

SEVERAL of the general and technical committees of the Institute held meetings during the recent winter convention at New York, N. Y., January 23–26, 1934. A summary of each of these meetings is given in the folowing paragraphs with the exception of the open meeting of the committees on education and Student Branches which was summarized in ELECTRICAL ENGINEERING for February 1934, p. 350, and the following committees for which no reports were made available for publication: research, general power applications, automatic stations, protective devices, production and application of light, and Sections, the sectional committee on electrical definitions, and the standards committee. Activities of the standards committee are reported month-by-month under the "Standards" department of ELECTRICAL ENGINEERING.

TECHNICAL PROGRAM

A part of the technical program commi tee meeting was devoted to the consideration of programs for the 1934 summer convention to be held in Hot Springs, Va., June 25–29, 1934, the Pacific Coast Convention to be held in Salt Lake City, September 1934, and the 1935 winter convention. The number of technical sessions for the summer convention program was limited to not more than 6, in order to allow ample time in the afternoons for sports, recreation, and other activities. The subjects which were tentatively suggested for the summer convention program are as follows: education, insulators, power generation, automatic stations, electrical machinery, electrical measurements, communication, and general power applications. For the Pacific Coast convention program members of the committee were asked for suggestions and a session on lightning was proposed. For the 1935 winter convention tentative plans are in progress for a symposium on recent vacuum tube developments and a session on illumination.

The methods of conducting some of the winter convention sessions were analyzed to gain the benefits from actual experience. The trial at the power transmission session to present papers by title only, in order to allow more time for discussion, was reported to have been very satisfactory. It also was suggested to be helpful if the presiding officers would ask for a showing of hands at the beginning of a meeting to determine the number of discussors and proportion the time accordingly. In general, it was believed that there should not be a fixed rule regarding the method of conduct of technical sessions but shorter presentations with the authors stressing the cardinal points in their papers and strict limitation of discussors to 5 min each seemed desirable.

Members of the committee were asked to expedite the early preparation of papers for the summer convention program. The editor also reported that many requests for the early publication of winter convention discussions had been received, and the members of the committee also were asked to complete the reviews of these discussions without delay. The committee voted to congratulate and thank the editorial department for their efforts in publishing in advance all winter convention papers.

COMMUNICATION

In line with views expressed at a recent meeting of the technical program committee to the effect that the Institute should give more attention to the subject of electronics, the committee on communication probably in coöperation with other interested committees, is tentatively planning to sponsor at the 1935 winter convention one or more sessions devoted to the subject of vacuum tubes. A considerable part of the discussion at the meeting of the committee was concerned with the plans being made for this program. The outlining of proposals for a group of papers dealing comprehensively with this subject is in the hands of a special subcommittee that has been formed for this purpose. The subcommittee has been asked to make its report and recommendations before the next meeting of the committee in March.

This subcommittee is also part of a group which is considering means of insuring adequate consideration of the subject of electronics in the technical programs of the Institute, including the desirability of a permanent technical committee on electronics. In this capacity the subcommittee is acting under the direction of the chairmen of the committees on electrophysics, electrical machinery, and communication to whom the job of recommending ways and means for most effectively handling the subject of electronics has been assigned by the technical program committee. There was an active discussion of this question at the communication committee meeting.

It was decided to request a session at the summer convention. For this session it is proposed to select the best from a number of papers which will be available at the time rather than to have a group of correlated papers or a symposium dealing with a single topic.

There was also discussion of a statement prepared at the request of the technical program committee outlining recommendations as to the scope of the committee's activities.

The annual report of the committee was discussed and each member was asked to prepare and send to the chairman a brief statement dealing with the technical advances made during the year in the branch of the communication art with which he is familiar. These statements are to be incorporated in a draft of a report to be circulated for comment.

ELECTRICAL MACHINERY

At a meeting of the electrical machinery committee reports of the subcommittees were read and a tentative list of papers for the summer convention at Hot Springs was approved.

A resolution was passed to recommend to the National Electrical Manufacturers Association that in drawing up the test code for induction motors, when tests for efficiency are to be required, the load losses be obtained by measurement and not to be included by an empirical factor.

It was reported that it was expected the final draft of the synchronous machine

test code was about ready for presentation to the standards committee and that the test code for d-c machines had been circulated to the members of the subcommittee for comments.

Electrochemistry and Electrometallurgy

At the meeting of the committee on electrochemistry and electrometallurgy, plans for continued activity in the line of meetings and papers were discussed. It was agreed to encourage papers relating to products of the electrochemical and electrometallurgical industries, especially those having application in the field of electrical engineering. The committee hopes to be able to present a symposium of such papers at a future meeting.

Discussion of the papers presented in the symposium on electric furnaces sponsored by this committee indicates the need for standardization of electric furnace ratings as well as a need for closer coöperation between electric furnace manufacturers, users, and power companies on the difficult problem of load characteristics and power rates. Among the future activities of this committee will be listed a consideration of these problems in coöperation with other committees interested.

Members of the committee expressed their commendation on the action of the board of directors in passing the resolution requesting adequate support for the standardization and research activities of the Bureau of Standards in the electrical field.

Power Generation

The items with which the committee on power generation were primarily concerned at their meeting were: first, the character of the committee report to be submitted at the summer convention; and, second, the survey of the field for available papers for publication in Electrical Engineering and for inclusion in the program for the summer convention.

With reference to the first, it was decided to follow the former procedure of the committee and prepare only on alternate years a comprehensive report covering the activities of the subjects within the scope of the committee. Since such a report was submitted and published last year it is expected that this year's report would not much more than cover the activities of the committee probably touching only the high spots of the past year.

With reference to the second subject, it was decided that the material prepared and submitted in tentative form by the subcommittee on water power survey would be reviewed by members of the committee with the thought of arranging for its presentation at the convention.

It was also decided to arrange for presentation at the same convention session a paper covering those problems which have become acute in the operation of large systems, such as the control of phase angle between bus sections and stations, load control, and the automatic control of frequency.

Other subjects for papers were discussed and capable authors suggested. These will be solicited to prepare papers for future publications.

Power Transmission and Distribution

The annual meeting of the committee on power transmission and distribution as a whole was held to receive reports of activities and plans from each of the subcommittees and to discuss the program for the annual convention at Hot Springs, Va., next June and the Pacific Coast convention at Salt Lake City in the fall.

The subcommittee on lightning and insulators reported progress on the standardization of preferred test waves and showed great progress in uniformity of impulse test results made by the various laboratories. Need for further 60-cycle test data was also mentioned as well as the need of more operating experience on lines protected by counterpoises, values of current in lightning strokes and the value of wood as an insulator. Sessions of 6 papers for the annual convention on insulators and 5 papers for the Pacific Coast convention on lightning were recommended.

The subcommittee on distribution reported that the main result of their work during the past year was the entire technical session held on January 25 on the subject of distribution, and distribution economics. More papers will be available on this subject and another session on the subject in the near future seems advisable.

The subcommittee on standards reported that their principal work has been in connection with the American Standards Association sectional committee on definitions. New definitions on grounding will be referred to the committee.

The subcommittee on cable developments reported that there has not been much activity in papers on underground cables, due primarily to the fact that there have been 2 recent sessions on cables.

The subcommittee on interconnection and stability factors reported that their activities had resulted in the 4 papers on stability presented on January 24 at the transmission session. There are numerous other papers on stability prepared or under preparation, but what is apparently needed at the present time is more information on actual operation, rather than on theory and calculation.

The subcommittee on steel towers and conductors is divided into 3 groups. Group I, which is concerned with towers, is studying the use of hinged and rigid crossarms, rotated towers and the applications of straight line compression formulas. Group II is studying clearances as effected by normal conditions of service, which involves the study of temperature rise of conductors from various causes. Group III reported on conductor studies, including numerous vibration studies; measurements of energy of vibration; whether the energy is consumed in the cable or the clamp; the question of pre-stretching of cables; correlating the available data on field vibration studies; the development of a vibration counter; laboratory methods of performing vibration and fatigue tests and improved terminal connections for such tests.

Transportation

At the meeting of the committee on transportation it was decided that a session would not be requested at the summer convention as papers in hand or in immediate prospect do not justify such a session.

The committee will, therefore, center its attention on developing papers for the winter meeting a year hence and papers

Generators for Boulder Dam Being Assembled

WORK on the 82,500-kva generators being built by the General Electric Company at Schenectady, N. Y., for installation at Boulder Dam, is in progress. The stator frame for one of these units, each of which will weigh more than 2,000 tons, is shown in process of assembly. As announced in a news item in Electrical Engineering for November 1933, p. 796–7, this unit is scheduled for completed installation early in 1935.

which might be available for this meeting were the chief topic of discussion.

Among the topics suggested for consideration was the possibility of securing reliable information on the amount of electric energy or steam required to heat passenger trains of various types under varying conditions of outside temperature and also variations in the amount of traction power required under varying conditions. Various railroads are to be canvassed to see whether a sufficient amount of information of this type can be secured to warrant preparation of a paper or a series of papers.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Public Versus Private Enterprise

To the Editor:

Referring to Private versus Public Enterprise (see ELECTRICAL ENGINEERING for April 1933, p. 234–7), Dr. Virgil Jordan's deductions rest upon 2 fundamental assumptions, with both of which the writer disagrees. The first is the doctrine of the profit motive, that worthy men will not exert themselves unless they profit with the correlary that those who profit are in the main at least those who benefit society. I suggest that anyone interested make out a list of say 100 of those who in his opinion have contributed in a large way to our civilization, the great musicians, artists, scientists, yes and engineers, and see how many of them were well rewarded and how many starved. Such a list will dispose quite effectively of the profit doctrine.

The other assumption is that our people are individualists. On the contrary our forte, I believe, is ability to organize as seen in our trusts and monopolies where it appears in its least desirable form. The masses in this country are, I believe, less given to individualistic thinking and action than in other first class nations. And that is where our greatest danger lies just now. A quarter of a century ago the man-in-the-street worshipped our millionaires and great executives, who had risen from nothing. This admiration was quite uncritical, but sincere. These demi-gods of 25 years ago have become today's "stuffed shirts," just as uncritically and sincerely. It is rather immaterial which valuation is the more correct, the danger lies in the inability and unwillingness of the masses to differentiate.

Secretary Wallace in a recent speech reported in *Science* (see also p. 395–402 this issue of ELECTRICAL ENGINEERING) criticized the engineers for their failure to take the existing social structure into account. I think he was right. In the richest country on earth we have one-fourth of our people suffering and in want. We may have the finest factories and the best machinery, but what of it? That is certainly not an aim in itself.

Professor Rautenstrauch has stressed the essential:

"The second principle is that the relative claim of labor and capital to the goods produced must be adjusted to workable proportions."

I believe it is the first principle also and the *sine qua non*. This is not brought measurably nearer by the engineering council's proposed 40 cents an hour minimum for engineers, as reported in the *New Republic* for January 24, 1934, p. 296.

Yours very truly,

B. F. JAKOBSEN (A '09, M '13)
(Consulting Engineer, Central Bldg., Los Angeles, Calif.)

A Theory Regarding Ionization in Cable Fibers

To the Editor:

No published explanation of the superiority of oil filled over solid type cables does justice to the facts. The usual explanation is that oil filled cable is always perfectly impregnated, whereas solid type cable can be perfectly impregnated only at or above a certain temperature. It is well known, however, to those who have done much experimental work with oil filled cables, that a rather poorly impregnated cable of this type is better able to withstand long application of high voltage than well-impregnated solid type cables. It is therefore obvious that the more constant impregnation of the oil filled cable is not the only factor in the relative lives of the 2 types.

At the time of the Chicago meeting of the A.I.E.E. in 1933, I offered the following theory:

"If there is any ionization of air in the channels of the paper fibers, it must be in the nature of longitudinal flow of ions, as there is not sufficient radial distance to permit ionization by collison. Here we may, perhaps, give in to the temptation of speculating on what may happen if air in a fiber becomes ionized. A stream of gaseous ions would shoot out of the ends of a fiber of paper into the oil and we may expect different effects according to circumstances. If the oil is in a thin film, as between tape faces, the ions will not get very far. If, however, the oil is in a tape edge channel, the gaseous ions have a considerable free path in which to move. If the oil is thin, these ions will be gradually retarded and absorbed by the oil. If, however, the oil is thick, the gaseous ions will be obstructed and hot spots will be developed. Perhaps a group of fibers shooting ions at one point in the oil may be necessary to start a destructive hot spot. This would explain why dendrite-forming hot spots practically always appear at the edges of tapes."

This material was edited out of my discussion [by technical reviewing committee—EDITOR] without my knowledge, but references to it (*e. g.*, Roper, A.I.E.E. TRANS., v. 52, 1933, p. 1,024) were allowed to remain. It has, therefore, seemed advisable to publish it in order to give some meaning to these references.

The above material, in quotation marks, should constitute a paragraph 20 lines from the bottom of the first column on p. 1,016 of the A.I.E.E. TRANS., v. 52, 1933.

This theory may seem somewhat speculative, but it is not entirely without experimental verification, as I hope to show on a more suitable occasion. Incidentally, if true, it would explain why, according to Dr. Whitehead's curves, it is immaterial what base oil is used in solid type cable, whereas in oil filled cable, the chemical base of the oil may have some significance. In the case of solid type cables, it is the consistency, more than the chemical nature of the oil that counts, whereas in oil filled cable, whatever deterioration may occur depends upon chemical instability under electric stress.

Yours very truly,

WM. A. DEL MAR (A'06, F'20)
(Chief Engineer, Habirshaw Cable and Wire Corp., Yonkers, N. Y.)

Improving A.I.E.E. Convention Sessions

To the Editor:

During the recent winter convention I had the good fortune to attend the session on education. All of the speakers talked very interestingly and loudly enough to be heard anywhere in the room. Each man who gave a discussion announced his name and college or company affiliation clearly. Consequently, I believe the session would have held the interest of any engineer who attended even if education were not his particular line.

On the other hand I found that the technical sessions were about the same this year as in previous years. The man who spoke in an interesting manner, loudly enough to be heard and who announced his name clearly, was obviously the exception rather than the rule. We all realize that engineers in general do not have the speaking opportunities or training which most educators have, but it is not the lack of a polished delivery which is felt by the average man who attends these conventions. It is rather the failure of the speaker to make any attempt to hold the interest of the audience and also his failure to speak so that he may be heard clearly.

Since the new arrangement whereby papers are printed in ELECTRICAL ENGINEERING before they are presented has gone into effect it is not necessary for a man to even try to present all the facts in the original paper. Consequently it would seem that a man in giving his presentation could prepare

an interesting statement of the purpose of his work, some high lights of what he has done and draw his conclusions without reading from his notes verbatim. Using the same line of reasoning a man who is interested enough in a subject to prepare a discussion should feel strongly enough to be able to present his discussion in an interesting manner.

Natural modesty probably prevents many a discussor from announcing his name in a loud voice. Therefore I believe it would be advisable for the chairman of a meeting to require that each man who gives a discussion should present a slip of paper on which are written his name and affiliation so that the chairman could announce clearly who was about to speak. Also, I believe that a body such as the A.I.E.E. should be able to provide a satisfactory public address system so that a man could easily present a paper or discussion in the auditorium and not have to worry about the acoustics at the same time.

If the convention sessions are for the purpose of allowing the experts to assemble and discuss their problems with each other, they are probably a success as they are conducted at present, although they would probably be more successful if conducted in a small room around a table. If the sessions are for us engineers who want to hear what the experts have to say I believe that they fail and I should like to make the following pleas:

To the Institute

1. That a good public address system be provided in the auditorium.
2. That the chairmen of meetings be instructed to conduct the meetings less informally, making sure that the audience knows who is talking.

To the Readers of Electrical Engineering Who Contemplate Presenting Papers or Discussions at Any Future Convention

1. That they be not satisfied to rise and read a mass of data or a tabulation of facts but to concentrate more on presenting the significance of the data or facts, stressing their relative importance and in general try to present the paper in the interesting manner that the usually very interesting subjects deserve.

Very truly yours,

James L. Holton (A'30)
(Division Engineer, N. Y. and Queens Elec. Lt. and Pwr. Co., Flushing, N. Y.)

[Editor's Note: There is a public address system in the auditorium. However, because some persons seem to object to it, it was not used during most of the convention sessions held in the auditorium.]

Graduate Engineering Study Remote From Industrial Centers

To the Editor:

As a former student of the plan of study initiated by B. G. Lamme, I read with interest the plan of work outlined in the paper "The Pitt-Westinghouse Graduate Program," by Prof. H. E. Dyche and Dr. R. E. Hellmund (see Electrical Engineering for January 1934, p. 103–8). It probably will be of interest to members of the Institute to outline a plan whereby corresponding advantages may be secured under special conditions with competent graduate students in colleges remote from industrial centers.

Early in 1931 a plan was worked out whereby 4 electric power companies in Oklahoma coöperated with the Oklahoma Agricultural Experiment Station in making a study of rural electrification in Oklahoma. An engineer was employed on a part time basis to carry out the project and write the report. In his spare time he was permitted to carry work leading to a master's degree. Under a suitable arrangement his final report was accepted as a thesis. It was published as Bulletin No. 207 of the Agricultural Experiment Station. The work was highly successful and received wide recognition.

In 1932 Bernard E. Lowe received the Institute's manuscript prize for the best Student Branch paper in the South West District with his paper entitled "Economics of Rural Line Distribution." This paper received recognition to a degree that it was possible to set up a so-called industrial fellowship, with one power company and the Agricultural and the Engineering Experiment Stations coöperating. The graduate program of study was carried out under the active supervision of power company engineers and college professors. The results were published as Bulletin No. 20 of the Oklahoma Agricultural and Mechanical College Engineering Experiment Station under the title "Rural Line Design Investigations."

Under the first plan the student, Earl R. Miller, spent 2 years in earning his master's degree while in the second case it required one school year. In the first case the student was paid for carrying out a project while permitted to earn his advanced degree; while in the second plan a fellowship was underwritten for the study of a field sufficiently comprehensive for a master's degree major.

In both cases the coöperating power companies received results that they were seeking, the college faculty had the stimulus of participation in active industrial problems, the engineering school students as a group absorbed some of the spirit that prevails when active projects are under way, and the holders of the 2 appointments received experience and did work much above that of the average master's degree student.

For this plan to be successful it requires special situations, competent students, suitable problems and willing coöperation of all concerned. Several smaller projects, encouraged in part by the first 2 larger setups, are now under way and the results seem promising to date.

Very truly yours,

A. Naeter (A'23, M'30)
(Head of Department of Electrical Engineering, Oklahoma Agricultural and Mechanical College, Stillwater)

Shunt Wound Neutralized Phase Advancer

To the Editor:

A brief introduction to this type of phase advancer was given in the author's contribution (see *I.E.E. Jl.*, 1931, p. 479–80, and *English Elec. Jl.*, 1929, v. 4, p. 186) to the discussion on "The Theory and Performance of Phase Advancers" (by Rudra and Walker) and the present article concerns itself with the theory of operation in greater detail.

Schmitz (see *E.T.Z.*, 1927, v. 49, p. 1,800 and *E.T.Z.*, 1028, v. 48, p. 1,739) has investigated the problem of the level and overcompensated shunt phase advancer and his solution of the latter type contains a cubic equation which, for practical purposes, is not capable of easy solution. His method of attack of the problem involved the use of trigonometrical equations, whereas the author's solution is arrived at by the use of the operator j, and straightforward algebra. A very simple method evaluating the rotor current at any given slip (except the special case of $S = 0$) both in the motoring and generating region is presented.

List of Symbols

s = fractional slip (+ indicates subsynchronous and − indicates supersynchronous)
E = standstill rotor voltage per phase (star)
X = total motor reactance referred to rotor per phase (star)
R_m = total secondary-circuit resistance per phase (star) of motor including brushes
R_a = resistance per phase (star) of the phase advancer commutating pole, compensating and armature windings, and brushes
A = electromotive force per phase (star) induced in armature per root mean square rotor amperes due to overcompensation of armature magnetomotive force
$K = \frac{I_{sh}}{\mathcal{E}}$
I_{sh} = shunt current, root mean square amperes
$\mathcal{E}$ = voltage induced in armature at above current per phase (star)
X_f = field reactance in ohms at full line frequency due to rise and collapse of main flux per pole
B = volts induced in field per root mean square rotor amperes due to over-compensation of armature magnetomotive force $= AKX_f s$
f = saturation factor $= \frac{b}{a}$ (see Fig. 1)
I_r = rotor current per phase (star) also the current per brush of advancer
Φ_0 = advancer flux per pole due to shunt current only
R_{sh} = resistance of each shunt field including regulation resistance

The shunt wound phase advancer is provided with commutating pole and compensating windings in addition to the shunt winding. The compensating winding

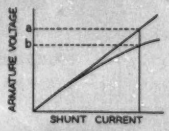


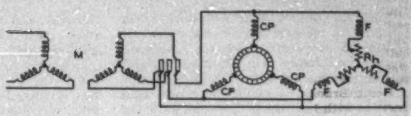
Fig. 1. The saturation factor, f, equals b divided by a

serves to neutralize the armature reaction and the commutating pole winding sets up an excess compensation which ensures good commutation. The armature reaction is thus not just neutralized, but actually overcompensation takes place. This sets up a field proportional to the armature current, and rotating at slip frequency, which induces a leading electromotive force in the armature if the advancer is driven against this field.

Furthermore, this "series" field interacts with the field due to the shunt current to set up a resultant field which determines the phase of the armature induced voltage.

Fig. 2. Diagram of connections

CP = compole and compensating windings
F = shunt fields
Rh = shunt rheostat
M = main slip ring motor



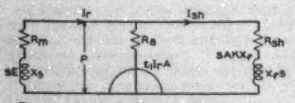


Fig. 3. Equivalent circuit diagram

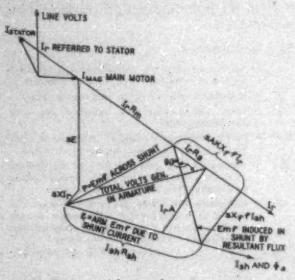


Fig. 4. Vector diagram

The diagram of connections is shown in Fig. 2. In Fig. 3 is shown the equivalent circuit diagram, everything being referred to per phase star. The vector diagram is shown in Fig. 4, in which the drop caused by the shunt current (which is only a fraction of the armature current) across the armature circuit is neglected.

We have

$$sE + \mathcal{E} = I_r[(R_m + R_a) + jXs - jAf] \quad (1)$$

$$P = sE - I_r(R_m + jXs)$$

$$= -\mathcal{E} - jAI_rf + I_rR_a \quad (2)$$

$$= -I_{sh}(R_s + jsX_{sf}) + I_rsAKX_{sf} \quad (3)$$

but

$$I_{sh} = \mathcal{E}\frac{K}{f}$$

From eq 2 and 3

$$\mathcal{E} = I_r\left[\frac{R_a - jAf - sAKX_{sf}}{1 - \frac{K}{f}(R_s + jsX_{sf})}\right]$$

Hence, from eq 1

$$I_r = \frac{sE}{R_m + R_a + jXs - jAf - \frac{R_a - jAf - sAKX_{sf}}{1 - \frac{K}{f}(R_{sh} + jsX_{sf})}} \quad (4)$$

For any slip or advancer field setting, we can calculate the magnitude and phase of the rotor current and by vector addition with the magnetizing current of the main motor obtain the stator or line current. If we open circuit the advancer field, R_{sh} becomes infinite and we obtain

$$I_r = \frac{sE}{R_m + R_a + jXs - jAf} \quad (5)$$

which will be readily recognized as the series or expedor advancer equation.

If the shunt advancer is level compensated, $A = 0$ and

$$I_r = \frac{sE}{R_m + R_a + jXs - \frac{R_a}{1 - \frac{K}{f}(R_{sh} + jsX_{sf})}} \quad (6)$$

Very truly yours,

R. D. Ball (A'31)
(Y.M.C.A., Forster Sq., Bradford, Eng.)

Applications of Nonlinear Circuits

To the Editor:

I have just read the article titled "Two Applications of Nonlinear Circuits" by T. M. Austin and F. W. Cooper, in the February 1933 issue of Electrical Engineering, p. 293–300. It appears to me that the writers have, in some portions of the paper, confused the saturable reactor control with straight resistance control through auxiliary transformers, and will attempt to justify my opinion by a few comments on individual points in the article.

Messrs. Austin and Cooper state that the decrease of primary impedance of a transformer with increase in secondary current is similar to the decrease with increase in primary current. It is true that there may be some saturation action of the secondary current, but, at least with alternating current in the secondary, the reduction in primary impedance is due simply to transformer action without saturation and occurs at any flux density. The 3-legged reactor shown in Fig. 1 of the article shows the a-c coils connected in series. Although such an arrangement is feasible, much superior operation results from connection of these windings in multiple; both improvement in magnitude of control and reduction of harmonics being achieved.

The scheme shown in Fig. 2 of the article is simply a series resistance adjustment, the 2-legged reactor illustrated acting as a transformer and the net being equivalent to placing a resistance proportional to R in the main line. With d-c supplied to the secondary, some saturation effect occurs but results are much poorer than with the usual 3-legged core: the control being less effective and harmonics being much more pronounced in the former case. In addition the induced a-c voltage in the secondary requires attention. Similar remarks may be made regarding the scheme shown in Fig. 5. Control in this case is wholly due to the negative resistance characteristic of the tube as used. The output is probably rich in second harmonic.

In Fig. 8, the windings indicated on the reactor make it the same as a regular 2-legged transformer instead of the usual 3-legged saturable reactor, and control is not by direct saturation, the main reactor, so called, being merely a series transformer with controlled secondary. The control in this case is very similar to that indicated in Fig. 5 and is subject to the same comments. The actual behavior of the circuit is considerably different from that indicated by the authors. The voltage on the plates of the tubes is not simply that due to the center tapped 220-volt transformer, but has, in addition, the induced voltage in winding B of the auxiliary reactor (or transformer) so that behavior is dependent upon the relative magnitude and phase of the 2 and hence on the power factor of the load.

I must also differ with the authors' statement that hunting is eliminated with these schemes since hunting can occur in purely electrical control schemes as well as with electromechanical arrangements. At no point do the authors indicate how the circuit has been made dead beat. It appears to me that the deciding factor as to hunting with the circuits shown is the characteristic of the load to changes in supply voltage.

Very truly yours,

Samuel Lubkin (A '31)
(Development Engineering, Otis Elevator Co., New York, N. Y.)

A Chart for Complex Quantities

To the Editor:

At the risk of tiring the readers of your correspondence column, I should like to add another item to the list of devices already described (see "Letters to the Editor," Electrical Engineering, August 1933, and subsequent issues) for computing the elements of right triangles. The present device is derived from a complex quantity slide rule utilizing logarithmic polar coordinates which I described in my discussion of Mr. Jesse DuMond's paper on "A Complex Quantity Slide Rule" (see A.I.E.E. Jl., v. 44, 1925, p. 627).

In its simplest form, diagrammatically indicated in Fig. 1, it consists of a chart

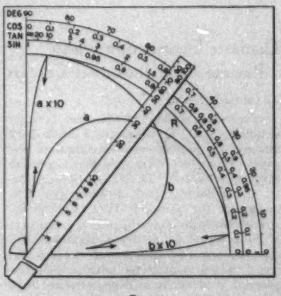


Fig. 1

carrying a knife edge pivot, and of a slide having a logarithmic scale, such as the slide of a discarded slide rule shaved down to a narrow edge, or a transparent rule having a logarithmic scale on its back. A quarter circle of arbitrary radius, designated by R, is drawn on the chart with the knife edge as center, and curves of $\rho = \log \cos \theta$ and $\rho = \log \sin \theta$ are drawn in polar coördinates, utilizing the horizontal radius as origin of angles and taking the circle instead of the center as origin of vectors. As sine and cosine functions are smaller than unity, their logarithms are negative and are therefore drawn radially inward from the circle instead of outwardly therefrom to form curves designated by a and b. The chart may also carry scales giving the value in degrees and the trigonometric functions of the angle comprised between the slide and the radius of reference.

As an example of the use of the chart, let the legs a and b of a right-angled triangle be given, and the length R of the hypothenuse, with the angle θ at the foot of the hypothenuse be required. The slide is moved against the knife edge so as to have the intersection of curve a with the slide read the value of a thereon, and the intersection of curve b with the slide read the value of b. The intersection of circle R with the slide will then occur at a point representing

$$\log a - \log \cos \theta = \log \frac{a}{\cos \theta}$$

and also

$$\log b - \log \sin \theta = \log \frac{b}{\sin \theta}$$

The length represented thereby is therefore:

$$\frac{a}{\cos \theta} = \frac{b}{\sin \theta} = \sqrt{a^2 + b^2} = R$$

the hypothenuse of the triangle. θ is the angle made by the slide and the reference radius. A single setting of the slide thus shows simultaneously all the elements of the triangle, so that any element can be found with the same setting when any 2 other elements are given. In the position shown in the figure, the slide indicates that in a right triangle having legs $a = 30$ and $b = 40$, the hypothenuse $R = \sqrt{a^2 + b^2} = 50$ while $\theta = 53$ deg 10 min, $\sin \theta = 0.8$ and $\cos \theta = 0.6$.

These readings are obtained by one setting without mental calculations, and the solution is clearly visualized as the slide and the reference radii form the same angles as the sides of the triangle. Reading the chart puts no strain on the eye as it carries only 2 curves of which the intersections with the slide stand out clearly. To conserve space the radius of circle R is chosen only slightly larger than one logarithmic unit, so that the portions of curves a and b corresponding to values of $\cos \theta$ and $\sin \theta$ comprised between 0.1 and 0.01 must be shifted radially by one logarithmic unit, and the readings on those portions must be divided by 10.

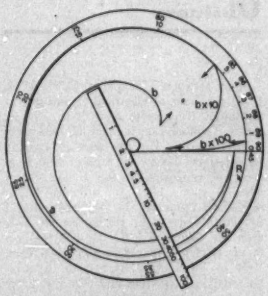


Fig. 2

In the chart illustrated in Fig. 1 the intersections of those portions of curves with the slide lack in precision, but they can be improved to any desired extent by increasing the angular scale of the chart. In the chart illustrated in Fig. 2 a complete circle represents 45 deg, and curves a and b are drawn for values of θ comprised between 0 and 45 deg. For values of θ comprised between 45 deg and 90 deg curves a and b are substituted for each other. To permit swinging the slide over a complete circle, the knife edge of Fig. 1 is replaced by a pin against which the slide is urged, so that the curves must be drawn in coördinates tangential to the pin instead of radially. As a result of the large scale of angles, it is possible to draw curves over a range of radii of 3 logarithmic units giving satisfactory intersections for angles of one degree and even less. Further improvement could be obtained by the use of a nonuniform angular scale varying according to a mathematical law, for example, logarithmically, or changing stepwise at suitable intervals.

Either form of chart illustrated could be converted into a fairly workable complex quantity slide rule by providing it with a pair of slides of transparent material arranged to slide side by side through a pivot member and with suitable radial and angular indicators.

Very truly yours,

D. Journeaux (A'27)
(Electrical Dept., Allis-Chalmers Mfg. Co., Milwaukee, Wis.)

Personal Items

L. B. Stillwell (A'92, M'92, F'12, member for life and past-president) consulting engineer, New York, N. Y., has been awarded the 1933 Lamme Medal of the A.I.E.E. The medal, which will be presented to Doctor Stillwell at the summer convention of the Institute to be held at Hot Springs, Va., June 25–29, 1934, was awarded him "for his distinguished career in connection with the design, installation, and operation of electrical machinery and equipment." Doctor Stillwell was born at Scranton, Pa., in 1863. He was a student in the Latin-scientific course at Wesleyan University, Middletown, Conn., 1882–4, and took a special course in electrical engineering at Lehigh University, Bethlehem, Pa. In 1885 he received the degree of electrical engineer from Lehigh University. He also has received the honorary degrees of master of science, Lehigh University, 1907; doctor of science, Wesleyan University, 1907; and doctor of science, Lehigh University, 1914. From 1886 to 1891, he was employed as assistant electrician of the Westinghouse Electric and Manufacturing Company, and served as chief electrical engineer of that company from 1891 to 1897. He was an outstanding leader in the development of alternating current, and invented the "Stillwell regulator" for the adjustment of voltage on outgoing lines. Two other inventions which he made and which today are more important, are the "time limit circuit breaker" and the "diagrammatic pilot-control switchboard." He had an active part in the determination of Westinghouse policy with respect to system development engineering and the establishment of 60 and 30 cycles as standard frequencies. His contributions, as Westinghouse engineer, to the general layout and design of the first plant of the Niagara Falls Power Company led to his appointment as electrical director of the latter company, which position he held from 1897 to 1900. Doctor Stillwell began his practice as a consulting engineer in New York City in 1900, and has filled engagements with many companies on large and important engineering projects, including: the electrification of the elevated lines of the Manhattan Elevated Railway Company, 1900–06; Rapid Transit Subway Construction Company, 1900–09; Wilkes-Barre and Hazleton Railway, 1902–05; Hudson and Manhattan Railroad, 1905–13; Erie Railroad electrification 1906; United Railways and Electric Company of Baltimore, Md., 1906–20; Interborough Rapid Transit Company, 1909–20; electrification of the Hoosac Tunnel of the New York, New Haven, and Hartford Railway Company, 1910–11; New York, Westchester, and Boston Railway Company, 1911–15; Lehigh Coal and Navigation Company, 1912–18; New York Municipal Railway Corporation,

L. B. STILLWELL

1913–16; board of economics and engineering of the National Association of Owners of Railroad Securities, 1921–22; Holland vehicular tunnel, 1924–27; and Port of New York Authority since 1927. Doctor Stillwell has served on many of the most important Institute committees, including the executive, code of principles of professional conduct, public policy (now Institute policy) Edison medal, standards, and board of examiners. He also has represented the Institute on the assembly of the American Engineering Council, the Engineering Foundation Board, John Fritz Medal board of award, and the coördination committee of engineering societies. He was a director of the Institute 1896–9, a vice-president 1899–1901, and the president 1909–10. He was vice-president of the American Engineering Council for 4 years, 1930–33 inclusive. He is the author of several important technical papers presented at Institute meetings and published in its TRANSACTIONS. In 1920, he was elected a trustee of Princeton University for life. He was a member of the board of directors of the Chamber of Commerce of the United States, 1921–23. His other memberships in leading engineering and scientific societies include: American Institute of Consulting Engineers, president 1918–19; American Society of Civil Engineers; Institution of Electrical Engineers, Great Britain; National Academy of Sciences; fellow, Royal Society of Arts, Great Britain; American Philosophical Society; and Franklin Institute. He was a member of the National Research Council during the World War. Among the clubs of which he is a member are the Century Association and the Union League Club of New York; Cosmos Club, Washington, D. C.; and Nassau Club, Princeton, N. J. He is a member of Alpha Delta Phi fraternity and of The Holland Society of New York. In 1899, Doctor Stillwell was awarded the Niagara Medal by the president of the Niagara Falls Power Company, Lord Kelvin being the only other electrician awarded this medal. In 1929 the American Society of Civil Engineers conferred upon him a medal "for leadership as chairman of Engineering Foundation in consolidating the research work of the Foundation and the Founder Societies."

A. E. ALLEN (A'06, M'13) vice-president, Westinghouse Lamp Company, New York, N.Y., has been elected vice-president of the Westinghouse Electric and Manufacturing Company, New York. Mr. Allen will have charge of the merchandising division which is now established as a separate operation distinct from other divisions of the company. He will have charge of all sales, manufacturing, and engineering activities of this new division. Mr. Allen has been with the Westinghouse company since 1902, first in the engineering division and afterward in the sales department of the electric company, until in 1925 he was made general manager of the lamp company, later becoming its vice-president.

JOHN WEST (A'10, M'28) who for the past 3 years has been manager of the northeastern district of the New England Power Association, with headquarters at Arlington, Mass., has been appointed district manager of a new grouping of the southeastern properties of the association, with headquarters at Fall River, Mass. He has been made president of the Fall River Electric Light Company in addition to having supervision over various utility properties of this group.

J. B. WHITEHEAD (A'00, M'08, F'12, life member, and president) dean, school of engineering, The Johns Hopkins University, Baltimore, Md., has been made an honorary member of the Société Française des Électriciens. On the occasion of the celebration of its fiftieth anniversary last month, the Société awarded this distinction to a prominent electrical engineer in each of the larger European countries, in Japan, and in the United States. Doctor Whitehead received the only award in this country.

F. E. HARRELL (A'26) has been made assistant chief engineer of the Reliance Electric and Engineering Company, Cleveland, Ohio, manufacturers of electric motors. Mr. Harrell joined the Reliance organization upon graduation from Purdue University in 1924. Following sales engineering work in Chicago he returned to Cleveland as special engineer for steel mill motor applications. He has since been chief draftsman and engineer in charge of a-c design.

E. G. FOX (A'12, M'20) has been elected vice-president of the Freyn Engineering Company, a firm of steel mill consulting engineers in Chicago, Ill. Since 1920 Mr. Fox has been power and electrical engineer of this company. As announced in ELECTRICAL ENGINEERING for October 1933, p. 729, he has been identified with the development of the steel industry in the Soviet Union for the past 5 years.

VICTOR SIEGFRIED (A'32) since August 1933 has been instructor in the department of electrical engineering at Worcester Polytechnic Institute, Worcester, Mass. Like his present superior, Prof. T. H. Morgan, Mr. Siegfried came to Worcester from Stanford University, Calif., where he had completed extensive graduate work.

H. D. JAMES (A'98, M'08, F'12) consulting control engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has recently opened an office in Pittsburgh as consulting engineer and industrial control specialist. Mr. James will continue to devote part of his time to the Westinghouse company.

F. M. FARMER (A'02, F'13) vice-president and chief engineer, Electrical Testing Laboratories, New York, N. Y. was elected vice-chairman of the Standards Council of the American Standards Association at its annual meeting held on December 12, 1933.

M. SPECTOR (A'25) formerly Assistant Examiner in the United States Patent Office, and for the last 6 years with Brown, Jackson, Boettcher & Dienner, Chicago, Ill., has opened an office for himself in Chicago, specializing in patents on electrical inventions.

E. A. BALDWIN (A'07), vice-president of the International General Electric Company at Paris, has been elected president of the American Chamber of Commerce in France. The Chamber, with a membership of 700, is 40 years old.

L. W. SMITH (A'22, M'28) formerly assistant electrical engineer with Sargent and Lundy, has recently been appointed district engineer in charge of the newly opened Chicago, Ill., office of the Doble Engineering Company.

B. C. J. WHEATLAKE (A'16) manager, General Electric Company, Salt Lake City, Utah, has been elected a director of the Electrical League of Utah for the present year.

C. A. WOLFROM (A'10) division manager, Utah Power and Light Company, Salt Lake City, has been elected a director of the Electrical League of Utah for the present year.

T. O. MOLONEY (A'12, M'21) president, Moloney Electric Company, St. Louis, Mo., has been elected to the board of directors of the General American Life Insurance Company of that city.

J. C. SMITH (A'03, F'12) president of the Montreal Tramways, and vice-president and general manager of the Shawinigan Water and Power Company, has been elected president of the latter company.

S. W. GREENLAND (A'11, M'17) manager for the receiver of the St. Louis (Mo.) Public Service Company, has been appointed vice-president and general manager of the People's Motor Bus Company.

S. B. WAY (A'03) president of The Milwaukee (Wis.) Electric Railway and Light Company, has been elected a director of the North American Company.

L. H. EGAN (A'08, M'15) president of the Union Electric Light and Power Company, St. Louis, Mo., has been elected a director of the North American Company.

Obituary

JOHN HAROLD MORECROFT (A'06, M'12, F'19) professor of electrical engineering at Columbia University, New York, N. Y., died in California on January 26, 1934, after a brief illness. He was born in 1881 at Barton-under Needwood, Staffordshire, England, but emigrated to the United States when a young boy. He attended public school at Syracuse, N. Y., and entered Syracuse University, graduating in 1904 with the degree of E.E. He was foreman in an electrical manufacturing shop from 1904 to 1905. He returned to Syracuse University as assistant and then instructor in both civil and electrical engineering, and

received the degree of B.S. in 1907. In the same year he became instructor in electrical engineering at Pratt Institute, Brooklyn, N. Y., in charge of the laboratories of the department of Applied Electricity. Beginning in 1907, Professor Morecroft began studying under Professor Michael I. Pupin and in 1908–09, he was university scholar in electrical engineering at Columbia University. In 1909 he became instructor in electrical engineering at Columbua University, where his promotion was rapid; in 1923 he was promoted to the rank of professor. During the World War he was employed by the U. S. Navy as a scientist in submarine defense, in which capacity he did much experimental work in this country and later worked in Europe in coöperation with the allied navies. In 1929 Professor Morecroft received the honorary degree of doctor of science from Syracuse University in recognition of many valuable contributions to the art of communication and particularly in the field of radio. He was a past-president of the Institute of Radio Engineers and served on many committees of both the I.R.E. and the A.I.E.E. He was also a member of Tau Beta Pi, Phi Beta Kappa, Sigma Xi, Epsilon Chi, the American Association for the Advancement of Science, and the Society for the Promotion of Engineering Education. Professor Morecroft was best known for his works on radio communication, his text on "Principles of Radio Communication," which first appeared in 1921, and as a third edition in 1933, was recognized the world over as the foremost authority on the subject. He also published books on electronics, electrical circuits, and machinery.

CYRIL FRANCIS MACKNESS (A'08, M'27) senior partner of the firm of Mackness and Shipley, consulting engineers, London, England, died December 17, 1933. He was born in 1872 at Broughty Ferry, Forfarshire, Scotland. He was educated at Heriot-Watt College, Edinburgh, and at Durham College of Science, Newcastle-on-Tyne. During 1898–99 he was in the drawing office of the Sunderland Forge and Engineering Company, Sunderland, England, and during 1899–03 was in the workshop and testing department of Bruce Peebles and Company, electrical engineers. During 1903–04 he was engaged on inspection for Carruthers and Elliot, Edinburgh, and during 1904–14 was manager and chief engineer of the Allgemeine Elek. Gesellschaft of Berlin, in London. During this same period he was, in 1909 and 1910, temporarily manager of the A.E.G. of South Africa, Johannesburg. During 1914 to 1920 he was manager and chief engineer of the electrical department of Vickers, Ltd., and during 1920 to 1924 was manager and chief engineer of the hydroelectric department of this same company. Since 1924 he has been a consulting and inspecting engineer on his own account. His firm carried out many important works for clients in England, the United States, Canada, and various European countries, including Germany, Austria, and Italy. He also undertook extensive work in South Africa and Australia. For the past 28 years he has been a member of the Institution of Electrical Engineers (England).

CARLETON WHITNEY SMITH (A'12, M'18) division engineer, Brooklyn Edison Company Brooklyn, N. Y., died January 16, 1934. He was born at Sommerville, Mass., in 1890. He graduated in both electrical and mechanical engineering at Lowell School, Massachusetts Institute of Technology, in 1911. During 1905–07 he was engaged as electrician in various electrical plants and during 1907–08 was assistant to J. S. Stone, consulting electrical engineer. During 1908–11 he was in the electrical engineering department of the Boston (Mass.) Elevated Railway Company. During 1911–13 he was electrical inspector for the Boston Board of Fire Underwriters, and consulting engineer to the Niagara Fire Underwriters Company and other organizations. During 1913–15, he was engaged on mechanical work in the development of manufacturing processes. During 1916–17 he was electrical engineer for the Honolulu Iron Works Company, New York, N. Y., in charge of the electrical engineering department. During 1917–19 he was senior lieutenant in the U. S. Navy. Here he had full responsibility for conducting an organization of 12 subordinate officers, 14 draftsmen, and 150 electricians, engaged on radio work. During 1920–23 he conducted an engineering and contracting business in and near New York City. In 1923 he became assistant engineer in the electric engineering department of the Brooklyn Edison Company. Here he was in charge of a section on station improvements and preliminary study, subsequently becoming division engineer.

JAMES G. FINDLEY (A'28) meter superintendent, and in charge of the service department, Washington Water Power Company, Spokane, Wash., died December 17, 1933. He was born in 1869 at East Pembroke, N. Y. In 1898 he graduated from the Vander Naillen School of Engineering. During 1899–1900 he was municipal burglar alarm operator at San Francisco, Calif., and during 1901–05 he was foreman of the meter department of the San Francisco Gas and Electric Company. During 1905–06 he was engaged on testing meters for the Oakland (Calif.) Gas, Light and Heat Company. In 1906 he transferred to the Washington Water Power Company, continuing as foreman of the meter department until 1920 when he became foreman of the meter and service department of this company.

CHARLES WELLS NITSCHKE (M'28) Denver plant superintendent for the Mountain States Telephone and Telegraph Company died January 23, 1934. He was born in 1883 in London, Ontario, Can. In 1898 he began a career which led to long and faithful service in the Mountain States Telephone and Telegraph Company at Denver. He started his work as a messenger boy in the Colorado Telephone Company, which company later merged and became a part of the Mountain States Telephone and Telegraph Company. Between the years of 1900 and 1912 he worked throughout the State of Colorado at various occupations from that of an installer, troubleman, lineman, foreman, combination man, and switchboardman, thus gaining an all-around knowledge and experience in his chosen work. In 1912 he was selected as district wire chief, with headquarters at Trinidad, Colo., and a year later was given the position of district plant chief, with headquarters at Grand Junction, Colo., which position he held until 1917, when he was transferred as acting plant superintendent in Denver during the war period. This position he held until 1919. His next advancement was that of District plant chief, with headquarters at Salt Lake City, Utah; a year later he was given the title of Utah plant chief, which position he held until 1921, when he was transferred to Denver as plant superintendent, which position he filled with credit until the time of his death. He was a charter member of the Telephone Pioneers of America.

Membership

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before March 31, 1934, or May 31, 1934, if the applicant resides outside of the United States or Canada.

Abrahams, N., 16 Jefferson St., New Haven, Conn.
Allen, E. C., Am. Tel. & Tel. Co., Denver, Colo.
Anderson, C. A. G., Detroit Edison Co., Mich.
Anderson, E. H., Simplex Elec. Co., Chicago, Ill.
Anderson, H. L., Narragansett Elec. Co., Providence, R. I.
Anderson, L. G., Indianapolis Rys., Ind.
Andis, M. G., Jr., Andis Clipper Co, Racine, Wis.
Angell, E. L., Narragansett Elec. Co., Providence, R. I.
Baker, E. F., Dodge Motor Car Co., Detroit, Mich.
Banta, L. V., McGraw-Hill Pub. Co., N. Y. City.
Barnett, E. E., Warner Bros. Studio, Burbank, Calif.
Bartholow, C. A., Jr., 26 W. Prentiss St., Iowa City, Iowa.
Bastedo, G. R., 102–36 86 Rd., Richmond Hill N. Y.
Battle, J. H., Memphis Pwr. & Lt. Co., Tenn.
Beck, G. R., C.W.A. Surveying, Mercersburg, Pa.
Belcher, A. B., Westinghouse Elec. & Mfg. Co., Springfield, Mass.
Bell, W. M., Box 994, Charlotte, N. C.
Bentley, A. T., British Col. Elec. Ry. Co., Ltd., Vancouver, B. C., Can.
Beyette, C. K., Texas Elec. Serv. Co., Fort Worth, Texas.
Bishop, LeR. D., C.W.A., Carlisle Barracks, Pa.
Black, F. S., Nantahala Pwr. & Lt. Co., Bryson City, N. C.
Blackburn, R. K., 600 Clinton Ave., Albany, N. Y.
Blickenstaff, I. C., The Chesapeake & Potomac Tel. Co. of Va., Richmond.
Block, I. D., Buffalo Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Blount, C. C., 509½ E. Walnut St., Cushing, Okla.
Boesch, A. J., Western Elec. Co., Phila., Pa.
Boughton, W. M., Western Union Tel. Co., Memphis, Tenn.
Bressler, H. E., N. J. Pwr. & Lt. Co., Dover.
Brownell, A. B., Commonwealth Edison Co., Chicago, Ill.
Bruhn, R. A., Electro-Dynamic Co., Bayonne, N. J.
Bryan, C. B., Ford Instr. Co., Inc., Long Island City, N. Y.
Burnett, J. H., Pub. Serv. Elec. & Gas Co., Newark, N. J.
Burns, J. F., 200 Lee Highway, Clarendon, Va.
Burr, K. E., 247 Elmwood Ave., Elmira Heights, N. Y.
Butler, A. G., Am. Concrete & Steel Pipe Co., Oakland, Calif.
Cahoon, E. F., 24 Milton Ave., Dorchester, Mass.
Campaigne, R. N., 78 Plymouth St., Montclair, N. J.

Capwell, R. I., 474 Fairview Ave., Anthony, R. I.
Carlson, R. C., Lock Box 88, Ludlow, Pa.
Carmody, J. F., Intl. Business Machines Corp., Endicott, N. Y.
Carns, W. L., 5112 Whitby Ave., Phila., Pa.
Carson, J., United Elec. Lt. Co., Springfield, Mass.
Carson, J., 402 Somerville Ave., Phila., Pa.
Cavela, F. C., 848 E. York Ave., West Chicago, Ill.
Clagett, J. L., Cincinnati & Suburban Bell Telephone Co., Norwood, Ohio.
Clagett, W. H., Jr., 124 Kellogg Ave., Kellogg, Idaho.
Clark, E. H., James Clark, Jr., Elec. Co., Louisville, Ky.
Clark, R. U., Magnavox Co., Ft. Wayne, Ind.
Coffman, B. S. (Member) Federal Pwr. Commission, Washington, D. C.
Colenda, S., C.W.A. Projects, Union City, N. J.
Collin, A. J., Montmagny Furniture Mfg. Co., Ltd., Montmagny, P. Q. Can.
Colpitts, A. L., Radisson, Wis.
Comer, W. F., Gen. Elec. Co., Bridgeport, Conn.
Coombs, W. C., Harrington, Wash.
Corrigan, D. J., Sunrise, Wyo.
Cree, J. G., Civil Works Project, Chambersburg, Pa.
Crein, C., 1000 Palms Camp, Indio, Calif.
Crick, R. W., 802 Grace Ave., Ft. Wayne, Ind.
Currie, A. A., Westinghouse Elec. & Mfg. Co., B. Pittsburgh, Pa.
Davies, P. T., Westinghouse Elec. & Mfg. Co., B. Pittsburgh, Pa.
Day, E. C., N. Y. Edison Co., N. Y. City.
Deise, L. F., 327 St. Paul Place, Baltimore, Md.
Detmers, F. H., 14542 Van Owen St., Van Nuys, Calif.
DiLello, P. J., 31 Hampton St., Albany, N. Y.
Dodge, C. M., Monterrey Ry. Lt. & Pwr. Co., Monterey, Mexico.
Dunlap, G. W., P. O. Box 36, Sonora, Calif.
Dunnington, W., Belle Alkali Co., Belle, W. Va.
Eddy, R. L., 188 Church St., Saratoga Springs, N. Y.
Ekstrom, I. R., Commonwealth Edison Co., Chicago, Ill.
Emanuel, V., 2330 Hillcrest Dr., Los Angeles, Calif.
Erikson, R., 1410 Farragut Ave., Chicago, Ill.
Evans, W. T., Texas Pwr. & Lt. Co., Trinidad.
Filion, O., 1227 N. Cass St., Milwaukee, Wis.
Fissell, J. A., Standard Elec. Inst. Lab., Kansas City, Mo.
Foster, J. I., Dept. of Utilities, Fremont, Neb.
Frazier, H. M., Pub. Works Administration, Fort Humphreys, Va.
Fredrickson, R. S., Deep Rock Oil Corp., Burlington, Wis.
Friebele, E. J., Kenyon Transformer Co., Inc., N. Y. City.
Fry, H. H., Assoc. Gas & Elec. Co., W. Reading, Pa.
Funk, R. J., Jr., C. M. Kemp Mfg. Co., Baltimore, Md.
Galiulo, F. L., N. Y. Edison Co., Bronx, N. Y.
Gama, P. J., North Seven St., Pearl, River, N. Y.
Gardner, J. E., U. S. Coast & Geodetic Survey, Ukiah, Calif.
Garrett, T. J., Jr., Harriet Cotton Mills, Henderson, N. C.
Gegenheimer, W. C., Westinghouse Lamp Co., Bloomfield, N. J.
Gess, M. M., Box 264, Dolton, Ill.
Gouse, H. H., Jr., Univ. of Tenn., Knoxville.
Graves, D. E., C.W.A., at Univ. of Wis., Madison.
Green, H. H., Jr., 1568 So. Fourth East, Salt Lake City, Utah.
Griesel, O. T., Odessa, Mo.
Guettler, R. O., Globe Union Mfg. Co., Milwaukee, Wis.
Hamm, J. E., Barboursville, Orange Co., Va.
Hanwick, T. J., Ford Instr. Co., Long Island City, N. Y.
Harper, J. D., Aluminum Co., of Am., Tapoco, N. C.
Hartman, W. R., Republic Steel Corp., Canton, Ohio.
Haworth, R. A., 114 E. Main, Madison, Wis.
Haynes, M. L., Balfour Tech. School, Regina, Sask., Can.
Hedley, J. B., West Kootenay Pwr. & Lt. Co., Ltd., South Slocan, B. C., Can.
Hegeman, G. D., Jr., Glen Head, L. I., N. Y.
Hegy, L., 70 B. So. 8th St., San Jose, Calif.
Heibel, J. D., 3302 Parade St., Erie, Pa.
Heinigle, O. H., Jr., 21 Winthrop St., New Britain, Conn.
Hejduk, A. A., Penn Evening Engg. Col., Cleveland, Ohio.
Herron, R. C., 901 40th St. Pl., Des Moines, Iowa.
Hess, E. F., Bklyn. Edison Co., Inc., Bklyn., N. Y.
Higgins, C. E., Box 45, Reader, W. Va.
Himes, C. F., Box 824, Hominy, Okla.
Hines, A. R., Gen. Elec. Co., Roanoke, Va.
Holmquist, R. H., Madison Gas & Elec. Co., Wis.
Huffman, E. W., Cunningham, Kans.
Hunt, R. W., Intl. Narrow Fabric Co., Keene, N. H.
Hunter, J. E., 372 Montford Ave., Asheville, N. C.
Ivaska, J. P., Mass. Highway Accident Survey, Boston, Mass.
James, L. I., 21 Emma St., Greer, S. C.
Johnson, M. D., Cabell Elec. Co., Jackson, Miss.
Johnson, R. B., U. S. Bureau of Reclamation, Denver, Colo.
Jones, M. P., Pollock Paper & Box Co., Dallas, Texas.
Karr, L. A., 733 Park Ave., E. Orange, N. J.
Kehoe, L. F., 860 15th St., La Salle, Ill.
Keller, B. H., 667 Jefferson Place, Bronx, N. Y.
Kirkpatrick, A. E., U. S. Bureau of Public Rds., Grangeville, Idaho.
Kisner, A. G., Gen. Elec. Co., Phila., Pa.
Knight, R. W., Stillwater Worsted Mills, Harrisville, R. I.
Kuehlthau, J. L., 384 Division St., West Bend, Wis.
Kunz, M. C., Weston Elec. Instr. Corp., Newark, N. J.
Kupka, A. J., 1115 So. 7th St., Minneapolis, Minn.
Kurman, H., 580 McAllister St., San Francisco, Calif.
Kyne, T., 107 Summit St., Norwich, Conn.
Lang, L. M., 47 Algonquin St., Providence, R. I.
Layton, J. W., Route 1, Osborne, Ohio.
Lefever, H. L., Armstrong Cork Co., Lancaster, Pa.
Leisure, E. C., 1017 Fairfield Ave., Ft. Wayne, Ind.
Lewis, C. H., Sesser, Ill.
Livingstone, J. T., Canadian Natl. Telegraphs, Winnipeg, Manitoba, Can.
Lomas, G. W., U. S. Coast & Geodetic Survey, Washington, D. C.
Lorensen, H., Western Sugar Refining Co., San Francisco, Calif.
Lowe, E. E., Continental Oil Co., Ponca City, Okla.
Lyshoj, G. J., Inter State Pwr Co., Clinton, Iowa.
MacKerr, M. M., Westinghouse Elec. Supply Co., Okla. City, Okla.
Magee, L., C.W.A. Project, Lubbock, Texas.
Magruder, S. H., 1517 Rhode Island St., Lawrence, Kans.
Martin, R. C., Crown Willamette Paper Co., Camas, Wash.
Matthews, W. J., Blackstone Valley Gas & Elec. Co., Pawtucket, R. I.
McBride, R. L., Canadian & Gen. Finance Co., Toronto, Ont., Can.
McCaa, J. R., 1130 Elm Ave., Lancaster, Pa.
McCann, H. J., N. A. Timmins Corp., Porcher Island, B. C., Can.
McKendry, V. J., Chrysler Corp., Detroit, Mich.
McLaughlin, T. F., 48 North Ave., Meriden, Conn.
McNabb, T., Wheeling Tile Co., Wheeling, W. Va.
McQueary, P. K., Texas-Louisiana Pwr. Co., Ft. Worth, Texas.
Meyer, P. C., Okonite-Callender Cable Co., Inc., Paterson, N. J.
Moody, H. H., 111 State Drive, Norman, Okla.
Moore, M. M., Clay Center, Neb.
Moore, R. R., 115 East Oak Ave., El Segundo, Calif.
Morgan, W. A., Metropolitan Water Dist. of So. Calif., Banning, Calif.
Morris, L. H., Jr., Richmond Dept. of Pub. Works, Va.
Munch, J. A., 247 River Ave., Lakewood, N. J.
Myers, A. F., Intl. Boundary Comm., Blaine, Wash.
Nelson, K. G., Michigan Bell Tel. Co., Houghton, Mich.
Newlon, A. R., U. S. Coast & Geodetic Survey, Washington, D. C.
Nixon, F. O., Box 115, West Summerland, B. C., Can.
Nord, G. L., 216 "J" St., La Porte, Indiana.
Olesinkof, F. J., Solar Mfg. Co., N. Y. City.
Ott, W. J., 3212 Decatur Ave., Bronx, N. Y.
Page, G. I., Southwestern Lt. & Pwr. Co., Lawton, Okla.
Page, H. H., 87 Gym, Rensselaer Poly. Inst., Troy, N. Y.
Painter, E. O., Duquesne Lt. Co., West Bridgewater, Pa.
Panzarella, M. A., 28 W. Main St., Falconer, N. Y.
Pearson, J. B., Oil Well Supply Co., Bradford, Pa.
Perkins, H. A., Jr., Fleetwings, Inc., Garden City, L. I., N. Y.
Perleberg, G. C., South St., Fort Lee, N. J.
Peterson, D. A., Radio Station KRLD, Dallas, Texas.
Pharo, E. W., Jr., High Pressure Pump Corp., Wilkes-Barre, Pa.
Philippi, C. L., Phila. Stor. Bat. Co., Pa.
Piper, W. A., Jr., C.W.A., Soil Erosion Project, Wauseka, Wis.
Pitts, W. L., Philco Radio & Television Co., Phila., Pa.
Pomeroy, K. L., North Carolina State Highway Comm., Elizabethtown, N. C.
Pratt, D., Radio Station WIBW, Topeka, Kansas.
Pretty, H. E., Okla. Gas & Elec. Co., Shawnee.
Price, W. K., 20 Washington Place, Newark, N. J.
Prieskorn, R. E., 710 Central Ave., Fort Dodge, Iowa.
Pringle, R. B., 53 West 150 St., Harvey, Ill.
Quick, C. R., Detroit Edison Co., Monroe, Mich.
Rader, L. T., Canadian Elec. Mfg. Co., Vancouver, B. C., Can.
Renton, W. B., 1137 Howard Ave., Utica, N. Y.
Reuss, W. H., Pub. Serv. Comm. of Wis., Madison.
Reynolds, J. H., Jr., Westinghouse Elec. Supply Co., Jacksonville, Fla.
Richardson, W., 1864 E. 71 St., Cleveland, Ohio.
Rigling, V. F., 137 Market St., New Cumberland, Pa.
Riner, W. B., U. S. Engrs. Depot, Sayler Park, Cincinnati, Ohio.
Roberts, F. A., 501 S. Main St., Monticello, Ind.
Roberts, O. W., Albany, Wis.
Rogers, J. V., R. M. D., 3, Cianford Ave., Victoria, B. C., Can.
Rohkohl, O. W., 7237 S. Oakley Ave., Chicago, Ill.
Rosenzweig, J., 335 Second Ave., Kingston, N. Y.
Ross, P. M., Frigidaire Corp., Dayton, Ohio.
Rotrosl, J., Logansport Machine Co., Logansport, Ind.
Roy, W. H., Pacific Can Co., San Francisco, Calif.
Rudd, W. C., N. Y. Edison Co., Bronx, N. Y.
Sanchez, J. R., Sria de Comunicaciones Mexico, D. F., Mexico.
Sander, M., 2647 E. Clearfield St., Phila., Pa.
Sandretto, E. D., Clough-Brengle Co., Chicago, Ill.
Schmidt, G. F., 731 State St., Madison, Wis.
Schneider, H. C., Nestle's Milk Products Co., Marysville, Ohio.
Schneider, V. W., 1423 5th Ave., So. Fargo, N. D.
Schroeder, H. E., 206 Hillside Ave., Glen Ridge, N. J.
Schwehr, L. J., Sanborn, N. D.
Seigfreid, C. R., W. G. Shelton Co., St. Louis, Mo.
Sfat, P., 829 St. Clair Rd., Grosse Pointe, Mich.
Shaad, P., Gen. Elec. Co., Schenectady, N. Y.
Shallcross, G. P., 4713 Pensacola Ave., Chicago, Ill.
Shields, C. I., 704 Remington St., Ft. Collins, Colo.
Skaff, F. S., E. I. du Pont de Nemours Corp., Charleston, W. Va.
Slay, W. B., 215 W. Georgetown St., Crystal Springs, Miss.
Sorenson, L. M., U. S. Coast & Geodetic Survey, Beloit, Wis.
Stelzer, W. A., 108 E. Jefferson St., Brooksville, Fla.
Stevens, T. E., Budd Mfg. Co., Phila., Pa.
Stringham, L. K., Lincoln Elec. Co., Cleveland, Ohio.
Sugden, A. C., 1418 Union St., Schenectady, N. Y.
Sullivan, S. A., Jerome, Idaho.
Sweetman, J. G., N. Y. Edison Co., N. Y. City.
Tamm, E. S., 1413 Carr Ave., Memphis, Tenn.
Taylor, R. L., U. S. Dept. of Commerce, Cheyenne, Wyo.
Thomas, G. J., Paramount Studios, Hollywood, Calif.
Thomas, S. O., 413 S. Market St., Troy, Ohio.
Tolentino, J. G., 3721 N. Cicero Ave., Chicago, Ill.
Trevor, J. B., Jr., 11 East 91 St., N. Y. City.
Trimble, R. M., 618 Herndon Ave., Shreveport, La.
Trussler, L. C., Am. Tel. & Tel. Co., Denver, Colo.
Tyler, G. F., Phila. Elec. Co., Pa.
Uffelman, W. R., Goodyear Tire & Rubber Co., Akron, Ohio.
Ulrich, G. H., Jr., Armstrong Cork Co., Lancaster, Pa.
Underhill, D. P., Gen. Elec. Co., Minneapolis, Minn.
Unger, S., Eagle Elec. Mfg. Co., Bklyn., N. Y.
Veno, M. R., 12 Second St., Attleboro, Mass.
Wages, R. W., U. S. Coast & Geodetic Survey, Auburn, Ala.
Walter, J. S., Stanco Distributors, Inc., N. Y. City.
Walton, J. H., 115 Ogden Ave., Swarthmore, Pa.
Ward, R. DeW., Am. Model R. R. Co., New Rochelle, N. Y.
Wasson, L. C., Tucker Duck & Rubber Co., Ft. Smith, Ark.
Watkins, R. V., 1005 S. 22 St., Columbus, Ohio.
Wesner, C. T., Standard Oil Co., Inc., Sugar Creek, Mo.
Westby, S. B., Commonwealth Edison Co., Chicago, Ill.
Wight, O. M., Gen. Elec. Co., Schenectady, N. Y.
Wille, C. L., Jr., U. S. Coast & Geodetic Survey, Falfurrias, Texas.
Wilson, E. C., 504 E. Church St., Marion, Ohio.
Wiltshire, G. W., D. L. & W. R. R., Scranton, Pa.
Wing, A. H., Jr., Col. of the City of N. Y., N. Y. City.
Winn, W. P., Metropolitan Water Dist. of So. Calif., Los Angeles, Calif.
Wisedell, D. E., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Wood, J. P., Cornell Univ., Ithaca, N. Y.
Woodsell, S. R., 21 Fairfax Pl., Clarendon, Va.
Woolman, S., 112 First St., Troy, N. Y.
Zane, R. B., The Okonite Co., Passaic, N. J.
Zeffren, H. E., Wagner Elec. Corp., St. Louis, Mo.
Zillafro, J. A., Messer Oil Corp., Olean, N. Y.

256 Domestic

Foreign

Appasamy, C. S., 51 Barton St., Kensington W.14, London, Eng.
Arias, J. L., Porto Rico Railway Lt. & Pwr. Co., Comerio, P. R.
Cage, A. O., Jr., South Porto Rico Sugar Co., of P. R., Ensenada, P. R.
Chawla, S. H. (Member), Sugar Factory, Mansurpur Dist., Muzarernagar, India.
Engineer, K. P., Municipal Pwr. House Sukkur, Sind, India.
Patel, P. V., Sunav, Via Anand, India.
Samson, I. H., 1443 Webb Rd., Cincinnatus Town, Karachi, India.
Stanbridge, C. H. (Member), P. O. Box 1230, Cape Town, South Africa.
Visvanathan, M. S., ASEA, Vasteras, Sweden.
Wang, K. S., Chekiang Univ., Hangchow, Chekiang Province, China.
Yakovlev, V. M., Moscow Elec. Pwr. Lt. Co., Moscow, U. S. S. R.

11 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these

addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Darcy, Harris B., 305 M. & M. Bldg., Houston, Texas.

Dean, George H., Corris, Old Shoreham Road, Shoreham-by-Sea, Eng.

Gentilini, Celso, 1512 Wood St., Wilkinsburg, Pa.

Griffith, Geo. M., R. no. 1, Tucker, Ga.

How, John H., 42 Wal Di Road East, Canton, China.

Lober, Charles, K. C. P. & L. Co., 1330 Baltimore Ave., Kansas City, Mo.

Mathisen, Karsten V., 912 Noyes St., Evanston, Ill.

Panton, H. D., Phoenix Utility Co., c/o Kansas Gas & Elec. Co., Wichita, Kans.

Shifrin, Leonard I., c/o Tanenbaum, 12 Pinehurst Ave., New York City.

Soskin, Samuel B., 1235 S. Calif. Ave., Chicago, Ill.

Sparks, Losey D., 1507 Sherwin Ave., Chicago, Ill.

Talbot, H. L., 55 Pine Ave. E., Montreal, Que., Can.

Whittemore, J. D., 126 State St., Albany, N. Y.

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, during January are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface or text of the book in question.

INVENTIONS, PATENTS and TRADE-MARKS, Their Protection and Promotion. By M. Wright. 2 ed. N. Y. and Lond., McGraw-Hill Book Co., 1933. 310 p., 8 x 6 in., cloth, $2.50. Tells how to choose a patent attorney, what patent-office procedure is, and how to estimate the value of a patent. Methods of disposing of patents are described, the relations of inventor and employer are discussed, and various traps set for patentees are noted.

LEITFADEN der ELEKTROTECHNIK, Band 1, Teil 1 and 2. Grundlagen des Gleich- und Wechselstromes. By F. Moeller and G. Bolz. Leipzig and Berlin, B. G. Teubner, 1933. 94 p., illus., 10 x 6 in., cloth, 9.60 rm. An introductory presentation of the fundamentals of electrical engineering, intended for students of other branches of engineering as well as for those who intend to specialize in this field. Graphic methods are used extensively and calculus is seldom used. Three-color diagrams are employed for greater clarity.

ROHRHYDRAULIK, Allgemeine Grundlagen, Forschung, Praktische Berechnung und Ausführung von Rohrleitungen. By H. Richter. Berlin, Julius Springer, 1934. 256 p., illus., 10 x 6 in., cloth, 22.50 rm. This monograph aims to present a practical summary of all the available information upon the flow of fluids in pipes which is of practical usefulness.

THÉORIE de la TRANSMISSION TÉLÉPHONIQUE. By M. G. Valensi. Paris, Librairie de l'Enseignement Technique, Léon Eyrolles, 1933. 626 p., illus., 10 x 7 in., paper, 80 frs. This textbook on the theory of telephonic transmission presents the course given at the Ecole Professionnelle Supérieure des Postes et Télégraphes at Paris. It supplies a summary of the subject, using only simple mathematics. The review covers both wire and radio circuits for transmitting music and for television.

TRADE ASSOCIATIONS, Management Policies, Organization, Personnel, Services. By W. J. Donald. N. Y. and Lond., McGraw-Hill Book Co., 1933. 437 p., 9 x 6 in., cloth, $4.00. The organization, management, and operation of trade associations are discussed in a practical way by an experienced executive. The business man is told how an association may be organized, what it can do, and what it may achieve; and the executive of an association is advised about his duties and their execution.

Der WÄRME- und STOFFAUSTAUSCH dargestellt im Molierschen Zustandsdiagramm für Zweistoffgemische. By A. Busemann. Berlin, Julius Springer, 1933. 75 p., illus., 10 x 6 in., paper, 6 rm. By introducing a new concept, "exchange flow," which includes radiation, diffusion, and convection, the author shows how the problems of heat exchange may be solved more easily and exactly than heretofore. The new factor may be introduced into the Mollier phase diagram for mixtures of 2 components, and is accurate for both laminar and turbulent flow.

JAHRESBERICHT 1932 DER ABTEILUNG für ELEKTROTECHNIK und FUNKWESEN der DVL. (Sonderdruck aus dem Jahrbuch 1932 der Deutschen Versuchsanstalt für Luftfahrt, E. V., Berlin-Adlershof). By H. Fassbender. Munich and Berlin, R. Oldenbourg, 1933. 96 p., illus., 12x8 in., paper, 6.75 rm. The papers presented at the annual meeting for 1932 of the electrical and radio section of the German Aviation Research Laboratory are here reprinted from the 1932 yearbook of the laboratory. Eleven papers are given, discussing various problems connected with airplane radio equipment, engine ignition, etc.

Aus der WIEGE des ELEKTRISCHEN TELEGRAPHEN (Deutsches Museum Abhandlungen und Berichte, Jg. 5, Heft 5). By R. Geyerabend. Berlin, VDI-Verlag, 1933. 143–174 p., illus., 8x6 in., paper, 90 rm. This essay discusses briefly early attempts at electric telegraphy, beginning with Soemmering's experiments and ending with Morse's invention. The account is illustrated from early apparatus preserved in the Deutsches Museum and is issued to commemorate the centenary of the Gauss-Weber needle telegraph, erected at Göttingen in 1833.

COST AND PRODUCTION HANDBOOK. Edited by L. P. Alford and a board of 80 authorities. N. Y. Ronald Press Co., 1933. 1600 p., illus., 5x7½ in., cloth, $7.50. Designed to give practical working information on cost and production problems to all engaged in manufacturing, whether in shop or office position, coördinated and organized to apply under present conditions; covers all the more important activities of industrial operation. (A.I.E.E.)

A T M—Archiv für technisches Messen. Nos. 27–30, Sept.–Dec. 1933. Munich and Berlin, R. Oldenbourg, p. 125–170, illus., 12x8 in., paper, 15 rm. each no. This work, which appears serially, is intended to form an encyclopedia of measuring instruments and methods used in engineering. Brief articles by specialists are included, and new instruments are described by the manufacturers. The material is so arranged that it may be placed in loose-leaf binders.

Book of A.S.T.M. TENTATIVE STANDARDS, 1933. Phila., Am. Soc. for Testing Materials, 1933. 1136 p., illus., 9x6 in., paper, $7.00; cloth, $8.00. This annual publication contains all the specifications, methods of test and definitions of terms which the Society has approved tentatively, but has not adopted as standards. They thus represent the latest ideas on subjects not yet standardized. 223 tentative standards are given, of which 47 are new and 41 newly revised.

CHEMICAL PATENTS INDEX, 1915–1924. Vol. 4, Subject Index, M-R. By E. C. Worden. N. Y., Chem. Cat. Co., 1934. 1132 p., 10x7 in., cloth, $25.00. This index covers the patents issued by the U. S. during 1915–24 which relate to chemical technology. The present volume covers the letters M to R. Over 6,000 references to "oil" are given; nearly 5,000 to "paper," and almost 3,000 to "nickel."

COURANTS de COURT-CIRCUIT. (Mises au Point Electrotechniques.) By J. Fallou. Paris, J. B. Baillière et Fils, 1933. 180 p., illus., 7x5 in., cloth, 27 frs. This brief monograph is intended as an introduction to the study of short-circuit phenomena in transmission systems. The calculation of short-circuit currents, the impedances of the various elements of a transmission system, and methods for the control of short-circuits in high-voltage lines are discussed concisely.

COURANTS de FOUCAULT. (Mises au Point Electrotechniques.) By P. Bunet. Paris, J. B. Baillière et Fils, 1933. 180 p., illus., 7x5 in., leather, 25 frs. This work, sponsored by the French Society of Electricians, affords a convenient summary of the widely scattered literature upon eddy currents. The various phenomena are discussed in a uniform manner, with special attention to practical details which will assist in the calculation of losses in circuits. Numerous numerical applications are given.

DEUTSCH-ENGLISCHES FACHWÖRTERBUCH der METALLURGIE (Eisen- und Metallhüttenkunde). Pt. 1, Deutsch-Englisch. Edit. by H. Freeman. Leipzig, Otto Spamer Verlag, 1933. 327 p., 7x5 in., leather, 25 rm. A dictionary for the reader of German metallurgical writings. Over 33,000 terms are included, with accurate English equivalents. The vocabulary includes terms in mechanical and electrical engineering, chemistry and physics, as well as metallurgy. The book is small enough for the pocket, and the print is legible, though small.

DIFFERENTIAL EQUATIONS. By L. R. Ford. N. Y. and Lond., McGraw-Hill Book Co., 1933. 263 p., illus., 9x6 in., cloth, $2.50. A course in the subject which can be covered in a year by a class of ordinary ability. In the introductory part of the presentation the geometrical and intuitive aspects of the subject are emphasized. Succeeding the rigorous method of approach is presented. A feature is a chapter on interpolation and numerical integration.

(The) DISCOVERY of the ELEMENTS. Collected Reprints of a Series of Articles Published in the Jl. of Chem. Education. By M. E. Weeks. Easton, Pa., Jl. of Chem. Education (Mack Printing Co.), 1933. 363 p., illus., 9x6 in., cloth, $2.00. A narrative of the discovery of the chemical elements. Bibliographies are included in each chapter and there is a useful chronological table. A valuable history of the subject.

DYNAMICS OF EARTHQUAKE RESISTANT STRUCTURES. By J. J. Crezkoff. N. Y. and Lond., McGraw-Hill Book Co., 1934. 127 p., illus., 9x6 in., cloth, $2.50. The problem of designing structures that are resistant to earthquakes is primarily a dynamic rather than a static one. In this treatise dynamic methods are applied and formulae developed which make possible the design of aseismic buildings at costs but slightly above those of ordinary structures.

ELECTRIC METERS. By R. R. Ranson. Chicago, Am. Tech. Soc., 1934. illus., 9x6 in., cloth, $2.00. An elementary text intended to give the reader a working knowledge of electric meters. The principles underlying the design of the various types, and the way in which each operates are explained. The uses are described and instruction given in caring for them.

ELEMENTS of HYDRAULIC POWER GENERATION. By A. M. Greene, Jr. N. Y., John Wiley & Sons, 1934. 58 p., illus., 9x6 in., paper, $1.00. A brief exposition of the apparatus used to develop hydraulic power. The uses, limitations, and names of the modern forms of hydraulic machinery are presented.

GREAT BRITAIN. Dept. of Scientific and Industrial Research. FOOD INVESTIGATION Special Report No. 8. MEASUREMENT of HUMIDITY in CLOSED SPACES. Lond., His Majesty's Stationery Office, 1933. 70 p., illus., 10x8 in., paper, 1s 6d. (Can be obtained from British Library of Information, New York, $.50.) Devoted largely to experiments with hygrometers, undertaken primarily to ascertain their reliability as measures of humidity. The existing types are discussed in detail. A brief discussion of methods of air-conditioning is included.

GREAT BRITAIN. Dept. of Scientific and Industrial Research. REPORT of the FUEL RESEARCH BOARD for the Year ended March 31, 1933 with Report of the Director of Fuel Research. Lond., His Majesty's Stationery Office, 1933. 140 p., illus., 10x6 in., paper, 2s 6d. (Obtainable from British Library of Information, N. Y., $.77.) Among the lines along which progress is reported are the cleaning of fine coal, carbonization and gasification processes, hydrogenation of tar and coal, firing of pulverised fuel, and various minor problems of fuel utilization.

(The) GREAT LAKES—ST. LAWRENCE DEEP WATERWAY to the SEA. By T. Ireland. N. Y. and Lond., G. P. Putnam's Sons, 1934. 223 p., illus., 8x5 in., cloth, $2.00. The effect of the waterway upon shipping rates and upon railways, its cost, the arguments for and against the project, its probable use and other questions are discussed in this volume. The author is an ardent advocate of the plan.

Engineering Societies Library

29 West 39th Street, New York, N.Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

Allis-Chalmers District Office Moved.—The Buffalo district office of Allis-Chalmers Mfg. Co. was moved to the Liberty Bank Building on February 24. A. D. Brown is district manager in charge.

Simplex Wire Co. Elects Officers.—At its annual meeting on February 19 the Simplex Wire and Cable Co. elected the following officers: president and treasurer, Henry A. Morss; vice-presidents, Philip R. Morss, Everett Morss, Jr., Charles R. Boggs; assistant treasurer, J. Arthur Gibson. Mr. Boggs was also elected a director.

Penn. R.R. Electrification Resumed.—Actual construction on Pennsylvania Railroad's $77,000,000 electrification and equipment project, financed by the Public Works Administration, is now under way. Present plans call for the employment of steadily increasing forces on the project, reaching a total of more than 6,000 men in the entire territory between New York, Trenton, Philadelphia, Baltimore, and Washington when the work gathers headway. In addition to the erection of steel supports and the catenary wire system over 108 miles of route between Wilmington and Washington, in seven great freight yards and on several branch lines, comprising 646 miles of track, the comprehensive project involves reconstruction of bridges, the rearrangement and relocation of signals and telegraph and telephone lines, lowering of station tracks and platforms, the rearrangement of certain trackage and the construction of 16 new substations and additions to 18 existing substations. Over a year will be required to complete the work, which will make possible the inauguration by the Pennsylvania in 1935 of through electrified service, both passenger and freight, between New York, Philadelphia, and Washington. The cost of this portion of the railroad's improvement program, financed by the Government is $45,000,000.

Electric Erasing Machine.—A new electric erasing machine, combining unusual lightness and compactness with high efficiency and durability, is announced by the Charles Bruning Company, Inc., New York and Chicago. The new device which is being marketed at a low price, is designed to be held in the fingers like a pencil, enabling the operator to maintain accurate finger control when erasing pen or pencil lines from tracings or drawings. It is operated by a small motor. A complete assortment of pen and pencil erasers accompanies the equipment.

A New Oil Insulation.—A new type of insulating material, known as Harvel Oil Stop, is announced by the Irvington Varnish & Insulator Co. of Irvington, N. J. It is a viscous, non-drying oil which is applied in the form of a liquid and then "sets" in location, even in the absence of air, to form a firm rubber-like structure which is not affected by oil or strong solutions of either acid or alkali, and is waterproof and weatherproof. Heat will not soften it but only hastens its reaction to a rubber-like solid. Oil Stop does not contain any solvents and adheres to rubber, varnished cambric, oil impregnated paper, and copper. These qualities, in addition to its excellent electrical properties, are said to make it particularly suitable for use in all types of cable splices and cable terminals and particularly for splicing oil impregnated paper insulated cables to rubber insulated cables.

G-E Impulse Circuit Breaker.—A new high voltage, large capacity oil circuit breaker, containing many unusual and new features, has been announced by the General Electric Co. Radically different in design, each single-pole unit of the new breaker is shaped like a cross in contrast to the tanklike construction of conventional equipment. Higher breaking speeds with short arcing times and the use of very little oil are among the distinct advantages offered by the new equipment. Only 96 gallons of oil per pole are required by a breaker with an interrupting rating of 1,500,000 kva at 138 kv compared with approximately 1700 gallons per pole for a conventional breaker of an equivalent interrupting rating. Horizontal containers, not much larger than conventional bushings, enclose the interrupting mechanisms. These containers are mounted on vertical central supports which, in addition to serving in an insulating capacity, also house current transformers when such equipment is required. The operating mechanism is located in the base of each single-pole unit and an insulated operating rod passes up through the central support to the container. The interrupting elements consist of several sets of contacts in a line and the inside of each container is so arranged that oil, driven by a piston, is positively directed across the arc path of each of the several arc breaks per pole during circuit interruption.

Trade Literature

Magnet Wire.—Catalog, 32 pp. Describes various types of magnet wire; includes comprehensive tables. General Cable Corp., 420 Lexington Ave., New York.

Ventilating Fans.—Bulletin, 30 pp., "Sensible Ventilation." Illustrates a wide variety of propeller fans and numerous, typical installations. Ilg Electric Ventilating Co., 2850 N. Crawford Ave., Chicago.

Relays.—Catalog. The regular standard line of Dunco relays, and many other types of units are described, as well as special thermostats, electric counters, etc. Struthers Dunn, Inc., 139 N. Juniper St., Philadelphia.

Texrope Drive Sheaves.—Bulletin 2134-A, 4 pp., gives engineering data, such as sheave diameters, number of grooves, bores and other dimensions on Texsteel sheaves for Texrope drives. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Fire Extinguishing Apparatus.—Bulletin, 12 pp. Describes Du Gas dry chemical fire extinguishing apparatus, appliances and systems, applicable to electrical machinery in central stations and substations. Garrison Engineering Corp., 307 Fifth Ave., New York.

Circuit Breakers.—Catalog 33-200, 36 pp. Describes a complete line of small oil circuit breakers, up to 50,000 kva, including tables giving the proper type of breaker for any indoor, outdoor, or subway requirement. Westinghouse Electric & Mfg. Co., East Pittsburgh.

Self-Tapping Screws and Fastenings.—Catalog 4, 34 pp. Describes labor-saving fastening devices such as self-tapping and drive screws for making fastenings to sheet metal, castings, Bakelite, slate, ebony, asbestos, etc. Applications in electrical and allied manufacture are outlined. Parker-Kalon Corp., 200 Varick St., New York.

Lathes.—Catalog 94, 72 pp. Describes a complete line of lathes and attachments adaptable for manufacturing production, machine, maintenance, and electrical shops. The catalog illustrates 96 sizes and types of lathes, all of the back-geared, screw cutting type, with prices. South Bend Lathe Works, South Bend, Ind.

Starting Switch.—Bulletin 709, 4 pp. Describes a new, across-the-line, a-c starting switch available with start and stop push button for general industrial and machine tool applications; with either 2 or 3 wire pilot controls, such as a float switch, thermostat, a separate push button, etc.; providing for regular automatic operation, with hand operation in case of emergency. Allen-Bradley Co., Milwaukee, Wis.

Pyranol.—Bulletin GEA-1886, 4 pp. Pyranols, cooling and insulating materials which have, in addition to the desirable characteristics of mineral oil, the distinctive properties of being non-inflammable and non-explosive, are described. Approximately 50,000 kva of Pyranol capacitors and more than 25,000 kva of Pyranol transformers are in service, and Pyranol treated paper cable is commercially available for cable rated at 600 volts and below. General Electric Co., Schenectady, N. Y.

Hour Counter.—Bulletin K-2, 4 pp. Describes the new Weston hour counter for the measurement of elapsed time. This device is a compact, small instrument, weighing slightly more than a pound, with dials indicating hour runs up to 9,999 and repeats. It was developed for use in connection with units of electrical equipment which have a rather definite life in hours of operation and which it is desired to replace at the end of the indicated life rather than wait for failure before replacing. Among its most important applications are those in conjunction with devices using vacuum tubes. Weston Electrical Instrument Corp., Newark, N. J.

Published Monthly by

American Institute of Electrical Engineers

(Founded May 13, 1884)

Electrical Engineering

Registered U. S. Patent Office

April 1934
Volume 53
No. 4

The Official Monthly Journal and Transactions of the A.I.E.E.

J. B. Whitehead, President
H. H. Henline, National Secretary

Publication Committee
E. B. Meyer, Chairman
R. N. Conwell — **H. H. Henline**
W. S. Gorsuch — **H. R. Woodrow**

Publication Staff
G. Ross Henninger, Editor
C. A. Graef, Advertising Manager

PUBLICATION OFFICE, 20th and Northampton Streets, Easton, Pa.

EDITORIAL AND ADVERTISING OFFICES, 33 West 39th Street, New York, N. Y.

ENTERED as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918.

SUBSCRIPTION RATES—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii and the Philippine Islands, Central America, South America, Haiti, Spain and Spanish Colonies; $13 to Canada; $14 to all other countries. Single copy $1.50.

CHANGE OF ADDRESS—requests must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered due to incorrect address cannot be replaced without charge. Be sure to specify both old and new addresses and any change in business affiliation.

ADVERTISING COPY—changes must be received by the fifteenth of the month to be effective for the issue of the month succeeding.

STATEMENTS and opinions given in articles appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters.

REPUBLICATION from "Electrical Engineering" of any Institute article or paper (unless otherwise specifically stated) is hereby authorized provided full credit be given.

COPYRIGHT 1934 by the American Institute of Electrical Engineers.

ELECTRICAL ENGINEERING is indexed in Industrial Arts Index and Engineering Index.

Printed in the United States of America. Number of copies this issue—

17,900

This Month—

Front Cover

A view of the 287-kv transmission line from Boulder Dam to Los Angeles, at the point where it crosses the Cronise Valley, Mojave Desert, about 200 miles from Los Angeles. These towers, each carrying a single 3-conductor circuit, are spaced about 1,000 ft apart. The distance between the 2 tower lines is about 300 ft, and the spacing between the 2 outer conductors on a given tower is about 65 ft.

Educational Series—No. 5

Electric Discharges in Gases—III Self-Maintained Discharges 511
By J. SLEPIAN and R. C. MASON

Special Articles

The Present Theory of Electric Conduction 523
By KARL F. HERZFELD

The New Italy-Sardinia Cable 528

A.I.E.E. Papers

Industry Demands and Engineering Education 518
By L. W. W. MORROW

Some Recent Relay Developments . . . 530
By LLOYD F. HUNT and A. A. KRONEBERG

Induction Motor Locked Saturation Curves 536
By HORACE M. NORMAN

Recent Developments in Power Line Carrier 542
By T. JOHNSON, JR.

A New Type of Warble Tone Generator . 547
By W. H. BLISS

Wide-Band Open-Wire Program System . 550
By H. S. HAMILTON

Line Filter for Program System 562
By A. W. CLEMENT

A Graphical Solution of Steady State Stability 566
By H. B. DWIGHT

A Vacuum Tube Controlled Rectifier . . 568
By CALDWELL B. FOOS

The Theory of Incremental Rates and Their Practical Application to Load Division—Part II 571
By M. J. STEINBERG and THEODORE H. SMITH

News of Institute and Related Activities 627

North Eastern District to Meet at Worcester 627
A.I.E.E. Executive Committee Meets 630
Pacific Coast Convention Dates Selected 630
Tentative Plans for Summer Convention Are Announced 630
Technical Committee Activities Proposed for Sections and Districts 631

Letters to the Editor 634
Membership 637
Engineering Literature 639
Industrial Notes 640
Employment Notes (See Advertising Section)
Officers and Committees (For complete listing see p. 658–81, September 1933 issue of ELECTRICAL ENGINEERING)

—Turn to Next Page

Discussions of A.I.E.E. Papers

Communication

Stabilized Feed-Back Amplifiers—Black 590

Education

The Pitt-Westinghouse Graduate Program—Dyche & Hellmund . 587

Electric Furnaces

Cast Iron and Its Production—Healey 590

High Frequency Induction Furnaces—Adams, Hodge & MacKusick 592

Rocking Indirect Arc Electric Furnaces—Crosby 591

The 3-Phase Electric Arc Furnace—Arnold 593

Electric Power Switching

Switching at Richmond Station—Bailey & Ford 586

Switching at the Connors Creek Plant—Fugill 586

Switching at the Hudson Avenue Station—Gilt 585

Electrical Machinery

An Experimental Ignitron Rectifier—Ludwig, Maxfield & Toepfer 602

Effects of Rectifiers on System Wave Shape—Blye & Kent . . 608

Equivalent Reactance of Synchronous Machines—Crary, March & Shildneck 603

Protecting Machines From Line Surges—Calvert. 608

Simultaneous Control of Voltage and Power Factor—Blume & Woods 607

Electrical Measurements

A New Demand Meter—Smith 625

An A-C Potentiometer—Burgwin 624

Heavy Surge Currents—Generation and Measurement—Bellaschi 622

Impulse Generator Circuit Formulas—Thomason 622

Portable Schering Bridge for Field Tests—Hill, Watts & Burr . . 618

Power Distribution

An Economic Study of Suburban Distribution—Sweetnam & Corney 610

Fundamentals of Design of Electric Energy Delivery Systems—Johnson & Henry 610, 612

Joint Use of Poles With 6,900-Volt Lines—Bullard & Keyes . 610

Radial Versus Primary Network Distribution—Wulfing 610

Power Transmission

Attenuation and Distortion of Waves—Bewley 595

Corona Losses From Conductors of 1.4-In. Diameter—Carroll, Cozzens, Blakeslee 600

Counterpoises for Transmission Lines—Fortescue 598

Power Limit of a Transmission System—Petersen 602

Power Limits of 220-Kv Transmission Lines—Kroneberg & Macferran 601

Power Limits of Synchronous Machines—Clarke & Lorraine . 601

Steady State Stability of Composite Systems—Crary 594

Protective Devices

Automatic Reclosing of Oil Circuit Breakers—Anderson . . . 614

Control of Distance Relay Potential Connections—Warrington . 617

Lightning Measured on 4-Kv Overhead Circuits—Halperin & McEachron 616

Petersen Coil Tests on 140-Kv System—North & Eaton 612

Transportation

Investigation of Rail Impedances—Trueblood & Wascheck . . 589

Pantograph Trolleys I—Design Features—Schaake 589

Mr. Institute Member:

Even though we have been "bumped" from the inside front cover we are still talking about membership from farther inside. And you can know more about membership from the inside, too, if you read Mr. Meyer's very fine story of the budget in the March number of ELECTRICAL ENGINEERING. Read it and get that membership feeling; then help your Section membership committee by sending in the names of those you feel should be invited to join the Institute. Do it now.

Chairman National Membership Committee

Electric Discharges in Gases—III

Self-Maintained Discharges

By J. SLEPIAN
FELLOW A.I.E.E.

R. C. MASON
ASSOCIATE A.I.E.E.

Westinghouse Elec. and Mfg. Co, E. Pittsburgh, Pa.

In the light of basic processes discussed in the 2 previous articles of this group, this article reviews some facts and current theories concerning the various classes of self-maintained electric discharges in gases. This is the concluding article of a group of 3 devoted to the general subject of electric discharges in gases, the 2 previous articles having reviewed current knowledge concerning ionization and excitation, and ions in dense gases, respectively; it is the fifth of a series of special articles developed under the sponsorship of the A.I.E.E. committee on education, for full details concerning which see p. 238 of ELECTRICAL ENGINEERING for February 1934.—Editor

WHEN the gaseous space between a pair of electrodes conducts electricity under the influence of an applied voltage alone, without any external ionizing agent contributing to any important extent to the production or introduction of ions within the space, a *self-maintained* discharge exists. Though often external agents are necessary to initiate a current, after the discharge is established it itself continues to produce ions as fast as they are removed at the electrodes or lost at the discharge boundaries. If only electrons are active in producing ions, then a self-maintained discharge cannot exist; current flows only as long as an external source produces some primary ions. Discharges of this type often are called Townsend discharges.

Instead of considering all the possible ways in which other ionizing agents may contribute to the establishment of a self-maintained discharge, discussed by Dr. Karl K. Darrow at the close of the previous article of this group (published in the March issue of ELECTRICAL ENGINEERING, p. 388–95), we shall follow Townsend's original suggestion that positive ions produce new ions within the gas by ionization by collision, for simplification and because many experimental observations may easily be explained thereby. Thus the production of ions may be described through the statistical quantities: β_2, the number of new ion pairs produced by an electron in traveling one centimeter in the direction of the electric field; and β, the number of new ion pairs produced by a positive ion. If ions are lost only by giving up their charges to one electrode or the other, then the physical condition for a self-maintained discharge is this: that the total number of positive ions produced by an electron in moving from cathode to anode must regenerate one electron by the time those positive ions reach the cathode. Townsend put the condition in mathematical form, for uniform electric fields, as

$$\beta_2 = \beta e^{(\beta_2 - \beta)l} \qquad (1)$$

where l is the separation of the electrodes. For nonuniform fields β_2 and β vary from place to place, so an integral relation must be satisfied,

$$1 = \int_0^l \beta_2 e^{\int_0^z (\beta_2 - \beta) dz} dz \qquad (2)$$

Equations 1 and 2 give the conditions under which the discharge just maintains itself. If the conditions are such that smaller values of β_2 and β obtain so that the "=" sign becomes a ">" sign, then the ions are not generated as fast as they are carried to the electrodes, the ions disappear, and the discharge stops. If larger values of β_2 and β obtain, such as to make the "=" sign becomes a "<" sign, then the ionization increases, and the current will increase if the field is kept constant.

Another simple type of self-maintained discharge may be obtained if the positive ions produce no ions within the gas, but free electrons upon their impact on the cathode. This activity of the positive ions, first suggested by Thomson, may be described by γ, the number of electrons liberated per positive ion impact; the resulting condition for a self-maintained discharge is

$$\frac{1+\gamma}{\gamma} = e^{\beta l} \qquad (3)$$

and a corresponding equation for nonuniform fields. A direct discrimination between the 2 ways of ionization by positive ions is not possible. The conditions for meeting eq 1, however, depend only on the nature of the gas, while those for eq 3 depend both upon the gas and upon the cathode material. Under some conditions at least, particularly those existing at the cathode of a glow discharge, the latter statement of the positive ion activity appears to be more nearly true.

SPARKING

As the previous articles in this series have discussed, the ionizing ability of electrons and positive ions depends upon the energy they possess, which is a function of E/p, while the number of collisions made varies directly with the pressure. Consequently, from the definition of the quantities we

should expect the functional relationships to be

$$\frac{\beta_2}{p} = f\left(\frac{E}{p}\right), \quad \frac{\beta}{p} = g\left(\frac{E}{p}\right), \quad \text{and } \gamma = h\left(\frac{E}{p}\right) \tag{4}$$

where each of the functions, f, g, h increase as their arguments increase.

Now suppose that voltage is applied between 2 electrodes in a gas, and that there is so little ionization in the space that the field is undistorted by space charge, so that the gradient E at each point may be determined from the applied potential by usual electrostatic principles. At each point, E determines the values of β_2, β, and γ by eqs 4. As the applied potential is increased, E at the various points of space increases, and with it β_2, β, and γ. When the applied potential is small, the inequality sign, $>$, replaces the "=" sign in the eqs 1, 2, or 3 and any ionization that may be in the space will not increase, but on the contrary will decrease in amount, so that the voltage will be borne by the electrodes without the development of large currents. If, however, the applied potential is large, then the "=" sign in eqs 1, 2, or 3 becomes a "<" sign, and any ionization in the space increases in amount, and the current increases as long as the field is applied. The potential that just causes eqs 1, 2, or 3 to be satisfied is called the *sparking potential*, and is the potential at which considerable current begins to flow between the electrodes. If the electrodes are large planes so that the field is a uniform one, then the gradient E corresponding to the sparking potential is called the *sparking gradient*. When the field is not uniform, the maximum gradient in the field corresponding to the sparking potential frequently is called the sparking gradient.

When the sparking potential is exceeded, the ionization quickly grows to such magnitude that the electric field becomes distorted, and new ionizing agents may make their appearance. The discharge changes quickly to one of the forms discussed later in this article—corona, glow, or arc.

Sparking Gradient. The condition for a self-maintained discharge in a uniform field, eq 1, may be transformed to

$$\frac{\beta_2}{p} = \frac{\beta}{p} \cdot \left(\frac{\beta_2}{p} - \frac{\beta}{p}\right) pl \tag{5}$$

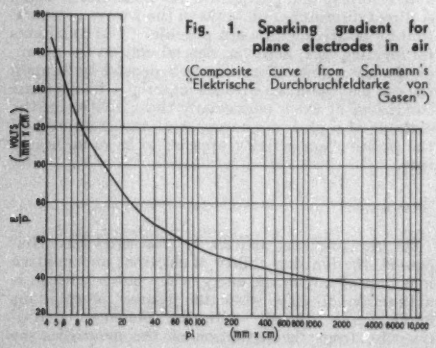


Fig. 1. Sparking gradient for plane electrodes in air

(Composite curve from Schumann's "Elektrische Durchbruchfeldtarke von Gasen")

Substitution of eq 4 in eq 5, shows that for sparking

$$\frac{E}{p} = F_1(pl) \tag{6}$$

An experimentally obtained curve is given in Fig. 1. The sparking gradient is not a constant, but is a function of electrode spacing and pressure. It commonly is stated that the sparking gradient for air at atmospheric pressure is 30 kv per centimeter. One sees, however, that this is only approximately true, and that wide departures may occur, for electrode separations often found in engineering practice.

Sparking Potential. From Fig. 1, one might construct a sparking potential curve, merely by multiplying the ordinate for any abscissa by that abscissa, for

$$\frac{E}{p} \cdot pl = F_1(pl) \cdot pl \quad \text{or} \quad El = V = F_2(pl) \tag{7}$$

Experimental curves for air, over 2 ranges of pl, are given in Fig. 2. The most striking feature is the definite minimum in the curve, with the rising branch for small values of pl, which results from the shape of the sparking gradient curve. One may account for the high values of V for low values of pl by the infrequency of collision of the ions in passage between the electrodes when pl is small.

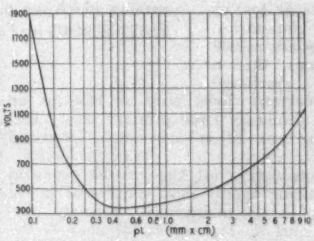
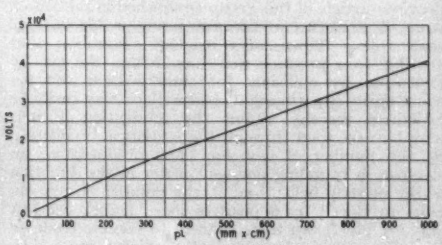


Fig. 2. Sparking potential for plane electrodes in air

(Data collected in Schumann's "Elektrische Durchbruchfeldstarke von Gasen")



The fact that V is a function of pl is expressed by Paschen's law: If the separation of plane electrodes is varied inversely as the gas density is changed, the sparking potential is unchanged. This is but a special case of the more general principle of similitude, which applies not only to sparking, but also to many parts of different discharge types: If all geometrical dimensions of a discharge space are

multiplied by k and the gas density is divided by k, then the same current flows with the same voltage applied. These 2 laws are very useful for transforming data obtained under one set of experimental conditions to other conditions.

Nonuniform Fields. An exact development of the criterion for sparking in nonuniform fields would be too extended for this space, but we can examine a qualitative explanation of the change in sparking potential when the geometry of the electrodes produces a nonuniform field. For simplicity, suppose the nonuniformity results from placing a grid midway between a pair of plane electrodes, all the potential being concentrated between one electrode and the grid, the field being zero from the grid to the other electrode. Now, if the conditions for a self-maintained discharge is met over the first space, ions may diffuse through the grid and carry the current through the second space. Thus, with the grid and the given field distortion, the sparking potential

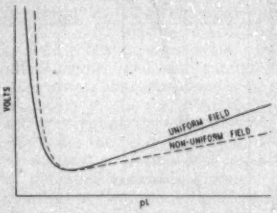


Fig. 3. Schematic representation of sparking potential in uniform and nonuniform fields

must be that for an electrode separation half the actual. For points to the right of the minimum on the V vs. pl curve, a reduction of effective electrode separation causes a decrease of sparking potential, while to the left of the minimum, a decrease of separation results in an increase of sparking potential. The effect in general of a nonuniform field, whatever the method of production, is different on the 2 sides of the minimum; to the left a nonuniform field *raises* and to the right *lowers* the sparking potential. A schematic representation is given in Fig. 3.

The voltage necessary to maintain a discharge with considerable current flowing differs from the sparking potential because of the development of *space charges*. When current flows, the electric field concentrates ions of one sign in front of the electrode of opposite sign; consequently, the field is distorted, being increased near the electrodes and reduced in the intermediate space. The effect is much larger at the cathode than at the anode, because the positive ions have much lower mobility than electrons. With the nonuniform field, the conditions, and the voltage, necessary for a self-maintained discharge are changed as discussed in the preceding paragraph. With increasing current, the space charges and resulting field distortions become larger, and the difference between the voltage necessary to maintain the current and the sparking potential grows. Since the effect is different on the 2 sides of the minimum on the V vs. pl curve, we have to the left a *rising* volt-ampere curve, and to right a *falling* characteristic, as sketched in Fig. 4. The latter, however, cannot fall below the minimum sparking potential.

The stability of the discharge depends upon the characteristics of the electrical circuit in which it is placed. The rising branch represents a discharge that is stable in any ordinary type of circuit. Any

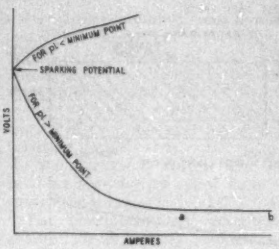


Fig. 4. Schematic representation of volt-ampere characteristics for low current discharges

point on the falling branch, however, may be obtained steadily in a d-c circuit only of the resistance in series with the discharge is larger than the slope of the volt-ampere curve at that point. For low resistances, as soon as the applied voltage is raised slightly above the sparking potential, the voltage falls discontinuously to the minimum voltage, and a current determined by the circuit conditions. In this case, "breakdown" occurs.

Thus, the "spark" or discharge which occurs when the sparking potential is applied, depends upon the characteristics of both the discharge space and the electrical supply circuit. Any of the 3 following types of discharge may result. Quite often, the electrical circuit is of limited continuous capacity, such as a charged condenser, so the discharge persists only for a short time; and in many cases, a "breakdown" occurs—large currents flow. Commonly, the term "spark" is used to apply to these cases of short time durations and large current discharges, in which a momentary flash of light accompanies the discharge, but there is no reason for making this distinction; such a discharge differs from an arc only in its transient nature. Perhaps the most common example is the lightning stroke, and on a smaller scale, the discharge of a condenser through a spark gap at atmospheric pressure.

Corona

The familiar faint bluish glow that surrounds a wire or sharp point to which a high voltage is applied, receives the particular name of *corona*. The small current characterizing corona results from the sharp radius of curvature of the conductor. The geometry of the electrode produces a nonuniform field. When the potential for a self-maintained discharge is applied and a small current flows, the resulting space charges, counteracting the effect of the curvature of the electrodes, tend to restore the uniformity of the field. At high pressures (atmospheric) a

more uniform field requires a higher voltage for maintenance of the discharge; thus, an increasing current requires an increasing applied voltage. The rising volt-ampere characteristic means that corona is a stable low current discharge, even in circuits of large capacity and low resistance. If the applied voltage and resulting current flow increases too far, the space

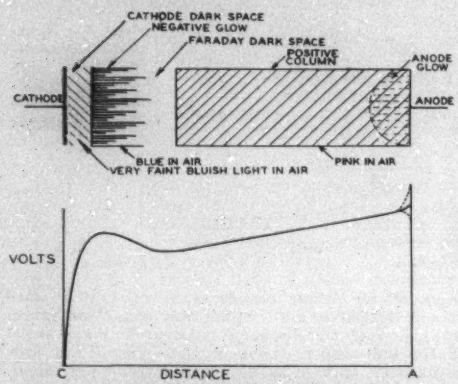


Fig. 5. Appearance, nomenclature, and potential distribution of a glow discharge

charges again distort the field, causing a lowering of the voltage necessary to maintain the discharge. Thus, above a certain current, the voltage required falls again; when this point is passed, "breakdown" may occur. The breakdown voltage may be considerably higher than the sparking potential, or corona voltage, at which current begins to flow.

Just as for plane electrodes, there is no critical gradient at the surface of the electrode at which corona starts; the corona gradient depends upon the curvature of the electrode. Both simple theory and empirical data give for the critical gradient at which corona forms on a negative wire in air at atmospheric pressure,

$$E_0 = 27.7 + \frac{9.53}{\sqrt{r_0}} \tag{8}$$

where r_0 is the radius of the wire in centimeters (the other electrode of lesser curvature is supposed to be remote) and E_0 is the gradient in kilovolts per centimeter at the surface of the wire.

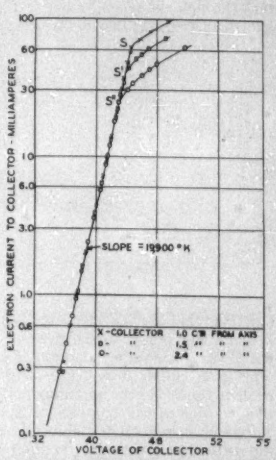
Glow Discharge

A self-maintained discharge, instigated by raising the potential applied to a pair of electrodes to the sparking potential, often takes the form of a glow discharge, as in the region *a-b* in Fig. 4. The appearance of a glow, with the color and shade of the main parts in air, together with the distribution of potential within the discharge is sketched in Fig. 5.

Cathode Region. The region next to the cathode—the cathode, or Crookes, dark space—is the part of the glow that is unique and essential. Most of the potential drop across the glow resides in the dark space. If the anode of the glow pictured in Fig. 5 were moved nearer to the cathode, some of the positive column would disappear without the rest of the discharge changing. If the anode approached progressively nearer and nearer to the cathode, the over-all voltage would change only slightly, until the anode reached the boundary of the cathode dark space. Then any further decrease in separation would demand a rapid increase in the voltage necessary to maintain the discharge. The evidence shows that the conditions for a self-maintained discharge must be met for the dark space. The discussion of the voltage necessary for maintenance of a current in the nonuniform field produced by space charges

Fig. 6. Current-voltage characteristic for a probe in mercury positive column

Arc current, 5 amp; pressure of mercury vapor, 7.13 baryes; tube diam, 6.2 cm; probe, 0.01 cm diam x 1.9 cm long, tungs, ten mounted parallel to tube axis (Killian, Phys. Rev., v. 35, p. 244, 1930)



showed that a voltage at least equal to the minimum sparking potential would be required. We identify 2 regimes for the glow discharge: the *normal glow*, in which the discharges does not completely cover the cathode, and the *abnormal* or *anomalous glow*, in which the cathode electrode is entirely covered.

For the normal glow, the voltage across the cathode dark space (the normal cathode fall, V_n), corresponds very closely to the minimum sparking potential for the gas and cathode material in use. The cathode fall is practically independent of pressure, but the thickness of the dark space, d_n, varies inversely with the pressure, in agreement with the principle of similitude. The cathode area covered by a normal glow grows or shrinks as the total current increases or decreases, so that always the current density remains constant. The normal current density, i_n, is directly proportional to the square of the gas pressure. We can write these conditions as $pd_n = C$ and $i_n = Dp^2$.

If the total current increases to such an extent that the entire exposed electrode area is covered, then the current density must increase above the normal value. The cathode dark space, being a region of space charge, must decrease in thickness; hence, by the analysis in the last section, the voltage required to maintain a discharge must increase: the abnormal cathode fall is larger than the normal, and increases with increasing current. The abnormal cathode drop also increases with decreasing pressure; an empirical relation is

$$V_a = E + \frac{F\sqrt{i_a}}{p} \tag{9}$$

The relation between pressure, current density, and dark space thickness in the anomalous case is given by

$$d_a = \frac{A}{p} + \frac{B}{\sqrt{i_a}} \tag{10}$$

also in agreement with the similitude principle.

A few values of normal cathode falls and constants appearing in the foregoing paragraphs are given in Table 1. As may be noted, the cathode fall is in general a few hundred volts. It is lowest with the alkali metals, and with the noble gases.

Negative Glow; Faraday Dark Space. At the sharp boundary of the relatively dark cathode fall space, a bright region, the negative glow, arises, and gradually fades into the Faraday dark space. The negative glow is a region of high ion density, within which a potential maximum exists. The concentration gradient of electrons is sufficient for diffusion against the opposing field to account for the passage of electrons toward the anode.

Positive Column. The positive column is independent of the phenomena at the cathode, so that really no distinction exists between the positive columns of glows and arcs, self-maintaining or non-self-maintaining. Since the glow is found more frequently at low pressures, in this section the low pressure positive column will be described, leaving the high pressure column to be discussed later in the section devoted to arcs. A distinctive feature of the low pressure positive column is that the discharge fills the whole of the section of the discharge tube.

A glow cannot exist with the applied voltage merely just equal to the voltage necessary to maintain a discharge in the cathode dark space. Some gradient, though usually small, is necessary in the positive column, because of losses of ions to the walls of the confining vessel. Since the walls are insulating, charge can be continually lost to them only if equal numbers of positive ions and electrons flow to the walls. Since the diffusion of the electrons is much faster than that of positive ions, the walls acquire a negative charge; a radial field opposing the motion of electrons and attracting positive ions establishes itself so that equal numbers of the 2 reach the walls in steady state. The walls of a discharge tube are negative by a few volts with respect to the axis of the tube.

The distribution of potential in the positive column, the ion density, and an important quantity—the electron temperature, Langmuir showed could be found from the study of the current collected with varying potentials applied to small probes placed in the discharge. The ratio of electron density at the surface of a probe bearing a potential V, negative with respect to the space around it, to the density remote from the probe is given by the Boltzmann relation

$$\frac{n_p}{n_0} = e^{\frac{eV}{kT_e}} \tag{11}$$

where T_e is the temperature of the electrons. Since the electron current flowing to the probe is proportional to the electron density at the probe, then the logarithm of the probe current will bear a linear relation to the probe potential (which may be measured with respect to any fixed point, the cathode, say, since only a constant will be added to V). In Fig. 6 are shown typical data illustrating the linearity. Equation 11 will hold only for *negative* potentials, so that a departure will occur at $V = 0$.

Table I—Normal Cathode Falls and Values of Various Constants for Several Cathode Materials in Different Gases

Cathode Material	Constants	Values of Constants in Different Gases							
		Air	O_2	N_2	H_2	He	Ne	Ar	Hg
Pt	V_n	277	364	216	276	160	152	131	340
	A		0.088		0.45				
	C				1.026				
	D		5.5×10^{-4}	3.83×10^{-4}	0.9×10^{-4}	0.11×10^{-4}	0.18×10^{-4}	1.41×10^{-4}	
Al	V_n	229	311	179	171	141	120	100	
	A		0.057		0.23				
	C		0.237	0.305	0.724	1.32	0.637	0.285	
	D		4.28×10^{-4}	1.39×10^{-4}	0.75×10^{-4}				
	E	230	290	230	144				
	F	105	78.5	107	255				
Fe	V_n	269	343	215	198	161		131	389
	A		0.085		0.34				
	C		0.311	0.419	0.9	1.66	0.722	0.356	
	D		3.01×10^{-4}		0.54×10^{-4}				
Cu	V_n	252		208	214	177		131	
	A				0.47				
	C				0.893				
Na	V_n			178	185	80	75		
K	V_n			170	94	59	68	64	
Hg	V_n			226	270	142			340
	C				0.89				

For all materials, B is approximately 0.004.
The units are: V_n in volts, current density in amperes per square centimeter, length in centimeter, pressure in millimeters of mercury.

Figure 6 shows a departure of the curve from a straight line at S; this marks the point at which $V = 0$ or where the probe is at the potential of the space around it. In this case, as the potentials are measured from the cathode, the space potential is 44.5 volts positive with respect to the cathode. The points S' and S'' give the space potential at points farther from the axis of the tube; the results show that the wall of the tube is negative with respect to the axis. Inspection of eq 11 shows also that the constant of proportionality between log i and V is e/kT_e, so from the slope of the curve of log i vs. V_s in Fig. 6 the electron temperature can be determined. As the probe current is directly proportional to the electron density and the square root of the electron temperature with a factor of proportionality given by the kinetic theory of gases, the current at space potential gives the density of electrons in the gas at once.

Experimental studies using Langmuir probes show electron temperatures from 5,000 to almost 100,000 deg K, while the gas temperature is a little, at the most a few hundred degrees, above room temperature. The explanation was given by Doctor Darrow in a previous article (*loc. cit.*). In general, the electron temperature decreases with increasing gas pressure. The electron temperatures are highest in noble gases. The electron density depends upon the current density, increasing nearly proportionally to the current; in many discharge tubes, the electron density is much less than 1 per cent of the gas molecule density.

Measurements of potential distribution show a constant low intensity field in the positive column, indicative of nearly equal average densities of electrons and positive ions. Since the loss of ions from the positive column is chiefly by diffusion to the tube walls, the ion loss increases as the tube radius decreases. The gradient increases too, in order to supply energy for the production of new ions to replace the ones lost. The gradient is thus inversely proportional to the tube radius. The gradient decreases somewhat with increasing current; it increases with increasing pressure. The changes are shown by curves in Fig. 7.

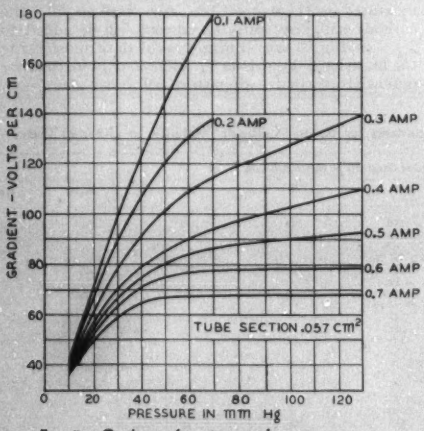


Fig. 7. Gradient of positive column in nitrogen as function of pressure for different currents

(From "Hand. der Experimentalphysik," after Matthies and Struck)

The production of new ions is probably chiefly through electron impact. In at least one case, Killian, from measured electron density and electron temperature, was able to calculate an ion production by electrons (using ionizing efficiency curves as given in the article by Dr. Lewi Tonks published in the February issue of ELECTRICAL ENGINEERING, p. 239–43) equal to measured ion losses to the walls.

In not all cases is the positive column and its gradient uniform; sometimes the column is broken up into regularly repeated bands or *striations* of alternate light and darkness. The heads of the bright regions, convex toward the cathode, are quite sharply defined and gradually shade off toward the anode into a dark region. The boundaries of the striations are equipotential surfaces, with a voltage difference between striations equal to an excitation or ionization potential of the gas. When examined stroboscopically, some apparently continuous positive columns are revealed to be made up of striations rapidly moving from anode to cathode.

The potential drop at the anode may be large, small, or even negative; it may or may not be accompanied by a visible glow or ball of light. This generalization may be made: the anode drop will be small, or negative, when the anode almost fills the tube; it will be large when the anode section is small compared to the tube.

Typical examples of the low pressure positive column may be seen in neon signs and mercury vapor lamps.

ARCS

Cathode Region. The arc is distinguished from the glow primarily by the phenomena at the cathode. The voltage drop at the cathode of an arc is only a few volts—usually of the order of the ionization potential of the active gas—which is small compared to that in a glow. Some new ionizing agent, not present in the glow and not considered in the previous discussion of the minimum voltage necessary for a self-maintained discharge, enters in the arc. One such agent, which is active at the cathode of some arcs such as those with carbon or tungsten cathodes, is thermionic emission of electrons. Electrons emitted from the cathode carry most of the current. Energy acquired in passing through the cathode fall of potential enable them to produce some new ions. The positive ions being attracted to the cathode impart to it the energy they have gained from the cathode drop and keep the cathode at a temperature high enough for thermionic emission. In this type of arc the cathode drop must be large enough for both of these functions.

In some arcs the cathodes do not reach a temperature high enough for thermionic emission; for

example, in the mercury pool arc the cathode temperature is probably only a few hundred degrees. For these, it was suggested by Langmuir that a very high intensity field existing at the cathode surface extracts electrons from the cold metal. Separate experiments show that fields of about 10^6 volts per centimeter are necessary to produce appreciable electron emission from materials at low temperature. In an arc, then, the cathode drop of only a few volts must be concentrated over such a short distance that a high intensity field exists at the cathode. The field is produced by the space charge of positive ions near the cathode, so the high field intensity necessary sets a lower limit on the positive ion current flowing to the cathode—a limit of about a 1,000 amp per square centimeter. In cold cathode arcs the total current density at the cathode is observed to be several thousand amperes per square centimeter.

Examples of the thermionic cathode arc may be seen in carbon arc lamps and in "sun lamps" with tungsten electrodes. Mercury pool arcs, iron welding arcs, arcs drawn by separating copper contacts, are all of the high intensity field type.

Positive Column. The positive column of the high pressure discharge distinguishes itself from the low pressure discharge in 2 features, which probably are connected: a definite section, and a high gas temperature. In contrast to the low pressure discharge, the high pressure positive column of an unconfined arc has relatively sharp boundaries; current flows only within a definite region, which expands and contracts with increases and decreases in current. The current density at atmospheric pressure is of the order of 100 amp per square centimeter.

The temperature of the gas in the high pressure positive column is high, also in contrast to the low pressure discharge. In arcs at atmospheric pressure, the gas temperature has been measured by 2 methods: (1) the absorption of X rays, α particles, or fast electrons gave the density from which the temperature was determined as the pressure was known; (2) the intensities of band spectra gave the relative population of certain excitation levels, from which, by means of the Boltzmann relation, the temperature was found. In fair agreement, the 2 methods give from 5,000 to 7,000 deg K for the arc temperature. As the electron temperature in low pressure discharges decreases rapidly with increasing pressure, it seems likely the electron temperature at atmospheric pressure is only a little higher than the gas temperature.

Though no bounding walls surround the positive column to which ions may diffuse and recombine, the cooler gases around the definite core of the discharge probably serve the same function. At the high temperature of the positive column, recombination of positive ions and electrons is negligible, but in the cool enveloping gas, recombination can take place. The chief loss of ions, then, is by diffusion to the boundary of the arc section, and recombination outside. Since the gas is at a high temperature, the positive column will lose energy by thermal conduction; probably a considerable part of the total is by this means. To overcome these 2 losses, energy must be put into the arc continually, through the intermediary of the electric field acting on the ions. The actual mechanism of ion production perhaps can be put under the heading of "thermal ionization," discussed by Dr. Tonks (*loc. cit.*).

The relation between current, arc voltage, and arc length often is expressed by an empirical equation (the so-called Ayrton equation)

$$V = a + bl + \frac{c + dl}{i} \tag{12}$$

where a, b, c, d are constants, and l is the arc length in centimeters. Different investigators find different values of the constants to make the equation fit their particular experimental conditions. In order to give some idea of the magnitudes involved, one set of constants out of the widely varying values reported is chosen:

Carbon in air	$a = 38.5$	$b = 2.15$	$c = 54$	$d = 6.1$
Copper in air	$a = 60$	$b = 11.8$	$c = 0$	$d = 35.5$

Over a limited range, Nottingham found the following relation for arcs of definite length between different electrode materials

$$V = A + \frac{B}{i^n} \qquad n = 2.6 \times 10^{-4}T \tag{13}$$

where T is the boiling point of the anode material. All results agree that both the total arc voltage and the gradient in the positive column (the coefficient of l in the Ayrton equation) decrease quite rapidly with increasing current for low currents, and approach a constant value for large currents.

Discharges With Separately Heated Cathodes. Though not truly self-maintaining, discharges with separately heated cathodes deserve mention because of their wide technical application. In these, a source of energy external to the discharge is used to maintain the activity of a thermionic cathode, usually an oxide coated filament of some kind. The gas pressure is usually low, so the negative glow and positive column are identical with those discussed under the glow. Commonly such discharges are called arcs, however, because of the low value of the cathode fall. Since the condition for a self-maintained discharge does not have to be met at the cathode, the cathode fall is much less than in the true glow. It is only necessary that the cathode fall be sufficient for the emitted electrons to produce positive ions necessary for the neutralization of the electron space charge. This requirement seems to be met in many cases by a cathode fall equal to the lowest excitation potential of the gas.

When the cathode filament emits electrons copiously, and usually when the cathode and anode are close together, the total voltage required may drop to a very low value—0.5 volt has been reported for sodium vapor, 1.7 volts for mercury, and 3.5 volts for helium. In these "abnormal low voltage arcs," close to the cathode the potential reaches a maximum at least equal to the lowest excitation potential, then falls again to the anode so that the over-all potential is quite low. Just as in the negative glow, a large concentration gradient carries electrons to the anode by diffusion against the opposing field.

Many grid-controlled gas-discharge tubes, such as those with the trade names "grid-glow tubes," "thyratrons" and similar devices, furnish examples of the independently heated cathode type of discharge at low pressure.

Bibliography

No attempt will be made to give references to original articles or to all the books covering this field, but a few are listed which will be valuable to those wishing to study the subject further:

1. Electricity in Gases by J. S. Townsend (Oxford Univ. Press) gives an account of the requirements for a discharge self-maintained by ionization by collision.

2. Elektrische Durchbruchfeldstarke von Gasen by W. O. Schumann (Springer) contains a complete and valuable summary of work on sparking gradients and sparking potentials up to 1923.

3. Der Elektrische Lichtbogen by A. Hagenbach (Akademische Verlag) contains a summary of older work on the characteristics of arcs.

4. The 2 German handbooks, Handbuch der Physik, v. 14 (Springer) and Handbuch der Experimentalphysik, v. 13, part 3, "Selbstandige Entladungen in Gases" (Akademische Verlag), in particular the latter, contain valuable résumés with complete references to original sources covering all types of self-maintained discharges.

5. The series of papers by Langmuir and Mott-Smith (*G. E. Review*, v. 27, 1924) develop the important Langmuir theory of probe characteristics, and apply the methods to the study of mercury arcs.

6. The last 5 chapters in Electrical Phenomena in Gases by K. K. Darrow (Williams & Wilkins) give a clear exposition of self-maintained discharges including arcs and glows, with many references to original work.

Industry Demands and Engineering Education

A study of the type of engineering graduate who will most satisfactorily meet the demands of industry and will be best adapted to present social conditions is contained in this paper. As a result of this analysis, changes in the type of college instruction now given are proposed. It is pointed out that the majority of students should be given a broad education which coördinates instruction in science, engineering, economics, and psychology, so as to fit the graduate for the managerial positions in industry; while a smaller group should be given specialized scientific and engineering instruction.

By
L. W. W. MORROW
FELLOW A.I.E.E.

Electrical World,
New York, N. Y.

AN ANALYSIS of prevailing conditions and opinions in this country shows 3 new and quite distinct aspects, when studied from the point of view of engineering practice and engineering education. The first of these is the idealistic concept that future engineering contributions must advance the standard of living and benefit mankind in his social relations. The second is that a large part of industry has become mechanized and requires a large staff of operators and managers which is now unsatisfactorily supplied from engineering graduates. The third is that industry requires only a relatively few highly trained engineers to do its diverse yet specialized technical engineering and research work. Add to these market demands the great expansion in fundamental scientific and engineering knowledge made in recent years together with the development of a high degree of specialization in each branch of industry and in each functional job in industry. This gives a perspective of the formidable and complicated problems now presented to engineers and to engineering educators. However difficult the task, it is necessary to take stock and to find out what may or may not be done to meet the new conditions.

Full text of a paper recommended for publication by the A.I.E.E. committee on education and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 5, 1934; released for publication March 7, 1934. *Not published in pamphlet form.*

The Social Side of Engineering

This country is reorganizing under an adversity-born movement to get a rationalized improvement in the conduct of its affairs. Under the impetus of this effort to bring about a new order, many believe that engineering becomes a major part of a planned economy whereby man becomes more fit and better able to control himself and his environment so that all his actions will benefit humanity as well as himself.

This is the idealistic concept that deranges many of our traditional ideas and practices. For example, our definition of pure science is very narrow; it is chiefly the gratification of man's inquisitiveness. It has no practical objective and no element of social well-being. It is an end in itself. Applied science or engineering is little different. Perhaps the greatest distinction is that engineering is always purposeful. It devotes itself to practical accomplishments in the realm of the material. It contains little conscious inclusion of the social or moral values that would be determined and weighed if an attempt were made to measure the effects of engineering contributions upon human welfare.

Thus both pure and applied science heretofore have stood detached from the social and moral aspects of man's career. In fact, it has been the ex-

perience that this detachment, this selflessness, this objectiveness was essential to professional success. Despite universal agreement as to the greater importance of these aspects of man's career, the cultivation of the social, legal, and economic fields of life has been left to other professions in this age of specialization.

But the new conceptions and the new plans attempt to bring science and engineering to bear upon man's social life; to improve his conduct, to advance his standard of living and to control his environment. In summary, to make one complete engineering problem of all earthly issues and then to obtain a single humanitarian answer. This ideal calls for imagination of the highest order and invests science and engineering with the dignity, importance, and utility which they could never attain were they to remain either a purposeless prying into hidden things or were they pursued in the hope of securing only material results.

The depression-born reason for these new ideas lies in the fact that the merits of engineering and of the civilization for which it has been largely responsible are questioned. Engineers are on trial because of breakdowns for which they are held responsible. Moreover, even engineers agree that drastic changes are necessary in national affairs before recovery can or should be had. The nation apparently is justified in its skeptical attitude toward a future premised only upon a continuation of scientific and engineering contributions similar to those that have proved of doubtful social value in the past. It is apparently logical to say that a social purpose must be combined with a practical purpose in the engineering work of the future.

Leaders in science, in engineering and in technical education must take cognizance of these new ideas and either act to carry them out or to prove them to be fallacious. If the ideas are good, then the endeavor must be to make social science a part of engineering education and professional engineers must find and use social yardsticks to measure the value of their work. If the concept is accepted, new and very difficult problems will be encountered in engineering education and in engineering practice. Social sciences are not formulistic or calculable for the reason that they deal with human actions and emotions. At best they permit only the use of a statistical analysis and at worst they deal with only the social and moral averages of a mob of irrational human beings.

But the engineer, the scientist, and the educator are called upon to apply their scientific methods of analysis and their finite solutions to the social sciences; to apply the cool-headed objectiveness whereby they are accustomed to reach quantitative conclusions, and yet they must retain the intelligent emotion that is necessary to motivate all human action. It is true that the engineer is only another human being in the final analysis, and yet the world, in its dire need, commands him to become that ideal creation—the social engineer. This is the climax of liberal opinion and suggestion that has been reached through the accumulating pressure from many sources, which has heretofore been typified by that oft-repeated phrase "engineers should have more of the humanities in their courses."

The Idealistic Concept Is Fallacious

A thorough analysis of the origin of this social concept of engineering and of the difficulties that confront the profession in endeavoring to carry it out leads to the conclusions that the concept is erroneous and that its practical application is impossible. It is analogous to the splendid generalization that poets should write only poems that contribute to man's well-being or to advocate that all medical practitioners must also be public health officials. But it is unsafe to use these idealistic generalizations when dealing with specialized fields of training and practice. Experience, not theory, has dictated specialization. The humanitarian ideal of engineering takes into account neither the function of the engineer nor the practical requirements of both his educational and professional activities. The engineer can build a bridge to withstand a definite stress, but he cannot protect his bridge from breakdown if human beings load it beyond its design limits. This is the functional job of the policeman.

Nor can engineers admit that the present troubles of civilization came about because their contributions were not in the public interest. They claim, instead, that the troubles resulted from the incapacity of other national leaders to make correct adjustments between capital, labor, power and machinery and were essentially financial in character. The engineer can and should do his part to get present maladjustments corrected, but he must do this largely as a citizen and not as a professional man.

Viewed accurately, the engineer is but one of hundreds of similarly specialized functional operators in this civilization. He can coöperate with other citizens to perform his broader obligations to humanity, but he cannot, in his specialized education and practice, devote concentrated attention to the social and moral aspects of life and weigh his work on these scales. He cannot succeed in his profession and at the same time carry on a Messianic rôle in civilization.

Engineers as Business Men

But social ideals should not be dismissed from a less idealistic consideration because undoubtedly there are practicable opportunities to introduce training for men who are not specialized functional engineers that will enable them to advance our standards of living. These opportunities lie in the possibility for training better equipped men to staff industry in those positions that do not require specialized or professional engineers as functional technical workers. With the growth of the use of power, engineering equipment and engineering methods and the coagulation of industry into business enterprises that consist of a large assembly of men, money, equipment, and materials there has come about a demand for semi-technical men to operate, maintain, and manage these enterprises. These men do not perform specialized engineering functions, yet they use engineering knowledge in combination with other knowledge to do the required work. In all manufacture, in transportation, in communication,

in light and power supply, and in many other industries the operating staffs must be competent and trained men and it is very desirable that a large number of these men should have training in fundamental science and engineering as a part of their preparation for their duties.

These men are responsible for getting results from the aggregations of capital, labor, power, and machinery that go to make up business enterprises and they must bring to bear a broad yet specialized knowledge of their work because they must use and weigh many engineering, social, and economic values in making decisions or in conducting their parts of the business. They should know pure science, applied science, economics, banking, accounting, and psychology in order to succeed. They are the cogs and controllers in the business mechanism. The requirements for their adequate training are as diverse as their functional tasks in business, but they do not conform to the definition or to the functional specification of the professional engineer. They may well be called professional business men.

Occupational records of engineering graduates during recent years show that from 60 to 70 per cent of them are now engaged in this class of work. They start as testers, apprentices, helpers, clerks, maintenance men, and operators and advance along various paths to become heads of departments and managers. They do not use their technical tools nor their technical knowledge in any direct specialized applications after graduation, even though many of them bear the title of engineer. Even the chief engineers of large enterprises are more nearly business men than engineers because they have not been able to keep up their technical proficiency during the lapse of years and have devoted their talents to management with stress upon its economic and organization aspects.

At present this industrial market is supplied largely, but in hit-or-miss fashion, by the engineering schools. But this is only because these graduates approximate the specifications most closely. And an unfortunate feature of this situation is that the men are not properly trained and perform their work too frequently by over-stressing their engineering point of view and under-stressing the social and economic aspects of business. And even their technical competency should be challenged after the lapse of a few years. They have become rusty and out-of-date, but will not acknowledge this fact when technical matters are under consideration. A combination of pride in their former training, in their label of engineer and the egotism that accrues with position causes them to believe they are still competent technical engineers and that they can and should make technical decisions without consulting specialists. As a consequence many very bad engineering decisions have been made in all industry and millions of dollars have been wasted. This type of man cannot function as a business man as well as an engineer. As a corollary, undoubtedly these men, coming from engineering, are not adequately trained to perform the other duties required of their positions in industry. Possibly this is one reason for many present social and economic maladjustments—their decisions have been technical and not social in too many instances. Good engineers are seldom good managers of men; their training and their type of mind are against them in dealing with human beings.

But the significant fact is that engineering graduates are going into industry to supply this demand and the demand will increase as industry grows and becomes more technical. It is in this field that the large group of men must be trained, and it is this fact, together with the functional duties that these men must perform after graduation, that makes it possible to consider the development of an educational course that will include the humanities. This would afford these men a knowledge and a perspective that would enable them to advance our civilization as well as themselves.

The Day of the Specialist Is Here

Industry does not need and cannot use in strictly engineering functions the large number of engineering graduates produced each year by the technical schools. This fact must be faced by engineering educators. This decrease in the market demand for engineers has been accompanied by very greatly raised standards of proficiency in engineering training and a high degree of specialization in engineering practice. Specialists in dielectrics, in electronics, in thermodynamics, and in many other lines of engineering have developed their branches to such a degree that a jargon as well as a knowledge prevails in each field that is not known by engineers in other fields.

All engineering educators and practicing engineers feel the pressure that comes from the enormous increase in the fundamental but highly specialized scientific and engineering knowledge gained in recent years and this knowledge continues to increase. The educators also feel the pressure of the demands from the extremely diverse and yet highly specialized fields of engineering practice. So that the educators find it possible only to give the essentials of engineering and science and the engineer is forced to specialize in his work and study by the stress of competition.

One practicing engineer can be quoted by hundreds of others when he says: "I am forced to concentrate upon my own specialized field in all my studies and practice and even then I find it difficult to keep ahead of my brother specialists. I have no time to keep informed about any other fields of science or engineering or even in those occurring in my own branch of engineering. I am forced to specialize to succeed."

Another engineer speaks to the same point from a different angle when he says: "The specifications for an engineer stated by the Engineers' Council for Professional Development are utterly impracticable. Most of us must concentrate upon one specialized field of engineering in order to succeed; it is impossible for us to be informed broadly or to be competent in the universe of engineering under present competitive conditions. This is the day of necessary specialization in engineering and yet the E.C.P.D. is attempting to legislate generalization."

Thus, in the technical realm, the field demand is for a thorough scientific and engineering training so that technical graduates may be equipped to start out in any of the numerous specialized fields of in-

dustry for which functional engineers are required. In this education, specialization must be discarded for thorough but a broad general training in science and engineering because of time limitations.

The foregoing analysis indicates that the present demands from industry reduce to the possibilities of training 2 types of men: (1) a large number of men with a broad training that includes some fundamental engineering and science to fill the functional positions of a large part of industry; and (2) a small but very highly trained group of technical men who can be developed into technical specialists. The first group would supply the future executives of industry and must, if possible, have training that will enable them to advance our social as well as our material standards. The second group would supply the needs of industry for the professional engineer. What can or should the engineering schools do to supply these demands? Particularly when the present product fills neither specification satisfactorily and yet meets with little, if any, effective competition from the products of non-engineering schools.

These 2 demands already have influenced engineering education directly and indirectly. One engineering educator says: "We are preparing men for life and not for professional engineering." Another says: "We are preparing men for professional engineering. We are raising our technical standards and are concentrating upon the use of rigid mathematical studies of the fundamental sciences. We are discarding all so-called practical and applied engineering courses." These 2 extremes are reflected in some degree in all engineering schools. This is evident from the debates about the advisability of shop work, the widespread adoption of courses in administrative and industrial engineering and in the frequent addition of advanced work in mathematics and physics. Yet in very few instances have the schools faced these 2 demands honestly in order to satisfy them or to refuse them.

The Ideal Business Course

Based upon the market for men, the type of training required, the advancement of society, and the present competition, each engineering school can well afford to measure the possibilities for instituting a course that will prepare men for the business positions of industry. This course is broader than engineering and requires a new perspective together with a university type of faculty and facilities.

Since the Civil War, or, rather, since the growth of industry and of the professions, the chief attention of educators has been given to specialization. The professional schools were created, the business schools were created to teach economics and banking from the point of view of business, the agricultural colleges grew large and the engineering courses of the traditional type were instituted. This left as the general course for students with a nonspecialized objective only the arts course with its A.B. degree. If this was too general some students entered the engineering, business, or agricultural schools even though they did not propose to follow these occupations.

Viewed from the standpoint of preparation for life in the present industrial civilization, the traditional arts course is more inadequate and more highly specialized than the engineering course. The mass of young men who graduate from engineering, arts, science departments, and economic departments enter upon a business career. Yet none of these courses is balanced as to content, coördinated in teaching, or operated to give a preparation for a business life. Specializing in languages, literature, or history is analogous to specializing in civil or electrical engineering as a preparation for life. The specialization is a matter of direction only. From the point of view of industry and of this type of student there is an unbalance in course content and a lack of purpose and viewpoint in the teaching.

Why not make a new course that incorporates the best elements of both the engineering and arts courses to prepare the large majority of college students for business life and relegate both the older courses to more highly specialized types of education? This new course would prepare men for life as interpreted by the occupational positions of industry and commerce. The base of such a course would be science, applied science, economics, and psychology, with electives in the humanities, in accounting, in banking, and in business law. Such a course should be taught by teachers who have been trained in the use of scientific methods so common to engineering, who are familiar with the equipment and operations of industry and who are broad enough to introduce and use humanitarian criteria in their educational measurements of value.

It is evident that the present courses in administrative or industrial engineering do not measure up to the requirements and possibilities of the proposed course, although they attempt to do this in some degree. These courses are unsatisfactory because present faculties in engineering and arts are like water and oil. They do not mix. In some instances the economics department dominates and in others the engineering department keeps control. There is a lack of unity, perspective, and coördination in developing and teaching these courses. The engineering instructors attempt to teach orthodox engineering as taught to technical students and use the technical point of view in teaching and then the economics instructors teach orthodox economics as given to arts students who specialize in the subject and use the academic point of view in their teaching. The usual result is either failure or a dominance by one department with a consequent unbalanced and inadequate training for the students.

Educators with the proper viewpoint and training can develop an adequate course for these students. It must be devised to train men to apply the principles of science and engineering to business and industry and yet must incorporate that other type of training that will enable these men to direct other men and to produce business results and those that will, in some measure at least, contribute to man's welfare. These men can be taught to use and control dollars, machinery, men, and power so that a social as well as an economic balance will prevail in their business enterprises. Their course should not be narrow or restricted so that a student could enter

either a specialized engineering or arts course readily if he has the desire and his capacity points in that direction.

The course proposed would find its chief present handicap in finding competent teachers—with knowledge, with point of view, and with courage to enter upon uncharted courses. Essentially the base for the student body, the faculty, and the course content must come from the engineering and economics departments, with accent on the engineering method and point of view. The course must be a welded whole and not a composite of courses already given in the 2 departments. It must have a content, a method, an administration, and an identity of its own to be successful. It should be a separate college in the typical university organization.

Or an Ideal Technical Course

An equally radical approach to technical engineering education is indicated if the schools wish to supply the elevated technical demands of industry. The number of engineering students must be reduced more than 50 per cent and the courses must be changed in content and raised greatly in their technical standards. Extreme specialization in either theory or practice is impracticable in engineering education and thus students must be trained to enter upon a career in any technical field. Only fundamental scientific and technical subjects can or should be taught. Since recorded knowledge in science and engineering is now so voluminous, all instructional time must be devoted to the intellectual advancement of the student and this necessitates the elimination of routine, practice, or informational courses.

Rigid treatment by the use of mathematics must be applied to the fundamental sciences to form the foundation for such a training and the course must be taught with a method and from a point of view that will develop initiative and adaptability for creative intellectual effort if it is to be successful. Undoubtedly the present engineering courses should be scrutinized closely and changed to conform to the new requirements and standards. Routine drawing and lettering, shop work to develop manual dexterity, laboratory work of the ordinary routine testing type, applied courses such as bridges, power, transportation, and even the present differentiation between civil, electrical, mechanical, and chemical engineering courses—all these must be weighed, changed, or discarded. In addition it might be advisable to weld together the pure science courses and the engineering courses to form one college in the typical university organization.

Because of the high standards demanded, the lack of time, the volume of fundamental knowledge and the educational goals that are sought, each lecture, each experiment, and each lesson must be checked to determine its essential value in the course and the part it plays in completing the training desired. Undoubtedly a mathematical approach must be used because of its time-saving attributes and because of its quantitative conclusiveness. Yet the basic principles of pedagogy must not be violated if this method and this type of course are to be taught successfully and are to be used to train men for specialized engineering and research.

It should not be forgotten that an engineer is more than a pure scientist; he must be able to apply his knowledge to get practical results. Some degree of technique and manual dexterity is desirable and should be taught, but this element should be an incidental contribution obtained indirectly from the more fundamental intellectual training. It must also be granted that less rather than more time can be devoted to nontechnical subjects, however desirable they may be. Perhaps an adaptation and concentration of the nontechnical subjects are also feasible so that the time spent on these courses will produce better results than are had at present.

An essential part of this conception of a technical course is a careful selection of the students and the instructors. They must be high in quality although relatively few in number and their capacities must be measured by technical yardsticks. Undoubtedly the student selective process should be introduced in his preparatory schools. Another essential of the instructional staff is practical experience and the ability to arouse the interest of students and to stimulate them to creative effort. Despite obvious difficulties, this type of course with an adequate follow-up after graduation appears best suited to supply the research men and the technical men who are needed in industry—men who will truly practice professional engineering.

Conclusion

If engineering educators agree to follow the demands of industry, the specifications for the 2 types of courses to give are as follows:

Course No. 1. A course for the mass of students that is based upon a broad education developed largely from science, engineering, and economics and taught chiefly by teachers using engineering methods and having both business and engineering knowledge, so as to train men to staff and operate mechanized industry.

Course No. 2. A course with very high standards in science and engineering to be taught by scientific and engineering specialists to be given a selected number of students so as to train men to supply the specialized technical needs of industry—the future professional engineers.

Undoubtedly some schools can and should develop both of these courses, but a large number of schools will find it wiser to offer only one of these courses. Since the demand for the greatest number of men is filled by course No. 1 and since only a small number of men are needed by industry from course No. 2 the indications are that a majority decision will favor course No. 1. Moreover, only a few schools can obtain and sustain the faculty and facilities needed to carry out the objectives of course No. 2, while most of the schools could readily adapt themselves to the specifications for course No. 1.

To be successful in completely meeting industry demands, it would be necessary to make a complete revision of the typical university organization and to form a separate college for course No. 1 and another college for course No. 2. This, of course, would involve a radical change of the present university organizations and would require recombination of the existing colleges and courses.

The Present Theory of Electric Conduction

The present theory of electric conduction in solid conductors and semiconductors is reviewed here by a recognized authority who interprets some of the results of modern physical research in the light of their bearing upon the theory of electric conductivity. First the author gives a short review of the present theory, then discusses the breakdown of ionic crystals, the quantum theory, and cold discharge phenomena.—Editor

By
KARL F. HERZFELD
The Johns Hopkins Univ., Baltimore, Md.

THE ELECTRON THEORY of conduction in metals was developed qualitatively about 1900 by Lorentz, Riecke, and Drude. They assumed the presence of free electrons which are accelerated in an electric field, but which lose by collisions with the atoms of the solid the additional energy that they have gained in excess of their average thermal energy. This lost kinetic energy appears in the form of Joule's heat. A quantitative development of this theory leads to the conclusion that the conductivity should be proportional both to the number of electrons per cubic centimeter and to the mean free path (that is, the distance over which an electron can travel on the average without losing its velocity) and also inversely proportional to the average thermal velocity. The same mechanism accounts for heat conduction; inasmuch as electrons of greater velocity would move to regions of low temperature or lower velocity. The high point in the theory is the deduction of the law of Wiedemann-Franz which states that the ratio between thermal and electrical conductivity for any substance should be equal to a universal constant multiplied by the temperature. This electron theory also accounts qualitatively for thermoelectric effects, the Hall effect, and similar phenomena. However, difficulties arose, the most important of which was the interpretation of the operations on the specific heat of metals. If, as was assumed, the electrons behave like gas molecules, as they should according to classical statistical mechanics, it also would follow that the electrons must have the same specific heat as gas molecules. However, the measured specific heats of metals led to the conclusion that only the atoms of the metal can contribute to the observed thermal energy, and that the electrons possess little or no thermal energy. From these considerations it would follow either that the number of free electrons is very small and, to account for the observed conductivity, it would be necessary to assume large mean free paths for the electrons, or that one would have to take the energy of the electrons independent of the temperature. This, evidently, left the Wiedemann-Franz law without a theoretical basis. There were other difficulties also which will be mentioned subsequently. A logical interpretation came with the application of the new quantum theory to free electrons by Fermi,[1] Pauli,[2] and Sommerfeld.[3] Only the conclusions of these investigators[4] will be given first; more details will be referred to later in the article.

Sommerfeld showed that although free electrons are present in large numbers (about one or more per atom) and possess very high average velocities, these velocities should be almost independent of the temperature. Consequently the contribution of the electrons to the specific heat would practically disappear. Thus according to classical theory the average thermal energy at room temperature; expressed in the usual notation (if e is the charge on an electron, an energy of V volts is an abbreviation for energy equal to eV), would be about $^1/_{25}$ of a volt whereas on the basis of the new theory this would be about 5 or 10 volts. However, in spite of the negligible specific heat, the Wiedemann-Franz law is found to be valid because the smaller variation with temperature is compensated for by a larger transport velocity. Furthermore, the experimental result that the resistance at room temperature is about proportional to the temperature could not be explained on the basis of the old theory without special assumptions. But this follows directly from the calculation of the interaction of electrons with the vibrations in the crystal lattice of the metal, as shown by Houston and others.[5]

The new theory also clears another difficulty. According to the old theory, if a temperature gradient is set up in an isolated metal rod, a potential difference should be set up. However, this could not be found experimentally, and this failure is explained by the new theory.[6] Because of the practical independence of the temperature of the electron pressure in the metal, a much smaller potential difference is necessary to compensate for a temperature gradient. The optical properties of metals are under investigation at present—experimentally by Professor Wood, and theoretically by Kronig, Peierls, and others.[7]

Insulating crystals have been shown to be insulating not because electrons cannot move freely between the atoms of the crystal lattice, but because these lattices contain no free electrons.[8] This has been demonstrated by the experimental work of Gudden and Pohl, who generated electrons inside of rock salt, diamonds, and zinc blend by illuminating the crystals (photoelectrical effect), showing that these electrons could move freely through the crystal lattice. The new quantum theory has helped us

Written especially for ELECTRICAL ENGINEERING embracing the substance of a lecture given before the National Research Council's committee on electrical insulation during its annual conference at Philadelphia Pa., Nov. 13–14, 1933. *Not published in pamphlet form.*

here to a deeper understanding of the difference between metals and crystals, i. e., between "free" and "bound" electrons. Even the free electrons are subject to the forces originating in the ions of the metal lattice, and further investigation is necessary to determine the boundary line, as will be reported later. In addition to this electronic conduction, typical ionic crystals—crystals built of positive and negative ions (like rock salt)—have an electrolytic conduction. In this case the ions themselves move as in a liquid solution, and as a result there occurs a decomposition of the crystals with deposition of the products at the electrodes. The mobility of the ions, and, as a result, the conductivity, increases very rapidly with the temperature (proportional to $e - Q/RT$). As has been shown especially by the investigations of Tubandt,[9] the mobilities of the 2 ions of opposite sign are very different; practically only one type migrates. As to which ion possesses the greater mobility depends upon the crystal, and no complete theory of this phenomenon as yet has been suggested.

Semiconductors (oxides and sulphides) have been investigated theoretically by Fowler and Wilson of the University of Cambridge with the help of the mathematical relations of the new quantum theory.[10] Practically, conduction electrons can be set free in sufficient number only from impurities present to a small extent. In this respect the deductions of Fowler and Wilson confirm older calculations. Based upon this point of view there exists a dissociation equilibrium between the atoms of impurity and their dissociated products (free electrons and positive ions); then the free electrons set free by this dissociation move through the lattice of the crystal.

Breakdown of Ionic Crystals

Ionic crystals constitute one of the simplest forms of solid matter and therefore investigations of their electrical breakdown promises to lead to a deeper understanding of this phenomenon. Such investigations have been made recently. However, before the conclusions of these investigations are outlined, the theories that have been developed for the breakdown in solids will be enumerated.

There is, firstly, the theory of the thermal breakdown developed by Wagner and Rogowski,[11] according to which a rise in temperature produced by the current passing during an initial period, is responsible for the effect. In solids, this current would cause fusion or carbonization in a narrow path, followed by conduction in the channels thus formed. In liquids, formation of vapor followed by a gas discharge through this vapor would result. In gases, the corresponding process is the thermal ionization of the gas and electron emission from the hot cathode, which is characteristic of the arc. While it seems obvious that these processes occur, they are not the elementary processes. They are more important in alternating current discharges than in the case of a single voltage pulse because a certain time is needed for the initial current to heat the material sufficiently.

Secondly, there is the theory of ionization by collision which has been developed by Townsend[12] especially for gases. This theory may be described briefly as follows: In the gas between the electrodes some ions and electrons always are present, due to traces of radioactive material, to cosmic rays, or to some similar source of radiation. If an electric field of sufficient strength is applied these electrons are accelerated. In colliding with gas molecules they will lose part of the velocity gained in the electric field, but if the field is sufficiently high, or the gas pressure sufficiently low so that collisions are rare, they may be enabled to accumulate an energy sufficient to ionize the gas molecules (between 10 and 20 volts). They produce new electrons which in turn are accelerated and move toward the anode, and ionize in turn. In that way the process of progressive ionization or an electron "avalanche" is built up toward the anode.

Everything would be over with this one avalanche, however, if it were not possible to generate at the cathode an increasing supply of electrons. According to Townsend's original theory this was accomplished by the positive ions that are generated in the ionization process and driven toward the cathode. It was assumed that these ions either ionized the gas at the cathode by collision, or extracted electrons from the metal, a process that is known to occur at high field strengths. A difficulty in this theory seemed to turn up, however, when experiments of Rogowsky[11] proved that it took only 10^{-8} sec to start the discharge, a time wholly insufficient for the heavy ions to reach the cathode. Franck and Hippel[13] showed, however, that this difficulty could be overcome by taking into account the space charge phenomenon which arises in the process. In the first electron avalanche the electrons which are swept away leave behind the positive ions which built up a space charge around the anode, diminishing the potential drop close to the anode, and increasing it accordingly in the neighborhood of the cathode. A few successive electron avalanches concentrate the whole potential drop directly in front of the cathode, resulting in a field intensity so high that electrons are extracted directly from the cathode in what is known as a cold field discharge, which will be discussed subsequently. As only the motion of electrons is involved, the time difficulty does not occur here. Some time later, of course, the positive ions do reach the cathode and establish then the normal cathode drop.

Experimental proofs of this idea can be found in recent experiments by Hamos, Marx, and Steenbeck[14] who, with the help of a Kerr cell used as an optical shutter, found that in the first 10^{-7} sec the luminous discharge grows out from the anode toward the cathode; they therefore conclude that the luminous region is the region in which space charge occurs.

Joffe,[15] and with him the Russian School, have interpreted the breakdown in crystals as being caused by a process in which some ions, which have been loosened in the lattice structure, are accelerated sufficiently to ionize by collision (tear loose other ions or eject electrons from them). Recent experiments of Hippel, however, are intended to disprove this view.[16] Hippel's experiments were made with sim-

ple crystals. His experimental advance arises from the fact that by short circuiting the discharge through a vacuum tube as soon as it has started, he avoids the subsequent destruction of the path of the first discharges. Thus it is possible to see the path of the first discharge in the crystal, which under usual conditions would be destroyed by the strong current that sets in after the breakdown. Hippel uses polished electrodes (not points) and is careful to avoid the edge effect. He finds that under these conditions there is always a fine channel starting out from the anode, which branches into several channels going in the direction of the cathode. This form occurs in the same general manner, both for sodium chloride and barium sulphate, in spite of the fact that the electrolytic conduction is carried on in the former by the positive sodium ions and in the latter by the negative sulphate ions. From this it is concluded by Hippel that it is not the ions, but the electrons originally present in the crystal (produced through either one of the effects mentioned before for gases, or through a photo-effect) that are responsible for ionization through collision.

The mechanism of the process is as follows: An electron, originally present and accelerated through the field in the first instant, starts to ionize on its path to the anode and leaves behind it a thread of positive space charges. As the first avalanche moves out, this thread is responsible for an increased field between the cathode and the starting point of the thread. Accordingly some electrons, out of the few that have been generated from the outside in the meantime, move toward this head of the space charge thread from the cathode. Because the field is now higher they ionize closer to the cathode than the first electron, so that there are space charge threads branching out toward the cathode from the head of the first one. This process is repeated a few times until the heads of the last space charge threads are close enough to the cathode to generate there fields of sufficient strength to cause cold cathode discharge and breakdown. A close examination of the direction of these branches, conducted by Hippel and by the Russian physicists, Inge and Walter,[17] have shown that these directions have definite orientations in respect to the directions of the crystal. In rock salt in not-too-high fields they are directed along the diagonals of the faces of the cube in which the salt crystallizes. As Hippel has pointed out, that is the direction in which only ions of the same sign are encountered, so that the electric potential due to the charge of the ions building up the lattice is more uniform (less bumpy), and accordingly the chances are greater for the electrons to pass through. It happens repeatedly that in this manner several branches of discharges tear a regular pyramid out of the crystal.

With increasing strength of external fields the electron may travel also along the octahedral edges, where the lattice field is less uniform. The non-uniformity does not matter so much if the external field is strong. In making the experiments it is important, as mentioned previously, that the edge effect (the occurrence of single discharges from the edge of the electrodes) be avoided, as these have an increased field at the end of the positive space charge thread that might induce a breakdown of the crystal before a sufficient strength of field is reached in general.

The dielectric strength of the crystal, avoiding the edge effect, has been investigated by Hippel, Inge and Walter, and Kurtschakoff. In general all these investigators reach the same conclusion: that this strength is of the order of magnitude of one million volts per centimeter, although, according to Hippel,

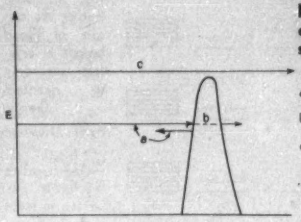


Fig. 1. Behavior of a particle as it strikes a potential barrier

a. Classical-reflection
b. Quantum-tunneling
c. Classical and quantum

it varies systematically with the crystal investigated. He finds for sodium fluoride (NaF) 2.4 million volts per centimeter, for sodium chloride (NaCl) 1.5–0.1, for rubidium iodide (RbI) 0.5, and for magnesium oxide (MgO) the highest strength of all the materials investigated. A calculation of the breakdown potential difference for a distance equal to the distance between 2 ions in the lattice shows it to be of the order of $^1/_{10}$ volt. In comparing this energy with the minimum energy necessary to excite the main vibration of the crystal, Hippel found that for all the crystals investigated the breakdown potential difference over the atomic distance is about 3 times the quantum of the ionic vibration, and interprets this result in the following manner: If the free electrons have just the energy equal to the quantum of the lattice vibration they are more apt to lose it by collision through a kind of resonance phenomenon and therefore cannot accumulate energy sufficient for ionization. If, however, between 2 collisions with ions of the lattice they can gain an energy sufficiently higher than the quantum, the probability of a loss is much smaller and they can proceed to accumulate further energy sufficient for ionization.

New Quantum Theory

There are 2 features in the new quantum theory that are of importance here. In classical theory, if a particle (electron, atom) encounters a potential hump (a place of high positive potential energy) it can pass the hump only if its total energy is greater than the highest value of the potential energy, because the total energy remains constant and the kinetic energy must be positive:

Kinetic Energy = Total Energy − Potential Energy

In the new theory that no longer is valid. Here electrons behave in many respects like waves, as shown by the beautiful interference experiments of

Davison and Germer. Waves, however, are not stopped immediately by any reflecting material, but can penetrate a thin layer of it and emerge with decreased intensity. Now, a potential wall acts for electrons just as a reflecting surface acts for light waves. Accordingly, electrons can penetrate a thin (Fig. 1) potential ridge, even if their energy is too small to get over the top. However, that is possible only if the ridge is narrow; the probability for penetration or the time it takes on the average to reach the other side of the ridge increases exponentially with the thickness.

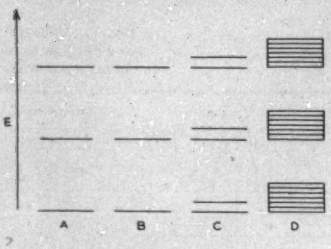


Fig. 2. Illustrating the origin of broad bands in crystals according to quantum theory

A, B. Two free atoms
C. Two atoms close together
D. Crystal

The importance of this phenomenon here is twofold: Firstly, it explains "cold electron discharges," which will be discussed in a subsequent section. Secondly, it emphasizes the fact mentioned before, that even the "free" electrons in metals are subject to forces exerted by the ions of the lattice. In classical theory, an electron could move under the action of an external electrical field if its kinetic energy, which was supposed proportional to the temperature, was sufficient to get it over the potential ridge, otherwise it was to be considered bound. If the ridge was too high (higher than $^3/_2kT$ or about $^1/_{25}$ volt) the electron was considered as bound and, if only such electrons were present, the material was regarded as an insulator. With the new theory, there is no such sharp limit of permitted potential energy, strongly dependent on T, since the electron also can pass through a potential barrier, although the probability of such passage decreases enormously with increases in the height and width of the barrier.

To get now a clearer understanding of the distinction between metal and insulator, it is necessary to turn to the second important new conception, the Pauli exclusion principle:

It is well known that the quantum theory permits only a discreet number of states (orbits with given energies). Assume a number N of separate atoms, say, of silver. Then, for example, each atom will have 3 lowest possible states (the "valence electron" can have 3 states of low energy). (Fig. 2.) All the atoms are alike, of course. If they are allowed to approach more and more, until they form a crystal, they will influence each other; this will lead to the result that instead of having the possibility of N identical lowest states, one for each atom, there are N different but closely adjacent states. A similar effect is obtained if N identical radio-circuits are coupled; the system of circuits then will be found to have N different, although closely adjacent, radio frequencies.[18,19]

Each state of the free atom gives such a band containing aN states where a_2 is a small integer.

According to Pauli no more than one electron can be in any particular state. If there are N electrons, they will of course fill the states of lowest energy in the lowest band. In case the number of electrons is just equal to the number of states in the lowest band, this band will be completely filled; there will be an equal number of electrons moving to the right and to the left, although how fast they get along will depend upon the height of the potential barriers within the crystal (between the atoms). Of course, because of the equal number going in each direction, there is no resultant current, and this will *not* change upon application of an external field. Such a field could generate a current only if it set more electrons moving, say, to the right. However, that is impossible because all states corresponding to motions to the right already are occupied, and because too much energy is required to put an electron into a higher band that is empty and where the electron therefore could get into a quantum state that corresponds to motion to the right. Therefore, we have an insulator. In a semiconductor, there are impurities that supply electrons into the empty bands of the surrounding medium and give rise to conduction. The same result is accomplished by the action of light of sufficiently short wave length.

If, however, the number of states in the lowest band is larger than the number of electrons present, empty states are available in the same band, and an external electric field has to raise the electrons only to a slightly higher energy to permit an excess of them to travel to one side. We have, therefore, an electronic conductor. There are, however, some electrons in the otherwise empty part of the band that lies above the completely filled part and below the top of the permitted band. The number of these electrons depends strongly upon the temperature.[19,3] See Fig. 3.

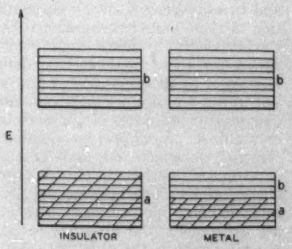


Fig. 3. Distinction between a metal and an insulator as explained by quantum theory

a. Full levels
b. Empty levels

Cold Discharge and Detector Action

The theory discussed in the preceding section gives an explanation for the cold electron discharges; that

is, for the possibility of extracting electrons from metals through the action of a high field.

As a result of the attraction of the positive ions, the electrons in the metal are at a negative potential energy with respect to the outer space as zero. The potential difference is of the order of 15 volts, where the electrons of highest kinetic energy at normal temperatures have about 10 volts, so that they have an energy of about 5 volts less than that of the potential barrier. Only at high temperatures are there enough electrons with 15 or more volts kinetic energy to enable them to pass over the barrier (thermoelectronic emission). However, a strong external field can lower the potential energy at some distance from the metal and thus limit the region of high potential to a thin layer at the surface of the metal which layer electrons then can penetrate in spite of the fact that their kinetic energy is not sufficient to carry them over the peak.[20] See Fig. 4.

In a crystal detector[21,22] there is a metal and a semiconductor which is assumed to be separated by a thin, highly insulating layer. When brought into contact, first without external electromotive force applied, electrons will pass from the substance where their energy is higher to the one where it is lower and thus set up a contact potential difference high enough to check this initial flow.

This state is such that the bottom of the first empty band for the electrons in the semiconductor is somewhat higher than the top of the filled portion of the band for the electrons in the metal, and hence the former lies within the height of the empty part of the metal band that is available for conduction. Assume the application of an electric field, as shown in Fig. 5. The potential drop will lie almost entirely in the high resistance of the intermediate layer and we will neglect to a first approximation the field inside metal and semiconductor and the changes it effects in the electron distribution. This change of course will be such as to supply the electrons that will pass out through the insulating layer.

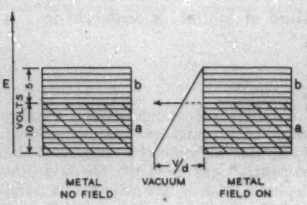
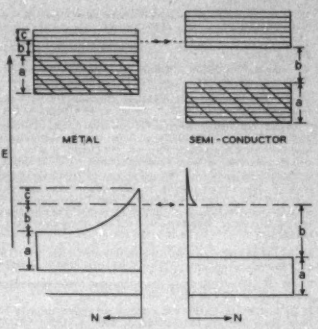


Fig. 4. Diagrams illustrating the possibility of extracting electrons from metals by a strong external field

a. Full levels
b. Empty levels

Assume first that the semiconductor is made negative (direction of high resistance). Without field, there would be an equal number of electrons going from semiconductor to metal and vice versa, therefore no current would be observed. Now, increasing the potential energy of the semiconductor may be said to raise the energy levels of the semiconductor which, although not affecting the number of electrons going from semiconductor to metal, diminishes the number of electrons going in the opposite direction, because fewer now have sufficient energy to reach the lowest empty state in the semiconductor, so that an electron current goes from semiconductor to metal. For high fields a saturation current is reached where no electrons pass from metal to semiconductor. However, if the field is in the opposite direction the potential energy of the electrons in the metal is raised in comparison to those in the semi-

Fig. 5. Metal and semiconductor close together showing electron equilibrium. The electron distribution is shown in the lower diagrams. Raising either metal or semiconductor above the equilibrium causes flow of electrons to the other



conductor, resulting in an increase in the number of electrons passing from the metal to the semiconductor. But, inasmuch as the number of electrons of low kinetic energy is larger than the number with high kinetic energy, the number passing across the boundary increases rapidly (exponentially) with the potential difference, and as a result we have decreasing resistance. At high potential, we obtain rectification and the relation developed on this point of view is given by

$$J = J_0 e^{-\frac{\alpha V_s}{RT}} - e^{(1-\alpha)\frac{V_s}{RT}}$$

where α is a constant between $^1/_2$ and 1. This is the form of equation required by the experiments.

Rectification occurs only if the potential hump in the layer between metal and semiconductor is not too large, that is, if the contact is not too bad.

A different theory has been developed by Schottky and amplified by van Geel.[23] According to this theory the layer between metal and semiconductor is so thick (10^{-4} cm) that no equilibrium is established without external electromotive force. Upon application of an external electromotive force a cold discharge is induced as a result of which electrons leave the negative electrode in an amount determined by the conditions for a cold discharge at this particular electrode, independent of the nature of the other electrode. The rectification is due to the difference in the currents that the same field draws out of the 2 different electrodes. The 2 theories differ experimentally in so far as the first gives a finite constant resistance at very low potential differences, whereas the second gives a resistance which increases to infinity very rapidly for very small fields because

the cold cathode electron discharge is very sensitive to variation in the magnitude of the field.

References to Recent Literature

1. F. Fermi, On Quantization of Ideal Monatomic Gases (German). *Zeit. f. Phys.*, v. 36 (1926), p. 902.

2. W. Pauli, Jr., On Degeneration of Gases and Paramagnetism (German). *Zeit. f. Phys.*, v. 41 (1927), p. 81.

3. A. Sommerfeld, On the Electron Theory of Metals According to Fermi's Statistics (German). *Zeit. f. Phys.*, v. 47 (1928), p. 1, 43.

4. Summaries:

K. K. Darrow, Statistical Theories of Matter, Radiation and Electricity, *Rev. Modern Phys.*, v. 1 (1929), p. 90.

L. Brillouin, Les Statistiques Quantiques, Paris (1930). (German translation, Berlin, 1932.)

R. Peierls, Electron Theory of Metals (German). Ergeb. der Exakten Naturwissenschaften, v. 11 (1932), p. 264.

5. W. V. Houston, Electrical Conductivity According to Wave Mechanics (German). *Zeit. f. Phys.*, v. 48 (1928), p. 449.

F. Bloch, On the Quantum Mechanics of Electrons in Crystal Lattices, *Zeit. f. Phys.*, v. 52 (1928), p. 555; On Susceptibility and Change of Resistance in a Magnetic Field, v. 53 (1929), p. 216; On the Law of Electrical Resistance at Low Temperatures, v. 59 (1930), p. 208. (All in German.)

R. Peierls, Theory of Electrical and Thermal Conductivity of Metals. *Ann. d. Phys.*, v. 4 (1930), p. 121; Two Remarks on the Theory of Conductivity, v. 5 (1930), p. 244; On the Theory of the Change of Resistance in a Magnetic Field, v. 10 (1931), p. 97; On the Question of the Law for the Electrical Resistance at Low Temperatures, v. 12 (1932), p. 154. (German.)

6. H. Horig, On the Electromotive Forces in a Temperature Gradient of a Metal (German). *Phys. Zeit.*, v. 14 (1913), p. 446.

7. R. W. Wood, Remarkable Optical Properties of the Alkali Metals. *Phys. Rev.*, v. 44 (1933), p. 353.

R. de L. Kronig, Quantum Theory of Dispersion in Metallic Conductors, *Proc. Roy. Soc.*, v. 124 (1929), p. 409; v. 133 (1931), p. 255; Remarkable Optical Properties of the Alkali Metals, *Nature*, v. 132 (1933), p. 601.

Y. Fujioka, Theory of Dispersion in Metallic Conductors (German). *Zeit. f. Phys.*, v. 76 (1932), p. 537.

H. Fröhlich, Absorption of Metals in the Visible and Ultraviolet (German). *Zeit. f. Phys.*, v. 81 (1933), p. 297.

8. See, for example, K. F. Herzfeld, The Influence of Surface Conditions and Space Charges on the Conductivity of Poor Conductors. *Phys. Rev.*, v. 34 (1929), p. 791.

R. H. Fowler, Note on Some Electronic Properties of Conductors and Insulators. *Proc. Roy. Soc.*, v. 141 (1933), p. 56.

9. C. Tubandt, s.f.e., Conductivity and Transfer Numbers in Solid Electrolytes (German). Handbuch der Exp. Physik XII.

10. A. H. Wilson, The Theory of Metals, *Proc. Roy. Soc.*, v. 133 (1932), p. 594; Theory of Electronic Semi-Conductors, v. 133 (1931), p. 458; v. 134 (1931), p. 277.

R. H. Fowler and A. H. Wilson, The Apparent Conductivity of Oxide Coatings Used on Emitting Filaments. *Proc. Roy. Soc.*, v. 137 (1932), p. 503.

11. See for example, W. Rogowski, Townsend's Theory and the Breakdown of Air Under Impulsive Potentials. *Arch. f. Elektrotechnik*, v. 16 (1926), p. 496; and Electrical Breakdown, Sommerfeld-Festschrift. Leipzig, 1928, p. 189. (German.)

12. J. S. Townsend, Ionization of Gases (German). Hand. d. Radiologie, v. 1, p. 291, Leipzig.

13. A. v. Hippel and J. Franck, Electrical Breakdown and Townsend's Theory (German). *Zeit. f. Phys.*, v. 57 (1929), p. 696.

A. v. Hippel, Development of the Electrical Spark and the Discharge Preceding It (German). *Zeit. f. Phys.*, v. 80 (1933), p. 19.

See also L. B. Loeb, The Mechanism of Spark Discharge in Air at Atmospheric Pressure. *Science*, v. 69 (1929), p. 609.

W. Nernst and W. Werner, On the Breakdown of Solid Insulators (German). *Ann. d. Phys.*, v. 86 (1928), p. 128.

14. L. v. Hamos, Optical Investigations With the Help of the Kerr Effect of the Beginning of the Spark in Air of Atmospheric Pressure (German). *Ann. d. Phys.*, v. 7 (1930), p. 857.

E. Marx, Rectification of Very High Alternating Potentials, *Electrotechnische Zeit.*, v. 51 (1930), p. 1089; Breakdown of Air in Inhomogeneous Electric Fields, v. 51 (1930), p. 1161. (German.)

M. Steenbeck, On the Formation of Carriers by Positive Ions in the Glow Discharge, *Wiss. Ver. a.d. Siemens-Konz.*, v. 8, III (1930), p. 83; An Experiment on the Mechanism of Electron Liberation on the Cathode, v. 8, III (1930), p. 93. (German.)

I. J. Torok, Surge Impulse Breakdown of Air. *Am. Inst. Elec. Eng.*, v. 47 (1928), p. 349.

W. Holzer, Optical Investigations of the Spark in Air of Atmospheric Pressure (German). *Zeit. f. Phys.*, v. 77 (1932), p. 676.

15. A. Joffé, Mechanical and Electrical Strength and Molecular Forces (German), *Phys. Zeit.*, v. 28 (1927), p. 911; The Physics of Crystals, N. Y. (1928).

16. A. v. Hippel, The Mechanism of Electrical Breakdown in Solid Insulators, *Zeit. f. Phys.*, v. 67 (1931), p. 707; v. 68 (1931), p. 309; Dielectric Strength and Crystal Structure, v. 75 (1932), p. 145; Remarks Concerning the Article of Mr. Walter, v. 77 (1932), p. 277. (German.)

17. L. Inge and A. Walter, Electrical Discharges in Rock Salt (German). *Zeit. f. Phys.*, v. 71 (1931), p. 627.

A. Walter, Remarks on the Article of Mr. Hippel (German). *Zeit. f. Phys.*, v. 77 (1932), p. 275.

J. Lass, On the Dependence of Electrical Breakdown in Crystals on the Direction (German). *Zeit. f. Phys.*, v. 69 (1931), p. 313.

18. K. F. Herzfeld, On Atomic Properties Which Make an Element a Metal. *Phys. Rev.*, v. 29 (1926), p. 701.

19. J. C. Slater, Cohesion in Monovalent Metals. *Phys. Rev.*, v. 35 (1930), p. 509.

20. W. V. Houston, On Electron Emission of Cold Metals (German). *Zeit. f. Phys.*, v. 47 (1928), p. 33.

L. Nordheim, On the Theory of Thermal Emission and Reflection of Electrons by Metals (German). *Zeit. f. Phys.*, v. 46 (1928), p. 833; The Effect of the Image Force on the Emission and Reflection of Electrons by Metals, *Proc. Roy. Soc.*, v. 121 (1928), p. 626; Theory of Electron Emission of Metals (German). *Phys. Zeit.*, v. 30 (1929), p. 177.

R. H. Fowler and L. Nordheim, Electron Emission in Intense Electric Fields. *Proc. Roy. Soc.*, v. 119 (1928), p. 173.

21. A. H. Wilson, Theory of Metals. *Proc. Roy. Soc.*, v. 138 (1932), p. 594.

J. Frenkel and A. Joffé, On the Electric and Photoelectric Properties of Contacts Between a Metal and a Semi-Conductor (English). *Phys. Zeit. der Sowjetunion*, v. 1 (1932), p. 60.

M. Bronstein, On the Theory of Electronic Semi-Conductors (English). *Phys. Zeit. der Sowjetunion*, v. 2 (1932), p. 28.

L. Norheim, On the Theory of Detector Action (German). *Zeit. f. Phys.*, v. 75 (1932), p. 434.

22. L. O. Grondahl, The Copper-Cuprous-Oxide Rectifier and Photoelectric Cell. *Rev. Modern Phys.*, v. 5 (1933), p. 141.

23. W. Schottky, On Cold and Hot Electron Discharges (German). *Zeit. f. Phys.*, v. 14 (1923), p. 87.

W. Ch. van Geel, On the Action of Rectifiers (German). *Zeit. f. Phys.*, v. 69 (1931) p. 765; Stopping Layers of Rectifiers, *Nature*, v. 132 (1933), p. 711.

The New Italy-Sardinia Cable

A brief description of the deep sea telephone circuit laid in 1932 between Italy and the island of Sardinia is contained in this article.*

TELEPHONE communication between Italy and the island of Sardinia was first established by means of a radio link in September 1930, and the traffic soon became sufficient to justify the laying of a submarine telephone cable. Accordingly, in April 1932, a cable was laid, and in June 1932 it was opened to traffic in connection with the pilgrimages from all parts of the world to Sardinia on the occasion of the fiftieth anniversary of the death of Garibaldi.

The cable consists of a continuously loaded core, with a concentric copper return, similar to the original (1921) Havana-Key West cables. The total length of the submarine part is approximately

* Abstracted from an article "The New Italy-Sardinia Telephone Circuit," by A. G. Pession, direttore generale delle poste, Telegrafi e Telefoni d'Italia, and published in *Electrical Communication*, v. 12, Oct. 1933, p. 76–85. Abstract prepared by George H. Gray (A'12, M'29), International Standard Electric Corp., New York, N. Y. *Not published in pamphlet form.*

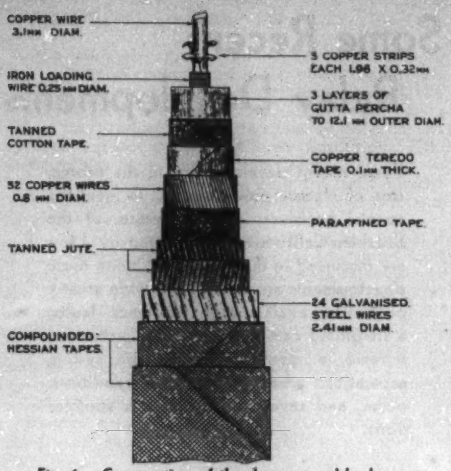


Fig. 1. Construction of the deep sea cable, known as type *D*

146 nautical miles, and it is therefore considerably longer than any submarine telephone cable previously laid. The weights in pounds per nautical mile for the deep sea section are about as follows:

Central conductor	370 lb
Loading	80 lb
Gutta mixture (55 per cent pure gutta)	409 lb
Copper Teredo tape	164 lb
Return conductor	980 lb
Total	2,003 lb

In addition to the telephone circuit, the system was designed to provide 2 duplex telegraph circuits: a low frequency composite channel and a carrier channel. Only the telephone circuit and the low frequency (d-c) composite telegraph channel are equipped at present. The other channel is to be obtained by using carrier frequencies of about 3,000 and 3,500 cycles for the 2 directions.

On the mainland side, the cable is landed at the village of Fiumicino, which is about 18 miles from Rome, and in Sardinia the cable is landed about a mile from Terranova. In each case a cable hut was constructed for terminating the submarine cable and for housing the terminal equipment. Terminal repeater equipment is installed at both ends.

A land cable of special construction was laid be-

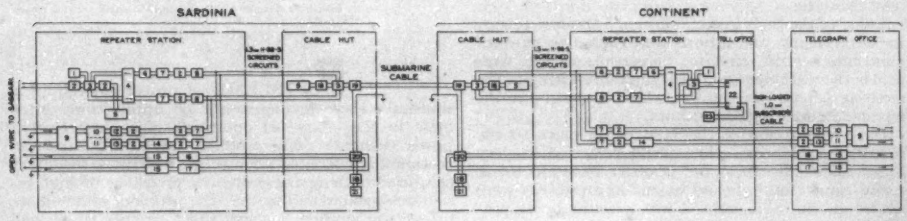


Fig. 2. System schematic diagram of terminal equipment

Table I—Comparison of Submarine Telephone Cables

Cable	Date Laid	Length: Nautical Miles	Length: Kilometers	Max. Depth Fathoms	Core Wts.—Lb per n.m.: Central Conductor	Gutta Percha	Return Conductor
Sicily-Lipari	1920	29	54	400	185	158	(a)
Key West-Havana (3 cables)	1921	105	195	1,000	350	315	850
Catalina Island, California (2 cables)	1923	23	43	500	350	App. 500 (b)	App. 850
Algeciras-Ceuta	1929	20	37	500	405	450	750
Tenerife-Gran Canaria	1929	40	74	1,500	405	450	750
Key West-Havana	1931	109	202	1,080	505	677 (c)	845
Italy-Sardinia	1932	146	270	1,140	370	409	980

(a) Figures not available
(b) Rubber insulation
(c) Paragutta insulation

tween Rome and Fiumicino, and a cable of similar construction was laid between the cable hut and the repeater station in Terranova. Rome and Sassari are the terminals of both the telephone and telegraph circuits, the latter town being connected to the repeater station at Terranova by an open wire line. Connections can be made to other toll circuits by means of cord circuit repeaters. At Rome the cord circuit repeaters are equipped with grid jamming echo suppressors. With this arrangement, when any 2 long distance circuits which are not equipped with echo suppressors are switched together at Rome, the echoes, which would otherwise become

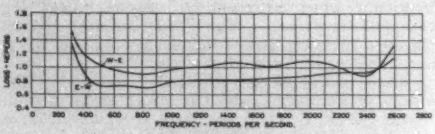


Fig. 3. Over-all loss-frequency curves of repeatered circuit

disturbing on the switched connection, may be suppressed by a comparatively few units of equipment, provided especially for such cases and, therefore, used efficiently.

Owing to the high losses and hence the low receiving levels, many precautions were taken to prevent noise entering the circuit. Screened circuits were used in the tie cables and the equipment wiring of the receiving curcuit was also screened throughout the repeater stations and cable huts.

Direct connection of the land cable pairs to the concentric submarine cable would have led to very considerable difficulties, and in order to avoid them, 4-wire terminating sets and balancing networks were located at the cable huts, 4-wire circuits being provided in the underground cables.

The 4-wire terminating sets thus perform a double function. They form the connecting links between the 2-wire and 4-wire portions of the system at the actual terminals of the submarine cable, thus eliminating the singing point troubles associated with changes of temperature of the land circuits and with differences between the impedances of the underground and submarine cable. They also act as screened repeating coils to connect the low impedance concentric submarine cable with the high impedance metallic land circuits, while, owing to their position in the circuit, changes in the magnetic properties of their cores do not affect the balance between line and network.

The high losses also necessitated paying special attention to the question of allocation; that is, the order in which the coils of core should be joined together in order to obtain as smooth an impedance-frequency curve as possible. This problem was solved by means of a very careful series of measurements on each coil.

A comparison between the Italy-Sardinia cable and cables previously laid is shown in Table I.

Some Recent Relay Developments

Some recent developments in the protection of electric power systems to meet the special problems on the system of the Southern California Edison Company, Ltd., are discussed in this paper. Among these developments are means to provide greater protection against high resistance faults, a simplified carrier current pilot protection scheme, a method of automatic system separation when out-of-step conditions occur, and several miscellaneous applications.

By
LLOYD F. HUNT
ASSOCIATE A.I.E.E.

A. A. KRONEBERG
ASSOCIATE A.I.E.E.

Both of the Southern California Edison Company, Ltd., Los Angeles

PROBLEMS of protection requiring unusual relay developments or applications often arise in the course of operation of a large electric power system. Some problems have confronted protection engineers for a long time defying satisfactory solution; among these are the problems of high resistance ground faults, and the problem of adequate protection against 3-phase short circuits which will not be operative during out-of-step conditions on a system. The problem of high-speed single-line protection is gradually approaching solution. This paper presents some of the problems encountered on the system of the Southern California Edison Company, Ltd., and the relay applications used in the solution of those problems.

A sensitive relay has been developed to protect low voltage radial feeders against high resistance ground faults. Protection of high voltage transmission has been reinforced through the use of instantaneous overcurrent relays and application of differential principles of protection in the form of carrier current pilot protection. Another relay has been developed to detect loss of synchronism on the system and to perform switching operations required in such a case. Applications of relays for protecting generators with grounded field windings, generators operated with neutral ungrounded, and generators with neutral grounded through reactors also are described in this paper.

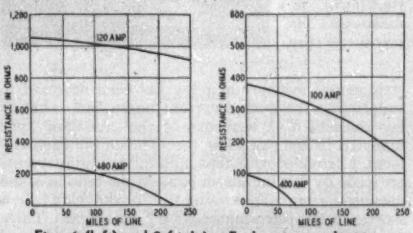
Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution. Manuscript submitted Dec. 18, 1933; released for publication Feb. 7, 1934. *Not published in pamphlet form.*

Ground Fault Resistance

High resistance ground faults represent one of many problems encountered in the operation of high voltage overhead lines. This problem is one of the most difficult to solve on account of the wide variation in fault resistance and its effect at the different voltages and under different fault conditions. The presence of a little resistance in faults to ground on lines of lower voltage may so limit the fault current that the relays will not clear a line that may be a hazard to life and property.

A study of the effect of fault resistance on values of ground current in a single-conductor-to-ground fault on a typical overhead system demonstrates strikingly the importance of ground fault resistance at lower voltages. Figures 1, 2, 3, and 4 present some of the curves plotted from the results of such a study. In these curves the resistance limiting the ground current in a single-conductor-to-ground fault is plotted against the distance along the line from the power supply bus to the fault.

Figures 1 and 2 show typical conditions on the 220-kv and the 66-kv systems. The areas under the



Figs. 1 (left) and 2 (right). Fault resistance limiting residual current to indicated value vs. distance along the line, for a 220-kv line (left) and a 66-kv line (right)

lower curves include faults that can be cleared properly by the existing protective equipment. An average minimum trip value of 480 amp is used on 220-kv lines and 400 amp on 66-kv lines.

From actual records of short circuit currents on the 220-kv system the average fault resistance is in the order of 100 ohms. However, in several cases the fault resistance has been in the order of 300 ohms which is beyond the range of the present single-line protective equipment. With the latest carrier current pilot protection it will be possible to reduce the minimum trip current to $^1/_4$ of its present value and correspondingly increase the range of protection to include the areas under the upper curves of Figs. 1 and 2.

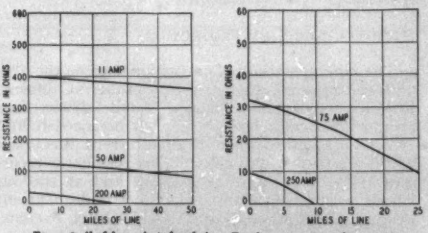
Figure 3 shows conditions on an 11-kv system. For minimum trip values of 200 amp a ground resistance of 25 ohms on a 10-mile section of line will limit the ground current to the minimum trip value; and with residual relays, with 50-amp minimum trip setting, 125 ohms on a 10-mile section of line will produce the same effect. A relay arrangement that will detect residual currents of approximately 10 or 11 amp will clear a fault with 375 to 400 ohms resistance even on a 30-mile section of line.

Figure 4 shows conditions on a 4-kv system. A ground fault resistance of 8 ohms on 2 miles of line will limit the current to the minimum trip value of 250 amp, and 30 ohms will limit the current to 75 amp if residual relays are used. This is still a rather difficult problem to solve on account of the unbalanced load currents due to single-phase connected loads. In order to increase the range of the protective equipment and obtain more sensitive minimum trip settings, the unbalance in load currents must be reduced to a value considerably less than the minimum trip setting.

In connection with the foregoing studies a series of tests were made on an 11-kv line. One end of a length of No. 6 B. & S. gauge copper wire was connected to one of the conductors of the line, and an ammeter was inserted in series with the wire; then the wire was lowered by means of a rope until it made contact with ground, and the ammeter was read through a pair of field glasses. The different readings ranged from 10 to 25 amp depending on whether the wire was lowered on grass, open ground, or dirt road, and on the length of contact with ground. The meaning of the readings will be apparent when the latter are compared with calculated values. Calculated ground current using reactance only was 480 amp, the one obtained when line impedances were used was 290 amp, while the peak load carried by the line was about 50 amp per phase. The fault resistance was of the order of 250 to 460 ohms limiting the current to 25 and 10 amp, respectively.

Distribution Feeder Protection

The relay arrangement proposed for protection of distribution feeders is shown in Fig. 5. It consists of the original phase overcurrent relays and a ground



Figs. 3 (left) and 4 (right). Fault resistance limiting residual current to indicated value vs. distance along the line, for a 11-kv line (left) and a 4-kv line (right)

current directional relay. The directional element of the ground current relay is operated by the current in the return wire of the current transformers; this element selects the faulted line. On a Δ-connected system current for the operating coil is obtained from the series connected secondaries of the

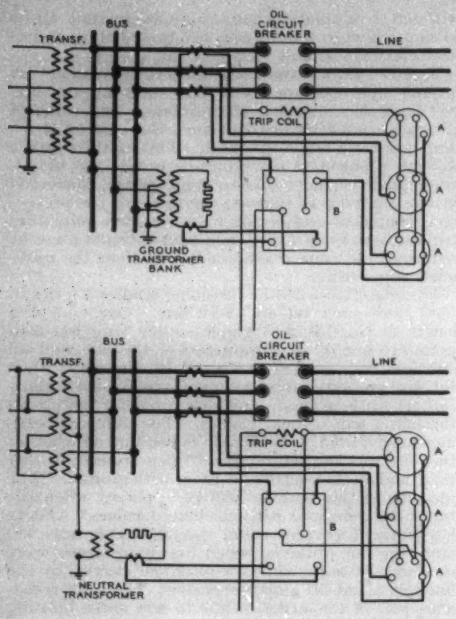


Fig. 5 (left). Wiring diagrams of protection for low voltage distribution feeders. Upper diagram is for a Δ-connected system; lower diagram for a grounded-Y system

A. Phase overcurrent relay

B. Ground current directional relay

Fig. 6 (right). Instantaneous trip over-current relay

grounding transformer bank; on a grounded-Y system it is obtained through a small transformer connected as shown in the lower diagram of Fig. 5. When several feeders radiate from the bus the operating coils of the ground relays are connected in series. A minimum trip value of 10 amp can be obtained with such a relay arrangement.

High Voltage Line Protection

The general method of protection used on the high voltage transmission lines of the Southern California Edison Company is as follows: Parallel 220-kv lines are equipped with residual current balanced relays. For single line protection residual current directional relays are used where possible and residual overcurrent relays at generating stations and at stations where directional relays cannot be used. Current balance relays protect parallel 66-kv lines, overcurrent relays protect 66-kv lines at 220/66-kv step-down substations, and power directional relays protect 66-kv lines at all secondary substations.

The use of residual currents for protection of 220-kv lines is due to the fact that nearly ninety per cent of the short circuits on these lines are single-conductor-to-ground insulator flashovers. Lower minimum trip settings are possible with residual relays than with relays operated by phase currents. However, a protective system of this kind does not detect 3-phase or phase-to-phase short circuits. An instantaneous overcurrent relay has been designed to supplement the ground current protection; this relay consists of 4 elements of the contactor type mounted in one case (Fig. 6). The coil of each element is provided with taps, and further adjustments are made by varying the air gap and the tension of the opening spring. The closing time of the relay is half a cycle and its performance is very consistent. Three of the elements are operated by phase currents and the fourth one by residual current. When these relays are set properly to be inoperative on out-of-step conditions and on short circuits on other sections of line, they protect an average of about 40 per cent of the line from the station. A line with a short circuit within this distance is relayed first at the nearest station and subsequently at the other end. The additional instantaneous relays fail to protect a short section near the middle of the line, and they operate in sequence which also is an undesirable feature.

Carrier Current Pilot Protection

Latest developments in carrier current telephony provide means for applying differential principles to the protection of long transmission lines, thus eliminating sequential relaying and permitting lower current and time settings. (See "Development of a Relay Protective System on the Lines of the Southern California Edison Company, Ltd.," by E. R. Stauffacher, A.I.E.E. Trans., v. 50, 1931, p. 80–8.) The current differential type of protection so far developed is very complicated, involving considerable auxiliary equipment to transmit by means of carrier current the phase relation of the current at one end of the line to that at the other end of the line. The

complication of the apparatus and its high cost are the chief drawbacks of this type of carrier current pilot protection. A simpler protective system has been developed by the Southern California Edison Company. It detects power flow from both ends into the line, a condition that exists when a fault or short circuit is on the line. When power flows out of one end of the line the sensitive tripping relays are made inoperative by short circuiting their operating coils. Following are the requirements for an ideal protective system:

1. It must clear all types of faults on the protected line.
2. It must not operate during out-of-step conditions on the system.
3. It must not operate during faults external to the protected line.
4. It must not fail to trip when the interlocking circuits are interrupted.
5. It must eliminate sequential relaying.
6. It must be faster than other types of protection.

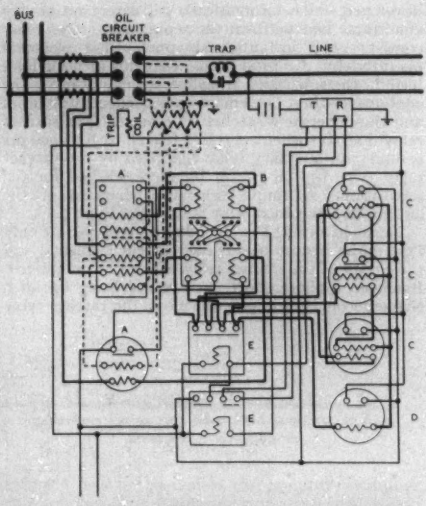


Fig. 7. Wiring diagram of carrier current pilot protection

A. Power directional relays
B. Instantaneous current relays
C. Current balance relays
D. Overcurrent relay
E. Auxiliary relays
T. Carrier transmitter
R. Carrier receiver

Unfortunately, requirements 1 and 2 cannot be met on systems where synchronous machinery is present at both ends of the line since out-of-step conditions correspond to an intermittent 3-phase short circuit at the electrical center of the system. It becomes necessary, therefore, to sacrifice one requirement in favor of the other. When the first requirement is to be met, overcurrent relays are used and a false operation during out-of-step conditions can be expected; when the second is to be met, current balance relays are used and the line is not protected against balanced 3-phase short circuits. The latter is shown in the wiring diagram of Fig. 7. The power directional relays are so connected that their contacts close when the direction of power is from the line to the bus. The contacts of the instantaneous overcurrent relays are in series with those of the directional relays in order to prevent locking out on load currents. When both the directional and the instantaneous relays operate and have their contacts closed, the lower auxiliary relay is energized and its 2 contacts close. One contact energizes the upper auxiliary relay, and the closing of the second contact transmits a signal to the other end of the line where it energizes the upper auxiliary relay. The upper auxiliary relay short-circuits the coils of the current balance or overcurrent tripping relays. The contact resistance of the auxiliary relay must be very low.

Time involved in the operation of this protective system is as shown in the oscillogram reproduced in Fig. 8. Less than a cycle is required for the contacts of the directional and instantaneous relays to close, less than a cycle for the lockout signal to be received at the other end of the line, and less than a cycle for the upper auxiliary relay to short circuit the coils of the tripping relays. A total time of $2^1/_2$ cycles is

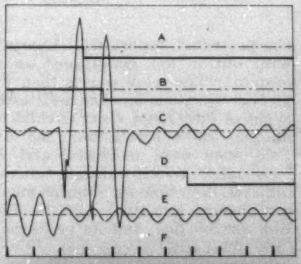


Fig. 8. Reproduction of an oscillogram showing performance of carrier current pilot protection

A. Operation of directional relay (external)
B. Lockout received at far end of line (external)
C. Current in tripping relays (external)
D. Operation of tripping relays (internal)
E. Voltage on directional relay
F. 50-cycle timing wave

Fig. 9. An experimental carrier current pilot protection relay panel

required for the lockout operation. The operating time of the tripping relays also is shown on the oscillogram, and is seen to be 5 cycles at 2,000 per cent tripping current.

Figure 9 shows 1 of the 2 experimental relay panels that were subjected to severe tests in the laboratory and in the field. The laboratory tests similated all types of faults and short circuits of a wide range of current and voltage values internal and external to

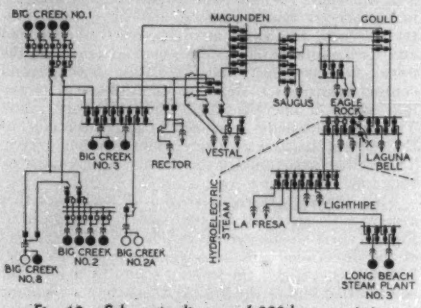


Fig. 10. Schematic diagram of 220-kv transmission system showing point of separation

■—Switches closed □—Switches open
X—Switches opened during out-of-step conditions to effect separation

the protected apparatus. Every test was repeated with out-of-step conditions on the experimental system. The relay panels then were installed on a 16.5-kv transmission line and tested by applying all types of faults and short circuits to that line and to another line operated from the load end bus. The field tests were successful and many oscillograms were taken to substantiate laboratory tests and to indicate direction for improvements. A permanent installation was made on the East Gould-Laguna Bell 220-kv line, and its performance is being carefully observed.

Automatic System Separation

When out-of-step conditions occur on the system of the Southern California Edison Company, the following procedure is used to restore normal operation: The system is separated into 2 groups, hydroelectric and steam; and after normal speed and voltage are obtained on the 2 separate groups, they are paralleled again at the point of separation. The point of separation is established beforehand, it being determined by generating capacity on line at the Long Beach steam station and loads on transformer banks at the nearest substations. A typical operating arrangement is shown in Fig. 10. In this particular case 200,000 kw of generating capacity is on line at the Long Beach station, and the separation point is shown at Laguna Bell by the 2 oil circuit breakers with crossing diagonals. After separation the steam station would carry La Fresa, Lighthipe, and 2 transformer banks at Laguna Bell, the balance of the system load being left with the hydroelectric plants.

On several occasions it was observed that when out-of-step conditions exist on the system, the synchronous condensers slow down to about 70 per cent of synchronous speed and run at that speed until switched off the line or until operating conditions are altered in some other way. If the system is allowed to operate for any length of time under such conditions, the condenser and generator damper windings and field structures will overheat rapidly and eventually will burn out. (See "Out-of-Step Conditions on a Synchronous System," by Alex A. Kroneberg, Electrical Engineering, v. 51, Nov. 1932, p. 769–72.) The synchronous condensers were equipped with underspeed relays which trip the condenser oil circuit breakers when the speed drops to 88 per cent of synchronous speed.

System separation is performed when the operator observes from his indicating meters that out-of-step conditions exist on the system. A relay has been developed which automatically will detect out-of-step conditions and perform the separation. This relay consists of 3 instantaneous overcurrent elements operated by the total phase currents in both lines feeding the substation from the steam station. The contacts of these 3 elements are connected in series and they operate a ratchet type relay. The ratchet relay operates when energized from 3 to 10 times per second; an auxiliary relay energized by the ratchet relay trips the oil circuit breakers selected for the separation. A simple schematic diagram of the automatic separation relay is shown in Fig. 11.

Faults involving 1 or 2 conductors will operate only that many instantaneous overcurrent elements, and the circuit of the ratchet relay will not be completed. Balanced 3-phase short circuits will bring up all 3 elements only once and will move the ratchet relay

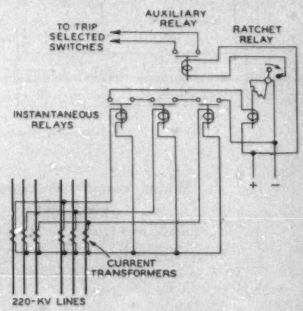


Fig. 11. Schematic diagram of automatic separation relay

one notch. During out-of-step conditions, however, the ratchet relay will be operated more than once. It can be set to operate on 2, 3, or 4 current swings.

Miscellaneous Relay Applications

Internal faults sometimes are detected on generators that cannot be taken out of service for repairs

without affecting operating economies. For example, failures of insulation to ground in the fields of 2 17,500-kw water-wheel generators were detected at Kern River No. 3 powerhouse during the spring run-off. Kern River No. 3 is a river flow plant with no facilities for storage. It was desired to keep the generators in service until fall when the flow of the river is low and the powerhouse operates at a fraction of its capacity. At the same time it was feared that a second fault to ground at some other point in field windings would result in serious damage to the machine. The situation was met by applying additional protection based upon the principle of a Wheatstone bridge. A 500-ohm potentiometer was connected across the field terminals, and a sensitive relay was connected from the sliding contact to ground. The point of zero potential to ground was located on the potentiometer, after which the sliding contact was clamped at that point. The contacts of the relay were connected in parallel with contacts of the armature differential relays. With this scheme of protection in operation, the generators were kept in service until conditions of river flow permitted their removal for repairs.

A somewhat similar problem was encountered at Big Creek No. 1 hydroelectric plant where a 28,000-kw generator relayed on differential protection, indicating a fault to ground in the armature windings. This generator is Y-connected with the neutral solidly grounded, and is tied to Δ-connected low voltage windings of a transformer bank. A high potential test with the machine at standstill failed to detect the location of the fault, making quick repairs problematical; therefore, the unit was placed back in service with its neutral disconnected from ground. In order to detect the recurrence of the ground fault 3 potential transformers were connected to the generator terminals. The primaries of the potential transformers were Y-connected with grounded neutral; the secondaries were connected in series and a bell ringing voltage relay and voltmeter were connected in the circuit.

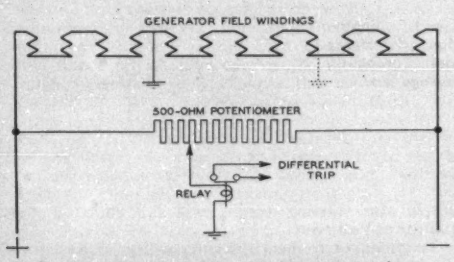


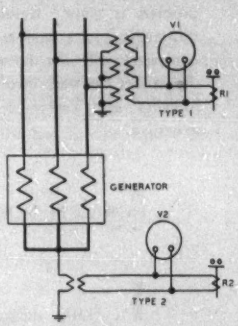
Fig. 12. Wiring diagram of field protection for 2 generators having grounded field windings at Kern River No. 3 powerhouse

With generators operating successfully with the foregoing arrangement, it was decided to use ground detectors and lift the neutrals on old synchronous machines on which insulation failure can be expected. Two types of ground detectors were devised, the one best fitting the physical layout of the generator to be used in each case: The first type was as described in the preceding paragraph; the second one was composed of a potential transformer the primary of which was connected from neutral to ground, and the secondary to a voltmeter and a bell ringing relay. The 2 types are shown in Fig. 13.

Additions of equipment to existing installations, particularly additions of current limiting reactors, often affect the sensitivity of existing relay protection. In cases of this kind additional protection must be developed. When current limiting reactors were installed in the neutral-to-ground connections of the 100,000-kw generators at Long Beach No. 3 steam plant, the current that would result from a fault to ground at the terminals of the Δ-connected low voltage sides of their transformer banks would be limited to only 20 per cent of the minimum trip value of the transformer differential relays. In order to protect the low voltage windings of the transformer bank and the leads and equipment between the windings and the region covered by the generator differential protection, an induction type overcurrent relay with a current transformer of sufficiently low ratio was connected in the neutral of each generator. The tripping contact of this relay was made to operate in parallel with the original transformer differential protection.

Fig. 13. Schematic diagram of ground detectors

V1. 200-volt voltmeter
V2. 67-volt voltmeter
R1. 20-volt bell ringing relay
R2. 7-volt bell ringing relay



Conclusion

In concluding, it can be said that nearly all problems of protection can be solved by exercising ingenuity in the application of standard relays and equipment or in the design of new relays. There is, however, an aspect which must be considered and that is the economic justification of the relay application. The cost of relaying equipment often makes it economically unsound to protect transmission lines properly, thus compelling the abandonment of reliability of service in favor of safety to life and property.

Induction Motor

Locked Saturation Curves

Predetermination of the bend in the locked saturation curves of squirrel cage induction motors is becoming increasingly necessary for design. The reasons why this curve deviates from a straight line are discussed in this paper, and a method of attacking the problem is given. Results calculated by this method for a number of machines are compared with the tested results. It is shown that the work involved in using the formulas and curves presented is not excessive.

By
HORACE M. NORMAN
MEMBER A.I.E.E.
Beloit, Wis.

IN THE design of squirrel cage induction motors it is important that some method of calculating the locked saturation curve be available in order to insure the proper values of locked rotor amperes and of starting torque. This saturation curve, expressed in locked rotor amperes for different applied voltages, tends to curve upward, and it is the deviation from a straight line which is considered in this paper. It is shown that, under certain conditions, an economy may be effected by the method presented herein.

Reason for This Work

Induction motors have always been popular because of their simplicity and consequent lack of trouble in operation; but the heavy current that the normal induction motor draws from the line at the instant of start has been a characteristic which has received its share of criticism. This criticism was met some years ago by offering 2 other types of squirrel cage induction motors in addition to the standard motors. They were the "line-start" motor having low starting current and normal starting torque, and the "line-start" motor having low starting current and high starting torque.

The problem for the designer of these motors is to obtain the required starting torque with the reduced starting current and at the same time keep the rotor running resistance sufficiently low to prevent the speed at full load from falling too far below synchronous speed.

If the starting current of any induction motor were exactly proportional to the applied voltage, then, assuming that the reactance formulas used were reliable, a given rating could be designed so that the starting current would come close to the limit set; and the starting torque would consequently test close to the calculated value. However, it is seldom that the starting current is exactly proportional to the voltage and if plotted against voltage it will usually be found to increase faster than the voltage is increased.

Now suppose that the reactance formulas give results which check the lower part of this curve, then the calculated starting current at full voltage will be lower than the test with the possibility that the test will exceed the guaranteed limit.

Suppose that to meet this eventuality the current is assumed to increase a certain percentage and the guaranteed starting torque will just be met if the current does make this increase; then, should the locked saturation curve be straighter than anticipated, the starting torque will fall short of the guaranteed amount.

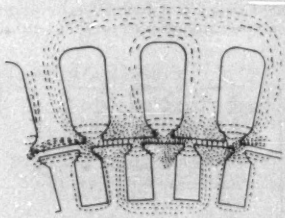


Fig. 1. Illustration of zigzag and tooth-tip leakage flux

To endeavor to meet the current limit if the curve bends up, and at the same time the torque limit if the curve is straight, is in most cases impossible, as the current is usually well up to the limit when the motor delivers the required torque. As the tendency has been to reduce the number of primary slots to the minimum in order to lower the cost of production, this situation has become more pronounced because the locked saturation curve tests straighter for the design which has the greater number of slots.

Of course, if there has already been a test taken on a motor which is similar to the contemplated design then it is possible to interpret the locked saturation curve of this old design so as to be sure of the performance of the new design; but if there is no such test available, then the previous arguments show why some method of calculation for this possible increase in current could be used to advantage.

Nature of Decrease in Leakage

The cause for the upward bend in the locked saturation curve is well known, this upward bend being due to the saturation of the leakage flux paths

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery. Manuscript submitted Jan. 11, 1933; released for publication Aug. 28, 1933. *Not published in pamphlet form.*

with a consequent reduction in counter electromotive force.

Suppose that a motor be started on greatly reduced voltage so that there is no saturation of the leakage flux paths, and that it draws a current of 10 amp from the line. This 10 amp will cause a leakage flux that in turn causes a counter voltage which, when added vectorially to the resistance drop, balances the applied voltage.

Now suppose that the voltage be increased so that the current becomes 50 amp, and that the leakage paths are now saturated; then the leakage flux will not be 5 times as great as in the first case because of the saturation. The counter voltage of the leakage will therefore be less than 5 times what it previously was and when it is added vectorially to the resistance drop, which is 5 times greater than before, it gives a total voltage of less than 5 times the original voltage. Since the current has increased from 10 amp to 50 amp with less than 5 times as much voltage it follows that the curve of amperes against voltage will bend. To be able to predict the amount of bend it is necessary, then, to be able to foretell the decrease in the leakage due to this saturation. The following arguments show how this can be done.

The flux densities of the leakage flux under locked condition are usually high in the iron which is close to the air gap, but low enough at all other points to assume that there is no saturation in the rest of the iron circuit. (See Fig. 1.) It is the zigzag leakage and the tooth-tip leakage that become saturated; and since both of these employ the tooth-tip iron to carry their fluxes, then it follows that they must both be saturated if there should be any saturation. This is an important point for it draws attention to the fact that, to be fundamentally correct, any method of calculating the changes in leakage should require an adjustment on both the zigzag and tooth-tip leakages if any adjustment is necessary.

Derivation of Formulas for Zigzag Leakage Change

Since the zigzag leakage is caused by both the primary and secondary windings then the average of the effect of each must be taken. For a full pitch winding the maximum ampere turns for one primary slot equals the amperes per conductor, times the square root of 2, times the conductors per slot. Each primary slot in which this group is represented has this same magnetomotive force. For a chorded winding, however, some of the slots will have a reduced magnetomotive force and the average is thereby lowered. This is taken care of by multiplying by the term K_s given in Fig. 3.

The peak value of the secondary current per slot with the rotor locked equals the amperes per primary conductor, times the square root of 2, times the primary conductors per slot, times the product of the primary distribution and chord factors, multiplied by the number of primary slots divided by the number of secondary slots. The average value of current per bar over a length corresponding to a primary group is the above peak value multiplied by the primary distribution factor.

The average magnetomotive force per slot is taken as the mean of the 2 average values based upon the above.

However, for some ratings, where the horsepower per pole is small, there may be an appreciable difference at start between the secondary current in terms of the primary and the primary current itself. To compensate for this the average magnetomotive force per slot is multiplied by the square root of (the no-load counter voltage divided by the impressed voltage).

This is all expressed in eq 1.

$$(AT) = \text{amperes per conductor} \times \sqrt{2} \times \text{conductors per slot} \times \left\{\frac{K_s + K_c \times K_d^2 \times S_1/S_2}{2}\right\} \times \sqrt{\frac{E_v}{E}}$$

$$= \text{amperes per conductor} \times \text{conductors per slot} \times 0.707 \times \left\{K_s + K_c \times K_d^2 \times \frac{S_1}{S_2}\right\} \sqrt{\frac{E_v}{E}} \qquad (1)$$

Where

(AT) = average magnetomotive force per slot of the primary and secondary over a phase group
K_s = winding constant from Fig. 3
K_c = chord factor
K_d = distribution factor
S_1 = number of primary slots
S_2 = number of secondary slots
E_v = no-load counter voltage per phase
E = impressed voltage per phase
$\sqrt{\frac{E_v}{E}}$ is usually close to unity and can in most cases be omitted

These average ampere turns drive the zigzag flux across 2 air gaps and through the iron. The problem resolves itself into finding the proportion of the

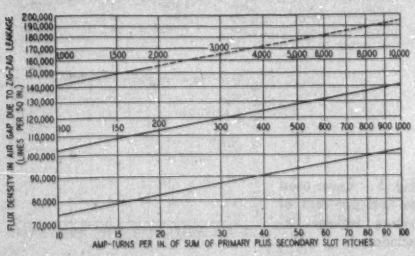


Fig. 2 (left). Iron saturation curve used for zigzag leakage flux

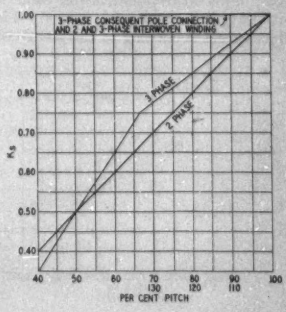


Fig. 3 (right). Curve for finding K_s for different throw or coils

ampere turns required to drive the flux across the air gap twice, to the total ampere turns; for this is the same ratio as the zigzag reactance with saturation to that without saturation.

The following assumptions were made: The saturation curve of the iron for the extremely high densities usually encountered was assumed to be a straight line when plotted on logarithmic section paper; the density in the iron was taken as that in the air gap, and the length of path was assumed to be equal to the sum of the primary and secondary slot pitches. These assumptions were perfectly logical because the position of the straight line can be changed around to compensate for the assumption of the length of path, and also of the density which was taken; and it is true that the saturation curve for high densities in iron does straighten out on logarithmic paper. By working back from tests on various designs the position of the line was found and is shown in Fig. 2.

Taking a particular case where the sum of the slot pitches is assumed to be unity and the air gap 0.02 in., and assuming various densities for the zigzag leakage flux, the ampere turns for the one inch of iron is found by Fig. 2, and that for the air by the usual air gap formula, remembering that there are 2 air gaps involved. Table I shows these figures. The sum of the ampere turns for the iron and the air is tabulated. The ratio of the ampere turns for the gaps to the total ampere turns times 100 gives the per cent zigzag.

If the actual density is divided by the per cent zigzag and multiplied by 100, then a fictitious value of density is found. This fictitious value, however, is the value which is the easier to find from the design of the motor, for it can be found by equating the average ampere turns given in eq 1 to twice the mechanical air gap in the usual formula for flux in air.

The percentage zigzag is plotted against this fictitious density in Fig. 4 together with 4 other similar curves for other ratios of the air gap to the sum of the slot pitches. The curves shown in Fig. 4 cover all the possibilities of this ratio which is encountered in practice.

By examining this family of curves it is found that the center curve alone can be used, which is shown in Fig. 5, provided that an adjustment is made on the value of the fictitious density previously referred to. This adjustment is the value given in eq 3 and it is applied according to eq 4. The curve in Fig. 5 has values according to the last 2 columns of Table I.

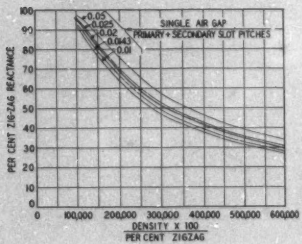


Fig. 4. Curves of per cent zigzag for various ratios of air gap to the sum of the slot pitches

Let

$$\alpha = \frac{\text{single mechanical air gap}}{\text{primary + secondary slot pitches}} \tag{2}$$

and

$$\beta = 2.5\sqrt{\alpha} + 0.64 \tag{3}$$

$$\text{Fictitious } B_L = \frac{(AT)}{0.628 \times g \times \beta} \tag{4}$$

Where

α and β = constants defined by eqs 2 and 3
Fictitious B_L = fictitious value of air gap density used to find per cent zigzag from Fig. 5
(AT) = ampere turns given by eq 1
g = single mechanical air gap

The per cent zigzag leakage can now be found for any value of line current, air gap, slot pitches, winding, or slot combination by using eqs 1, 2, 3, and 4 and the curves shown in Figs. 3 and 5.

Derivation of Formulas for Tooth-Tip Leakage Change

The tooth-tip leakage is reduced when the zigzag leakage is sufficiently heavy to cause saturation of the tooth tips. The effect is as though the tooth tips were partially removed, or in other words as though the slot openings were enlarged; thereby reducing the leakage flux. By working with a large number of tested motors, so that the assumption could be checked, and manufacturing variations and variations in materials eliminated, the amount that the tooth tips apparently changed was found. This indicated that the tooth face was approximately reduced in the same proportion as the reduction in zigzag leakage.

Using this larger slot opening, the slot leakage

Table I—Figures for 0.02-In. Air Gap and Sum of Slot Pitches Equal to Unity

Zigzag Leakage Air Gap Density. Lines/Sq In.	Amp-Turns for 1 in. of Iron	Amp-Turns for 2 0.02-in. Air Gaps	Total Amp-Turns	% Zigzag	(Zigzag Density × 100) ÷ (% Zigzag)
75,000	10	942	952	99.0	76,000
90,000	39	1,130	1,169	96.8	93,000
95,000	57	1,190	1,247	95.5	99,500
100,000	84	1,254	1,338	93.8	106,000
110,000	165	1,380	1,545	89.3	123,000
120,000	310	1,506	1,816	82.9	145,000
130,000	555	1,630	2,185	74.6	174,300
140,000	940	1,756	2,696	65.2	215,000
150,000	1,560	1,881	3,441	54.7	275,000
160,000	2,400	2,008	4,408	45.6	351,000
170,000	3,750	2,132	5,882	36.5	468,000
180,000	5,650	2,260	7,910	28.5	630,000

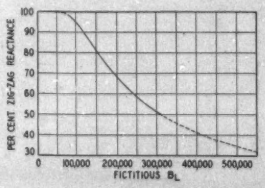


Fig. 5. Curve used to find per cent of zigzag leakage reactance

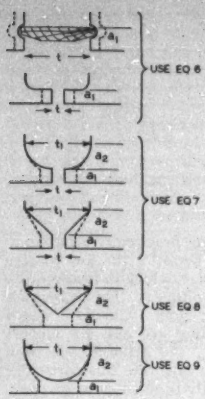


Fig. 6. Various slot shapes and indication of which equation to use

constants are then recalculated and the new slot leakage found from these smaller constants. The calculating of this change in leakage can, however, be reduced by using the formulas of eqs 5 to 9, in conjunction with Fig. 6. In Fig. 6 the sketches of the different slots have dotted lines showing how the slot shape is assumed to change when saturated; the formulas indicated alongside of the different slot shapes give the change in the slot leakage constants. These apply equally well to either the primary or the secondary. The formulas are as follows:

$$C = (\lambda - t)\left\{1 - \frac{\text{Per cent zigzag}}{100}\right\} \tag{5}$$

(See diagrams of Fig. 6 to determine which of the following formulas should be used.)

$$\delta k = \frac{a_1}{t}\left\{\frac{C}{C+t}\right\} \tag{6}$$

$$\delta k = \frac{a_1 + 0.58a_2}{t}\left\{\frac{C}{C+1.5t}\right\} \tag{7}$$

$$\delta k = \frac{a_1}{0.02}\left\{\frac{C}{C+0.02}\right\} + \frac{3.3a_2}{t_1}\left\{\frac{C}{C+0.4t_1}\right\} \tag{8}$$

$$\delta k = \frac{a_1}{0.02}\left\{\frac{C}{C+0.02}\right\} + \frac{2a_2}{t_1}\left\{\frac{C-0.15t_1}{C+0.6t_1}\right\} \tag{9}$$

where

C = apparent change in slot opening due to saturation
λ = slot pitch at air gap (primary or secondary)
δk = change in slot constant (primary or secondary)

For a_1, a_2, t, t_1, see diagrams of Fig. 6.

The derivation of eqs 5 and 6 is as follows:

$\lambda - t$ = unsaturated tooth face

$(\lambda - t)\dfrac{\text{Per cent zigzag}}{100}$ = saturated tooth face

$$C = \lambda - t - (\lambda - t)\frac{\text{Per cent zigzag}}{100}$$

$$= (\lambda - t)\left\{1 - \frac{\text{Per cent zigzag}}{100}\right\}$$

Slot constant for tooth tip (unsaturated) $= \dfrac{a_1}{t}$

Slot constant for tooth tip (saturated) $= \dfrac{a_1}{C+t}$

$$\delta k = \frac{a_1}{t} - \frac{a_1}{c+t}$$

$$= \frac{a_1 \times C + a_1 \times t - a_1 \times t}{t(C+t)} = \frac{a_1}{t}\left\{\frac{C}{C+t}\right\}$$

The derivation of eqs 7 to 9 is not given but these equations are derived in a similar manner to eq 6 with the exception that approximations are made to simplify them. These approximations have all been checked for various per cent zigzag leakages and for all likely slot dimensions, and are sufficiently accurate to use.

After the change in the slot constant is found, from whichever of eqs 6 to 9 that applies, the per cent slot leakage is given by inserting this value in eq 10. This is done for both the primary and the secondary.

$$\text{Per cent slot leakage} = 100 \times \frac{\text{normal slot constant} - \delta k}{\text{normal slot constant}} \tag{10}$$

Where

δk = change in the slot leakage constant

The percentage zigzag and both the percentage primary and secondary slot leakage having now been found it only remains to multiply the normally calculated values by these percentages divided by 100 to get the adjusted values. These added to the primary and secondary end leakages which do not change give the total reactance. Adding this vectorially to the resistance gives the new impedance and this combined with the locked amperes assumed when filling out eq 1 gives the voltage necessary to produce this current.

Should this voltage be appreciably different from the full voltage rating of the machine then the full voltage value can be found by plotting the approximately full voltage point together with a reduced voltage point where the current gives a fictitious B_L of 75,000. For this latter point it can be assumed that there is no saturation.

A curve is now drawn through these 2 points and the value of locked amperes for full voltage is taken from this curve. It should be remembered when drawing in this curve that the curvature is greatest at the value of current or voltage that gives a fictitious B_L of approximately 95,000. Therefore the curve will probably be much straighter at full voltage than at this lower voltage. This is evidenced by the curves shown in Figs. 7 and 8. Should it be inconvenient to plot these points then a fairly accurate approximation can be made by using eq 11.

$$\text{Full voltage locked amperes} = \text{assumed amperes} + K\,(\text{full voltage} - \text{calculated voltage}) \tag{11}$$

Where

$$K = \frac{\dfrac{\text{fictitious } B_L}{100{,}000} - 1}{\dfrac{\text{fictitious } B_L}{100{,}000}(Z_s) - Z}$$

Z_s = impedance calculated with saturation
Z = normal impedance without saturation

This formula should be filled in with values for the leg of the winding.

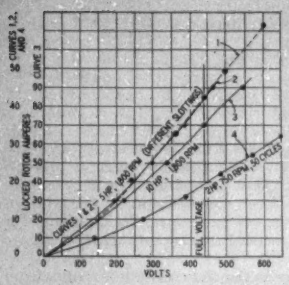


Fig. 7. Locked saturation curves for various ratings having partially closed slot primaries, showing how close the test curves check the calculated points

Curves are test values
Points are calculated values

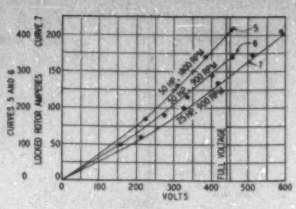


Fig. 8. Locked saturation curves for various ratings having open slot primaries, showing how close the test curves check the calculated points

Curves are test values
Points are calculated values

Comparison of Calculated and Tested Values

If there ever was a mathematical analysis that needed proving it is surely this one. The only justification for publishing these working curves and formulas is that they attain a desired result with reasonable accuracy. It is next to impossible to test the individual steps in the procedure of building up the theory, but it is possible to test the total, and this has been done on many different designs. The calculated values and the test curves of some of these are given in Figs. 7 and 8.

It is seldom that the designer of a new machine is interested in more than the full voltage and some reduced voltage value of locked amperes. However, in checking the previous work a number of points were calculated for various designs for voltages from about 50 per cent to as high as 150 per cent of full voltage, where tests at voltages this high were available. The reason for this is to show that no matter what the field strength should have been for the particular punchings of each machine the calculated locked rotor amperes, using the formulas and curves given in this paper, is very close to the tested result.

The 4 curves shown in Fig. 7 are all for motors having partially closed primary slots. Curves 1, 3, and 4 have bridged secondary slots, while curve 2 is for a secondary having partially closed slots. In Fig. 8 are shown 3 curves for motors having open primary slots and partially closed slot secondaries. It is evident from examination of these curves that the method outlined in this work is well within the accuracy required, especially when it is considered that the difference between tests on 2 motors of the same design will sometimes vary more from each other than the calculated values shown in Figs. 7 and 8 vary from the test values.

One point of special interest is brought out by curves 1 and 2. Curve 1 is for the same rating as curve 2 but the motor has both more primary and secondary slots than the motor for curve 2. The usual calculation for the impedances of these 2 motors is different but the adjusted values of impedance to take into account the saturation of the leakage paths are practically the same for each and the tests indicate that this is correct.

All the curves shown have a decided bend, but there are some designs on which calculations have been carried out, indicating very little change in the reactances; the test shows that this is correct, the locked saturation curve being practically straight.

Curve 1 shows a decided bend for the low voltage values up to about half voltage, which indicates quite a large reactance for these voltages. This is because of the totally bridged rotor slots. Curves 3 and 4 also show this effect, as they are also for motors having bridged rotor slots. No attempt has been made in this paper to try to calculate this particular part of the curve when totally bridged slots are used. However, the effect of added saturation of the bridge due to the presence of zigzag leakage flux is taken into account when the proper formula is used as indicated by Fig. 6.

Scope and Limitations of the Paper

The various formulas are built up with the thought in mind of fitting a wide variety of conditions such as freak slot combinations, multispeed motors, short time ratings where the iron is worked to the limit, ratings having any number of poles, a wide range of air gap possibilities, a range of chording of the winding which covers all that is used in practice, and all the slot shapes usually used at this time including those for double cage and deep bar motors.

The curve given in Fig. 5 has been checked as far down the curve as 50 per cent zigzag against tests on many machines. It is probably correct for much lower percentages, however. Not having sufficient tests at reasonably high voltages to build up other curves similar to that shown in Fig. 5 for high grade silicon irons it cannot be claimed at this time that motors having grades of iron other than the usual low silicon content can be calculated accurately by using Fig. 5.

Since the leakage flux densities vary according to the relative position of the rotor and stator, and also are different for different parts of the tooth end, then it can be seen that Fig. 2 is for the average of all these conditions. Since the saturation curves of low grade and high grade silicon iron cross, then it is probable that Fig. 2, and consequently Fig. 5, are not very far from that which should be used for the different grades of iron encountered.

As explained before, this paper does not take into account the bend in the locked saturation curve which is caused by totally bridged slots, this bend being at much lower voltages than the full voltage. It does, however, enable the upper part of the curve, say from about half voltage, to be calculated.

Another condition that this paper does not cover is that in which the saturation is not primarily caused by the zigzag flux but by the tooth-tip flux, more

often the secondary. In this case, which is most marked for a buried winding machine, the magnetomotive force of the slot is great enough to drive a sufficient flux across from one tooth tip to the other to cause saturation of these tooth tips. This in turn causes saturation of the zigzag leakage flux.

It is possible to calculate the decrease in both leakages by making up suitable curves and reversing the procedure outlined in this work; in other words, the per cent secondary leakage is calculated first and then from this the percentage zigzag is found.

This problem does not lend itself to clean cut formulas, however; and for this reason, together with the fact that the bend is not so great as that which can be caused by the zigzag magnetomotive force when it is the prime cause of the saturation, no attempt has been made here to cover this particular case.

Other than these limitations it is believed that this paper covers all the possibilities met with in practice today, and that in so doing it will help in the more precise design of ratings where the starting requirements are exacting.

In the opening paragraphs it was pointed out that the locked saturation curve bends more as the number of slots is reduced. It is also true that as the iron dimensions are reduced the curve also bends to a greater degree, as the saturation is naturally higher to maintain the torques required for the rating. In the effort to try to design these squirrel cage motors economically the aim has been in the direction of fewer slots, or smaller iron dimensions, or both; but the difficulties encountered by the problematical effect of the saturated leakage paths with no method available to calculate its effect has naturally had the tendency with some designers to limit their steps of economizing in these directions. It is hoped that this paper will help to lift this barrier to progress in the direction of more economical motors.

Appendix—Calculation of a 7.5-Hp 1,800-Rpm Motor

This motor had 36 primary slots and was delta connected. There were 60 conductors per slot and the throw of the coils was 1 to 8. The full rating was 7.5 hp, 1,800 rpm, 3 phase, 60 cycles, 440 volts. The total resistance of the primary and secondary windings with 10 per cent added for eddy current effect and higher temperature encountered under locked condition = 6.3 ohms per leg of the winding.

The reactances calculated without any adjustment for saturation were:

Primary slot	= 3.51
Secondary slot	= 2.42
Primary and secondary end	= 3.68
Zigzag	= 7.19
Total reactance	= 16.8 ohms per leg of the winding.

The impedance $= \sqrt{(16.8)^2 + (6.3)^2} = 17.94$ ohms.

If there were no saturation of the leakage paths, then the locked rotor current would equal $\sqrt{3} \times 440/17.94$, or 42.4 amp in the line.

Assume that the current bends up to 53 amp in the line for some voltage near 440, then from eq 1:

$$(AT) = \frac{53}{\sqrt{3}} \times 60 \times 0.707 \left\{0.834 + (0.96)^2 \times 0.94 \times \frac{36}{48}\right\} = 1{,}930$$

because $K_s = 0.834$, $K_d = 0.96$, and $K_s = 0.94$.

The air gap equaled 0.015 in., and the primary slot pitch equaled 0.611 in., and the secondary 0.456 in.

$\alpha = 0.015/(0.611 + 0.456) = 0.01406$, from eq 2

$\beta = 2.5\sqrt{0.01406} + 0.64 = 0.936$, from eq 3

$$\text{Fictitious } B_L = \frac{1{,}930}{0.628 \times 0.015 \times 0.936} = 219{,}000, \text{ from eq 4}$$

Per cent zigzag = 64.3, from Fig. 5

For the primary $t = 0.12$, $a_1 = 0.05$, $a_3 = 0.125$

Primary $C = (0.611 - 0.12)(1 - 0.643) = 0.175$, from eq 5

$$\text{Primary } \delta k = \frac{0.05 + 0.58 \times 0.125}{0.12}\left\{\frac{0.175}{0.175 + 1.5 \times 0.12}\right\} = 0.50 \text{ from eq 7}$$

$$\text{Per cent primary slot leakage} = 100 \times \frac{2.25 - 0.50}{2.25} = 78, \text{ from eq 10}$$

For the secondary the opening = zero, $a_1 = 0.005$, $a_4 = 0.06$, $l_1 = 0.165$

Secondary $C = 0.456\,(1 - 0.643) = 0.163$, from eq 5

$$\text{Secondary } \delta k = \frac{0.005}{0.02}\left\{\frac{0.163}{0.163 + 0.02}\right\} + \frac{3.3 \times 0.06}{0.165}\left\{\frac{0.163}{0.163 + 0.4 \times 0.165}\right\} = 1.08, \text{ from eq 8}$$

$$\text{Per cent secondary slot leakage} = 100 \times \frac{2.17 - 1.08}{2.17} = 50, \text{ from eq 10}$$

The reactances with 53 amp flowing in the line equal:

Primary slot	= 3.51 × 0.78	= 2.74
Secondary slot	= 2.42 × 0.50	= 1.21
Ends	=	3.68
Zigzag	= 7.19 × 0.643	= 4.62
Total reactance		= 12.25

$$Z = \sqrt{(12.25)^2 + (6.3)^2} = 13.78$$

$$\text{Voltage} = \frac{53 \times 13.78}{\sqrt{3}} = 422$$

In Fig. 9 is shown the point 53 amp and 422 volts plotted together with the point 18 amp and 186.7 volts, the 18 amp being the value of current which gives a fictitious B_L of 75,000, approximately. At this point the curve begins to bend, and it has its greatest curvature approximately at the 23-amp point. As explained before, it straightens out again as the current and voltage increase. Knowing these

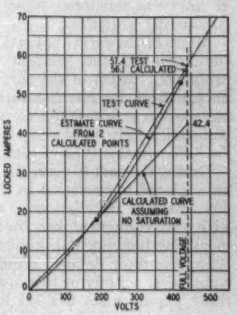


Fig. 9. Illustrates method used to find full voltage locked rotor amperes

characteristics, the curve can be drawn in accurately enough to get the full voltage point, which shows 56.1 amp for 440 volts. The test curve shows 57.4 for 440 volts which is about 2.4 per cent higher. Had the saturation of the leakage paths not been taken into account, then the calculated value would have been taken as 42.4, the test value of 57.4 being 35.4 per cent higher.

It is interesting here to note that the value obtained from eq 11 which eliminates the necessity of plotting the points and drawing in a curve, is 56 for the current in the line as compared to 56.1 found from the curve.

Recent Developments in Power Line Carrier

Some recent developments in power line carrier telephone equipment that greatly enhance the value of this type of communication are described in this paper. Two outstanding developments have been an automatic volume control, and means for interconnecting the carrier circuits with 2-wire telephone facilities. In addition, much has been achieved in lowering installation and maintenance costs, and in improving reliability of operation.

By
T. JOHNSON, JR.
ASSOCIATE A.I.E.E.

General Elec. Co.,
Schenectady, N. Y.

IN THE OPERATION of power transmission systems, carrier telephony over power conductors has been of great service over the longer distances and where it is necessary to reach power plants in sparsely settled locations. It also has been viewed to some extent as a communication factor of safety in territories where other communication is normally available.

Many of the early applications were of a character that required the solution only of fundamental problems. Much of the earlier apparatus included no provision for meeting various requirements that have arisen as installations have expanded and power companies have indicated the necessity for greater flexibility in this type of communication.

During the past 10 years the various manufacturers have placed in operation in the United States some 300 station installations. Operating experience with this equipment has been invaluable not only in solving fundamental problems, but also in formulating the more detailed requirements of the power companies. Study of this operating experience and these requirements has led to the development of carrier equipment of a new design embodying features that should render this method of communication of even greater practical value.

It is believed that these developments mark an important advance in power line carrier telephony, in that the more serious technical and economical limitations previously encountered now are removed.

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted Jan. 22, 1934; released for publication March 5, 1934. *Not published in pamphlet form.*

The unit type of mechanical design permits manufacture of standard unit assemblies that can be used in many special and unusual combinations, in addition to the 8 standard simplex and 6 duplex assemblies. Much has been achieved in lowering installation and maintenance costs, and in improving reliability of operation. Interchangeability of units provides a means of easily adapting the carrier system as a whole to changes in communication requirements as they arise, even to the extent of converting "simplex" into "duplex" assemblies.

Electrically, the new circuits eliminate serious variations in received signal levels, and afford trunk line service through standard means of connecting the carrier to existing private branch exchange boards and other telephone terminal facilities. The usefulness of power line carrier telephony is much enhanced and the field of application considerably enlarged.

Advantages of Single-Frequency Systems

For a large part of this communication field the use of a single carrier frequency per communication channel has been conceded quite generally to have a number of inherent advantages over methods employing 2 frequencies per channel. Conservation of available frequencies and channels, minimum effect of transmission irregularities and switching operations, and equal transmission losses in both directions are outstanding among these advantages. Single-frequency systems reduce appreciably the problems of tuning coupling circuits and permit the full party line communication feature deemed important by many power system operators.

Fig. 1. Single-frequency power line carrier telephone equipment showing 10-watt duplex assembly

With a single-frequency system it is obviously necessary that the transmitter operate only during speech or call transmission, and that during periods of transmitted speech the associated receiver be effectively blocked. The simplest and least costly method of accomplishing this is by manual control, a button conveniently located on the handset being depressed while talking and released while listening. This method of operation generally is referred to as "simplex." Methods of automatic control by means of voice-actuated schemes generally are referred to as "duplex." Thus in connection with power line carrier telephony the terms "simplex" and "duplex" have meanings slightly different from those with which they are associated in wire line telephone and telegraph practice.

Simplex carrier apparatus has found rather wide application in power dispatching communication and for patrol and unattended stations. In the development and design of simplex apparatus the problems have been quite fundamental in nature.

Duplex apparatus, however, has required much more extensive study and development. Here there has been a growing demand for more flexibility so that a communication problem might be met more economically by applying only those elements of apparatus required for the particular case, but with the possibility of making additions or alterations, conveniently and at reasonable cost, as requirements changed. In this connection there has been a demand for duplex apparatus that might initially be installed for simplex operation.

Two outstanding and related problems have been the development of an automatic volume control and a means of readily interconnecting carrier equipment with 2-wire telephone facilities involved in direct extensions or those through private branch exchange boards. A volume control was required that automatically would compensate for variations in signal levels due to the different power line distances between stations and due to varying conditions on the power transmission lines such as switching. The volume control constituted the prior problem in that a substantially constant audio output level from the receiver was essential to the development of the 2-wire extension apparatus.

In considering this extension apparatus there was sought the complete elimination of the hybrid transformer and wire-line balance network which has proved successful only under rather limited conditions. Effort also has been made to increase reliability and reduce maintenance by the elimination of all batteries and multiple-unit motor generators supplying the various demands for potential. Much attention also has been given to minimizing wear on relays and selector mechanisms. Another point worthy of mention is that considerable provision has been made to accommodate in the standard equipment any apparatus required for special problems.

Several years pursuit of these various objectives have culminated in the design illustrated in Fig. 1. The equipment is divided into main units, each assembled on a separate shelf, mounted in an enclosing steel cabinet. Some shelves embrace several subunits. These units and subunits are used in various combinations to form complete equipment of either simplex or duplex type.

Most of the units have separate rectifier and filter equipment for supplying the necessary plate and grid bias voltages to the various vacuum tubes used. This allows these units to operate independently of other units in this respect regardless of the combination used; it also simplifies rectifier design and requires less wiring between units.

The units are designed to operate from a single-phase a-c power station lighting circuit of 110 or 120 volts, 50 or 60 cycles. No rotating machines such as high voltage motor generator sets or ringing converters are used. As provision against failure of the lighting circuit supply, arrangement may be made whereby on such failure a small 2-unit motor alternator or dynamotor starts, operating from the station control battery and furnishing the 110-volt 60-cycle supply normally provided by the lighting circuit. No batteries of any kind are used with any of the units or combinations.

Fig. 2. Basic 10-watt transmitter unit

The interior of the cabinet, the shelf supports, and all of the shelf units are finished in aluminum paint. This finish gives the equipment a pleasing clean-cut appearance and is very durable. It also contributes to ease in maintenance by the better reflection of light in the interior of the cabinet. The exterior of the cabinet is finished in a dull black to conform with other interior station apparatus.

Description of Units

With the exception of the relay units, which are divided into sections to accommodate the subunits or attachment units, a uniform type of mechanical construction is used throughout. Details of this construction are shown in Figs. 2, 3, 4, and 6. The base is formed by bending down the front and rear edges of a flat steel sheet to give the equivalent of a shallow channel section 15 in. wide by $32^1/_2$ in. long and $2^1/_2$ in. deep. All of the main apparatus parts such as transformers, reactors, and vacuum tubes, are mounted on top with terminals extending through to the under side where are located small parts such as resistors and small fixed condensers. As shown in Fig. 4, the main terminal blocks and practically all of the wiring also are located on the under side.

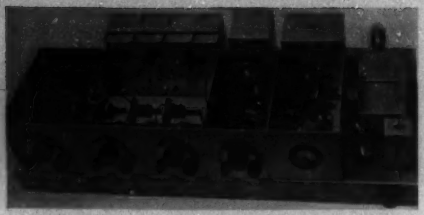


Fig. 3. Receiver unit

Fig. 4. Receiver unit showing wiring restricted entirely to under side of base

This arrangement simplifies manufacture and permits the terminals of all parts to be reached easily for testing or inspection.

The units are supported by means of angle pieces at the sides of the cabinet and held in place by bolts extending through the shelf and the supporting angles. However, for increased accessibility, the shelves may be pulled forward and tilted up or down.

Transmitter Unit. The unit illustrated in Fig. 2 is used as the basic transmitter portion of all transmitter-receiver assemblies, both simplex and duplex. A modified Hartley type master oscillator, covering a frequency range of from 50 to 150 kc, provides excitation for a class *C* power amplifier to produce a normal carrier output of 10 watts. The modulator circuit uses 2 tubes of the zero grid bias type operating class *B* push-pull, and produces sufficient output on voice frequency peaks to modulate the 10-watt carrier 100 per cent. A class *A* speech amplifier tube prevents speech distortion by supplying the modulator grid losses. All filament and plate voltages for the vacuum tubes of this unit are cut off during "stand-by" periods. The rectifier circuit, which supplies plate and grid bias voltage for these tubes, uses a small full wave rectifier tube of the mercury vapor type. Because of its slower starting characteristics the filament of this tube normally is arranged to operate continuously.

The 3-winding output transformer of this unit is designed to work either into output circuits using cable or open-wire lead-in construction, or into the grid tank circuit of the output amplifier unit when the latter forms a part of the assembly. To provide "intersystem" operation, where the same equipment is used to communicate on either of 2 channels of differing frequencies, provision is made on this unit for the addition of a second master oscillator variable condenser and a relay to accomplish the necessary switching operation.

Output Amplifier Unit. Where communication distances or transmission losses require greater transmitter output than that provided by the transmitter unit, an output amplifier can be used with both simplex and duplex assemblies to obtain an unmodulated carrier output of 50 watts, and a peak power output of 200 watts with complete modulation. Two 50-watt tubes are used in a class *B* push-pull linear amplifier circuit. Excitation for the grids is obtained from a grid tank circuit consisting of a tapped inductance and a variable capacitor which, in turn, is fed from the output transformer of the transmitter unit. Two half-wave rectifier tubes of the mercury vapor type supply the 1,000-volt d-c plate potential. The output transformer of this unit is designed to operate into circuits using either cable or open-wire lead-in construction.

Receiver Unit. Figures 3 and 4 show 2 views of the receiver unit used with all simplex and duplex assemblies. This receiver has a number of unusual features. Referring to the simplified schematic diagram, Fig. 5, the 3 inductively coupled circuits preceding the carrier frequency amplifier tube *V-1* are tuned by means of individual variable condensers, to form a band pass filter adjustable to any frequency in the 50-to-150-kc range. The plate circuit of the screen-grid variable-amplification-factor tube *V-1* also is tuned to the carrier frequency resulting in an over-all characteristic of the filter and amplifier such that side-band frequencies within 3,000 cycles from the carrier are not attenuated appreciably. At the same time, the selectivity obtained permits adjacent channels to be spaced from 10 kc apart at the lower, to 15 kc apart at the upper end of the range.

The detector or demodulator, *V-2*, is a 3-element vacuum tube of the indirectly heated cathode type. The 2 secondary windings of the detector output transformer are connected to the amplifier tube *V-3* and to a 500-ohm telephone circuit. During "stand-by" periods, this latter tube can be connected either as a class *A* audio amplifier to operate a loudspeaker, or as a relay amplifier to actuate the sensitive calling relay of the selective bell ringing apparatus. When the carrier equipment is in use during a conversation, tube *V-3* can be used if necessary as an audio amplifier in connection with the voice operated control circuits. For simplification, the relay and associated circuits for making these connections are not shown.

The automatic volume control operates so that an increase in detector plate current caused by an increase in the received signal level results in a corresponding increase in voltage drop across resistor *R-1*, which is in series with the detector cathode return. This voltage drop across *R-1* is applied to the rectifier tube *V-4*, in series with the high resistance *R-2*. The increase in voltage across *R-2* charges the large condenser *C-2* to a higher potential and at the same time swings the grid of the screen-grid tube *V-5* in a positive direction. This causes *V-5* to

draw more plate current through the resistor *R-3* which in turn increases the negative bias on the grid of the amplifier tube *V-1*, thereby decreasing the amplification of the signal supplied to the detector. Because of its variable amplification factor, a comparatively small change in the grid bias voltage of tube *V-1* causes a large change in the gain on this stage, the action being such that a decrease in gain takes place very quickly. An increase in gain, however, can take place only as rapidly as the charge on *C-2* decreases by leakage through *R-2*. Thus the values of *C-2* and *R-2* can be selected to obtain the desired time constant.

In operation, the volume control makes a quick adjustment of gain at the beginning of the first quarter impulse received, and unless there are intervals of longer than approximately 30 sec between following impulses, the gain established is maintained practically constant throughout a conversation. In practice, it has been found that the circuit will provide an essentially constant audio output level for variation in carrier input level of approximately 40 db, which is sufficient to take care of the maximum variations usually encountered.

In addition to its functions as a volume control and a carrier frequency amplifier, tube *V-1* also serves as a receiver blocking tube. During operation of the transmitter the screen grid of this tube, which normally is maintained at a positive potential of 100 volts, is connected to a negative point in the voltage divider by means of relay contacts located on another unit. This action effectively blocks the receiver and prevents any of the transmitted signal from appearing in the receiver output.

A full wave rectifier of the mercury vapor type is used to provide all plate and grid bias voltages. As shown in Fig. 3, all carrier frequency portions of the circuit are enclosed in an aluminum shield with separate compartments for the filter, carrier frequency amplifier, and demodulator circuits.

Duplex Control and 2-Wire Extension Units. The duplex control and 2-wire extension equipment form an essential part of all duplex assemblies. They comprise the third and fourth shelves from the top of the assembly shown in Fig. 1. Electrically, these 2 units are associated closely with each other and with practically all parts of the complete circuit.

One of several unusual features of these circuits is the method used to obtain a speech signal delay. Since cost, complexity, and space limitations prohibited the use of electrical delay network, search for a suitable method of delay was confined largely to some of the simpler forms. After considerable development, a device based upon the principle of the Poulsen telegraphone finally was selected. This mechanism is incorporated in one of the units shown in Fig. 6. It consists essentially of an accurately machined disc of insulating compound mounted on the shaft of a small induction motor and wound along its cylindrical edge with a single layer of hard steel wire. Two small coils with suitably shaped pole pieces mounted in close proximity to the periphery of the disc respectively record and reproduce a magnetic record in the steel wire. The audio signal appearing at the terminals of the pick-up coil is similar to the original impressed on the wire by the recording coil, except that it is delayed by the interval of time required for a point on the disc to travel from the recording to the pick-up coil. A small permanent magnet then erases the record and reestablishes the proper magnetic status of the steel wire necessary for continuous operation.

Within the limits of signal levels used, the device has negligible amplitude distortion. The frequency characteristic, which is largely a function of the peripheral speed of the steel band, inherently drops off at the higher audio frequencies, but with a comparatively simple equalizer a sufficiently uniform characteristic between 300 and 3,000 cycles readily can be obtained. The over-all attenuation of about 20 db is recovered in a 2-stage amplifier forming part of the same unit.

The schematic block diagram, Fig. 7, illustrates the essential circuit and operations involved in the

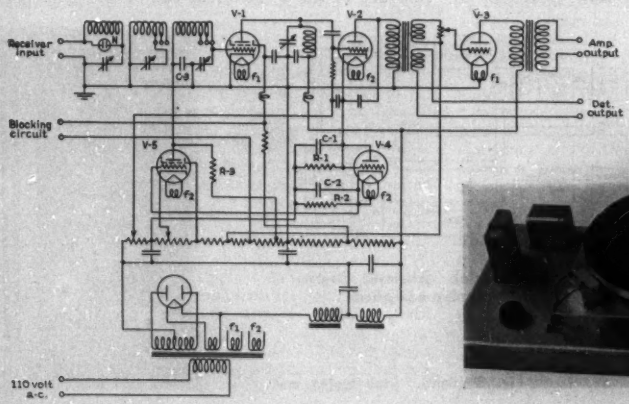


Fig. 5 (left). Schematic diagram of receiver unit

Fig. 6 (below). Speech delay unit

duplex equipment during transmission and reception. The circuit as shown represents conditions when there are no signals being transmitted or received. During transmission, the voice signal originating at the connected telephone set passes through transformer *T-2* and the contacts of relay *R-1*, and then divides between amplifiers *A-5* and *A-8*. That part of the signal passing through amplifiers *A-8* and *A-9* causes relay *R-2* to operate. Operation of *R-2* closes 2 pairs of contacts, one of which starts the master oscillator through the master oscillator control tube, and thus causes the carrier wave to be transmitted, while the other contacts block the receiver in the carrier frequency amplifier stage.

The path taken by the voice signal through amplifiers *A-5* and *A-6* leads to the delay mechanism, where a delay of approximately 0.04 sec is introduced. From the pick-up of the delay mechanism the signal then passes through amplifier *A-7*, contacts of relay *R-1*, speech amplifier *A-1*, and then to the modulator system where it modulates the carrier previously started.

During reception, the received carrier frequency signal passes through the input filter and the carrier frequency amplifier to the detector, where it is demodulated in the usual manner. The audio signal output of the detector divides between amplifiers *A-2* and *A-4*. The amplified output of *A-4* operates relay *R-1*, thereby opening the input to amplifiers *A-1*, *A-5*, and *A-8*, and connecting the output of amplifier *A-7* to the telephone line. The circuits thus are prepared by the time the delayed signal reaches the telephone line through amplifiers *A-4* and *A-6*, the delay mechanism, and amplifier *A-7*.

The relay amplifiers *A-3* and *A-9* contain 3-element hot-cathode mercury-vapor tubes which operate the associated relays *R-1* and *R-2*. These tubes must operate on a d-c plate supply, and therefore require a third tube of that type operating on alternating current to cut them off when the voice signal falls below a certain minimum level. The large amount of power obtained from these tubes permits the use of standard quick-acting relays of rugged design. These relays are made slightly slow to release to assure that the ends of the delayed signal will not be lost. Quick pull-in is retained by shunting the winding of each relay with a small copper oxide rectifier.

Since the telephone line never is connected to both transmitter and receiver circuits at the same time, there is no need for a hybrid balance circuit. The only adjustments necessary are those of signal level input to the carrier transmitter. Where both long and short telephone extensions are connected to the same equipment, the adjustments of the amplifiers in the control units are set up for the longest extension. For the shorter extensions, a variable attenuation pad automatically is cut into the circuit by relays in the relay unit.

Relay Units. The 2 relay units, one for simplex and one for duplex operation, centralize the majority of all switching functions involved in starting and stopping, receiving and placing calls, and in ringing and switching extension circuits. Their mechanical construction differs slightly from that of the other main units in that provision is made to accommodate subunits or attachment units as required by each individual installation.

One arrangement of the duplex relay unit is shown as the second shelf from the top of the assembly illustrated in Fig. 1. The right-hand half of the unit contains the parts that are common to all of the different arrangements. It includes a full wave Tungar rectifier for supplying a d-c potential of 48 volts to the relay and telephone circuits, and for generating the 400-cycle dialing tone. The left-hand section contains the relays, rotary switch selector, and other auxiliary parts to provide selective bell ringing and full control from a remote point. The relays and selector switch used are standard automatic telephone parts. For convenience in inspection and maintenance they are mounted in a group on a removable subbase.

Provision is made for 4 2-wire extension circuits that can be connected directly to standard 2-wire central battery telephones or through private branch exchange boards to a large number of extensions. Any one of the 4 extensions can be wired for pre-

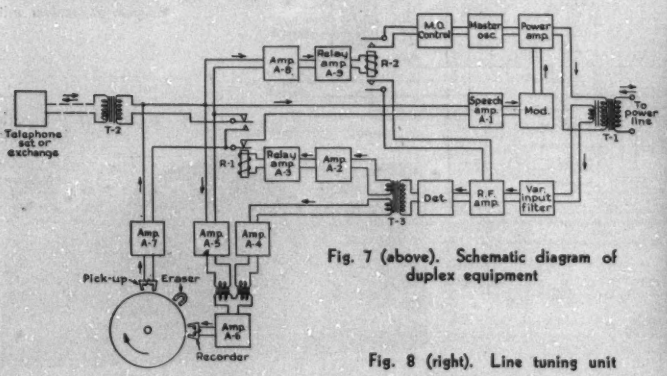


Fig. 7 (above). Schematic diagram of duplex equipment

Fig. 8 (right). Line tuning unit

ferred service so that if desired a power system load dispatcher can break in on a conversation to obtain the use of the carrier channel. Extensions not connected for preferred service are normally locked out and receive a busy tone when an attempt is made to use the carrier channel already in use by other stations or by another extension of the same station.

The selective ringing circuits are designed to respond only to dial impulses and, therefore, voice signals cannot cause false rings or excessive wear of the relays and selector mechanism.

An alternative and relatively simple relay arrangement for duplex operation provides one local telephone circuit with a loud speaker for reception of calls. This circuit can be extended through a private branch exchange board or interconnected to another extension circuit, but it is necessary for a local operator to set up these connections and supervise the incoming and outgoing calls.

The simplex relay unit performs functions for the simplex assemblies similar to those described for the duplex combinations except that the simplex method of operation inherently prevents interconnection with standard telephone circuits. The simplest arrangement in this case provides for local 6-wire extensions with loudspeaker reception of calls. Control and operation over 2-wire extensions from remote points can be provided by adding a simple attachment to this unit and using special extension equipment at the remote end. Selective ringing, where required, can be added also by means of a second attachment.

Cabinet. The standard cabinet used for all simplex and duplex assemblies is illustrated in Fig. 1. It has a width of only 36 in., a depth of 18 in., and an over-all height of 78 in. The steel angle framework arranged to accommodate 6 shelf units is fastened to the top and bottom so that the weight of all shelf units is carried directly to the floor through feet beneath the supporting frames. For combinations requiring more than 6 units, 2 cabinets are bolted together side by side. All external connections including lead-ins from the coupling equipment are brought in through knockouts in the bottom of the cabinet.

Line Tuning Equipment

Where carrier equipment is applied to some of the higher voltage transmission systems, the cost of the coupling capacitors often represents a considerable portion of the investment. It is therefore important that the capacitors be used as efficiently as possible. Considerable economy is effected by using the same coupling capacitors as a source of potential for operating certain instruments and relays, and for several carrier channels.

To meet these requirements, as well as those of a large variety of coupling circuit conditions, the unit principle also has been applied to the tuning equipment. Figure 8 shows one arrangement of units in a standard weatherproof cabinet. Other combinations of standard tuning panels are used to tune one set of coupling capacitors for 1, 2, or 3 carrier frequency channels involving one or more transmitter-receiver assemblies at the same location.

A New Type of Warble Tone Generator

In testing various types of apparatus used in electrical communication circuits, it is often desirable to obtain a single average reading over a range of frequencies. For this purpose a "warble" tone, or a tone the frequency of which varies cyclically over the desired range, is used. In this paper is described a new type of electronic tube warble tone generator which utilizes a "relaxation" oscillator and has no mechanically moving parts.

By
W. H. BLISS
ASSOCIATE A.I.E.E.

University of Maine, Orono

MUSIC or the human voice has so irregular a wave form that it is not satisfactory for use in many tests of units that enter into the construction of various communication systems. If either the frequency or intensity of an electric wave is changing constantly, the deflections of the meters in a test circuit using this wave are too unstable to be read accurately. Although an "over-all" characteristic can be obtained by testing a unit with one frequency at a time and plotting a frequency curve, it is often desirable to get a single average reading for a range of frequencies. For this purpose a tone having a pitch that varies regularly over the desired frequency range is needed.

Such a tone has been called a warble tone and usually is produced by an ordinary vacuum tube oscillator having the inductance or capacitance of its tuned circuit varied cyclically by mechanical means. This article describes a new type of warble tone generator having no mechanically moving parts and having a wide flexibility of control. In the many uses of thermionic vacuum tubes one of the common methods of obtaining controlled variation of some factor in an electric circuit is to control the current through a resistor by means of a triode relaxation oscillator. The variable voltage produced across the terminals of this resistor then may be used to control the circuit. Such a system is used in the unit described in this paper.

A generator of this kind has been designed and constructed in the communication laboratories of the

Full text of a paper recommended for publication by the A.I.E.E. committees on instruments & measurements and communication, and scheduled for discussion at the A.I.E.E. North Eastern District meeting, Worcester, Mass., May 16–18, 1934. Manuscript submitted Jan. 17, 1934; released for publication March 12, 1934. *Not published in pamphlet form.*

electrical engineering department at the University of Maine (Orono). It is being used to supply a warble tone for regular student laboratory experiments in testing telephone transmitters, receivers, subsets, transformers, and other apparatus.

Construction and Operation

The new warble tone generator consists of 4 parts: (1) a constant radio frequency oscillator, (2) a second oscillator, the radio frequency of which is controlled by a relaxation oscillator, (3) a detector and amplifier, and (4) a power supply unit. The constant frequency oscillator produces 250 kc per second. This wave is combined with the variable frequency output of the second oscillator to produce a beat of variable audio frequency. The detector, together with an additional stage of amplification, raises the power of the audio wave to a level suitable for laboratory test purposes. The frequency of the second oscillator is made to fluctuate by "warbling" or varying its grid bias. This is accomplished by allowing the current drawn by a relaxation inverter to pass through the grid biasing resistor of the oscillator.

Referring to the accompanying connection diagram, Fig. 1, the constant frequency oscillator is seen in the upper left-hand corner. A type 227 tube is used operating in the well-known series-fed Hartley circuit. Condenser C_1 and coils L_1 and L_2 comprise the tuned circuit, which resonates at 250 kc. Coil L_3 takes some of the high frequency power from the tuned circuit and delivers it to opposite corners of the 4 resistor net composed of R_1, R_2, R_3, and R_4. The other 2 corners of this net are connected to the pick-up coil of the other oscillator. This resistor arrangement reduces the coupling between the 2 oscillators, and hence, decreases the tendency for them to pull into step. Condenser C_2 has a value of 0.5 μf and is used as a by-pass.

The second oscillator (lower left-hand corner of diagram) also uses a type 227 tube and the Hartley circuit. The variable tuning condenser C_9 furnishes a means of adjusting the frequency. The fluctuating grid bias for this oscillator is supplied by a variable *IR* potential drop across the upper end of resistor R_{10} (explained later) plus the fixed *IR* drop across resistor R_{14}. It should be noted that the cathode of this tube is grounded. Condensers C_{10} and C_{11} are by-pass condensers for the d-c plate and grid potentials, respectively. Voltmeter *V* registers the grid bias.

In the lower central part of the diagram is the relaxation inverter T_5. This is a type *FG*-17 "thyratron" tube (mercury vapor filled). The principle of operation is somewhat different from that of the ordinary vacuum tube oscillator. A condenser, C_{12}, is charged through a resistor R_{12} from the output of the rectifier. When the charge on this condenser or the voltage across its terminals has reached a certain point the condenser is discharged quickly through the plate circuit of the tube. The point at which this action takes place is determined by the grid bias of the tube. Consequently, the condenser continues to charge and discharge at a rate depending also upon its size and the size of the series resistor R_{12}.

The complete d-c charging circuit may be traced from resistor R_{12} (plus terminal of the rectifier unit) to resistor R_{12} and the plate circuit of tube T_5. The charging current then returns to the rectifier from the filament of T_5 through resistors R_{11} and R_{10}. The wave form of this current is triangular, which means that the current varies linearly with time. The inductance L_4, in series with the discharge circuit, undoubtedly decreases the peakedness of the wave form. At first, this feature might seem objectionable since it alters the uniformity of the saw tooth wave form; however, the author has found that the presence of a small amount of inductance at this point produces a warble tone more pleasing to the ear as far as smoothness is concerned.

In actual use the frequency of relaxation inverter tube T_5 is adjusted by means of the sliding contact on resistor R_{11}. At the instant when condenser C_{12} starts to charge the current flowing is large. Consequently, the voltage drop across R_{11} holds the grid voltage of the inverter tube sufficiently negative to prevent tube conduction until the condenser has acquired its charge. By moving the slider on R_{11} downward (see Fig. 1) the condenser is not allowed to acquire such a large charge before it is discharged, and so the cycle of operation is completed in less time. A variation of the relaxation frequency from 1 to 40 cycles per second readily can be obtained by this adjustment. A switch is provided in the plate lead to stop oscillations of the inverter so that a steady tone may be produced by the generator if desired.

The detector tube T_2 has as its grid excitation the *IR* potential drop across R_3 of the resistor net. This *IR* drop is a result of the combined output of the two radio frequency oscillators. Resistor R_5, by-passed by condenser C_3, insures the proper bias on this tube. The plate circuit of the detector is resistance-coupled to a pentode amplifier by means of plate resistor R_6, by-pass condenser C_5, and volume control potentiometer R_7. Condenser C_4 by-passes the radio frequency energy to ground. The pentode amplifier is choke-coupled to an output transformer as shown. Grid bias for this tube is obtained by means of resistor R_9 connected between ground and the center tapped resistor R_8 across the filament.

The power transformer P_3 with the 2 half-wave rectifier tubes, T_6 and T_7, supply the necessary d-c power through the filter composed of choke L_9 and condensers C_{13} and C_{14}. Variable resistor R_{14} furnishes a means of adjusting the average value of the grid bias of the variable frequency oscillator tube T_4. This resistor carries the steady d-c current returning from the plate circuits of all the tubes except that of the relaxation inverter. Consequently, the common ground potential can be raised to any desired point above the potential of the negative terminal of the d-c power supply (center tap of high voltage winding on power transformer). This resistor also carries the direct current supplied by the grid of the oscillator in question.

In the following discussion the practically constant d-c voltage across resistor R_{14} will be desig-

nated as $-E_{14}$ (the minus sign signifying that the minus terminal is connected toward the grid of tube T_4). To this voltage ($-E_{14}$) must be added the d-c voltage E_{10} (across the upper part of R_{10}) to obtain the total applied grid bias for T_4, that is: $E_g = -E_{14} + E_{10}$. It already has been pointed out that E_{10} varies according to the oscillations of the inverter since R_{10} carries the varying direct current from the inverter. Denoting the maximum change in E_{10} as E_v, it is evident at once that the voltage E_g applied to the grid of T_4 varies from $(-E_{14} + E_{10})$ to $(-E_{14} + E_{10} + E_v)$. This variation produces a small fluctuation in the output frequency of T_4 and, hence, a large swing or variation in the frequency of the resulting audio wave. To illustrate this, suppose a warble wave varying between 400 and 700 cycles per second is being produced. If the fixed oscillator is producing 250,000 cycles per second, then the frequency of the other oscillator can be varying from 250,400 to 250,700 cycles per second. This is a variation of 0.12 per cent, which is very small.

The variation of the frequency of a Hartley oscillator due to change in grid bias probably is due to the change in the internal operation of the tube. Changing the grid bias changes the current drawn by the grid. This, no doubt, changes the potential distribution among the electrodes which alters the effective internal plate and grid resistances. Since the frequency of the oscillator does not depend entirely on the values of inductance and capacitance used in the tuned circuit, a small variation can be obtained by changing the tube characteristics.

By setting the slider of R_{10} at its upper position the grid voltage of T_4 can be made to swing as much as 15 volts. Under this condition it is possible to vary the output of the generator over the entire audio range when a low warble frequency from the inverter is used. For testing purposes a warble frequency of at least 10 cycles per second is desirable since with a lower frequency the pointers of any meters in a test circuit may vibrate over too wide a range to be readable. The oscillogram shown in Fig. 2 was taken with a warble frequency of 60 cycles per second. The audio frequency of the warble waves varies from 620 to 860 cycles per second; the upper wave is a 60-cycle timing wave.

Considerable time was spent in trying to obtain a good wave form of output audio frequency. All the voltages on the detector and amplifier had to be adjusted to rated values, and then the coupling of the radio frequency pickup coils L_2 and L_6 had to be adjusted to obtain as much undistorted power output as possible. Loose coupling between the coils for each radio frequency oscillator, of course, tended to decrease harmonics. Since the oscillators had a tendency to pull into step when a low audio frequency beat was being produced, they were shielded separately as indicated by the dashed lines on the diagram. The oscillogram of Fig. 3 shows the wave form of the generator at 150 cycles per second with the warble effect not in use.

The output transformer P_1 is quite necessary with the type 247 pentode amplifier in order to match any practical load impedance to the plate impedance of the tube. An undistorted output of 1 watt readily can be obtained by this means. The voltage variation of the output is very small over a wide frequency range in the central portion of the audio band. For very high and low frequencies the voltage decreases somewhat.

Method of Adjustment

For ordinary student laboratory use the necessary adjustments are made while the operator listens

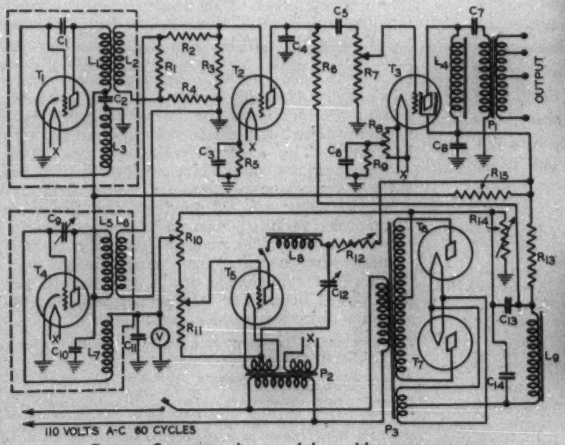


Fig. 1. Connection diagram of the warble tone generator

Fig. 2. Output of the warble tone generator showing a frequency sweep of 620 to 860 cycles per second

Fig. 3. Wave form of warble tone generator at 150 cycles per second (warble effect not in use)

to the output applied to a loud speaker. The circuit is allowed to warm up for about 30 minutes. After this the average value of the tone first is adjusted roughly by means of condenser C_9 to the desired range—high, medium, or low frequency range. The frequency of warble then is adjusted by means of potentiometer R_{11} to a suitable value. The amount of swing or variation of the output frequency is adjusted by potentiometer R_{10}. Final adjustment is obtained by additional manipulation of these 3 controls.

The d-c voltmeter V, which registers the grid bias of the variable frequency oscillator, gives a visual check on the warble action. Although the pointer of the meter cannot follow the voltage fluctuations exactly, its vibration does give a good indication of the warble frequency and warble sweep when the former is not too high.

Of course, it is impossible to adjust the generator output exactly to any desired audio range by this method of judging by ear. Until the circuit is perfected to a higher degree, it would be extremely difficult to calibrate the dial settings to any high degree of accuracy because the stability of operation is dependent on the constancy of the supply voltage.

To adjust the audio range more accurately an oscillograph may be used to compare the warble output to the output of a fixed oscillator producing a known frequency.

The range of the audio output can be shifted easily and quickly from a low pitch warble to a high pitch warble or *vice versa* by the adjustment of the tuning condenser C_9. This does not affect the frequency of warble swing. The magnitude of warble swing in cycles is approximately constant for any setting of R_{10} regardless of the range being produced. This means that for a low warble tone the percentage swing is much greater than for a high warble tone. Usually the setting of R_{10} also is changed when a different audio range is obtained.

As mentioned previously, the power output can be adjusted by volume control potentiometer R_7. Resistor R_{14} is manipulated to give an average bias on tube T_4 of from 10 to 20 volts, indicated by the voltmeter. For ordinary use condenser C_{12} and resistor R_{12} need not be altered.

Wide-Band Open-Wire Program System

Radio programs are regularly transmitted between broadcasting stations over wire line facilities furnished by the Bell System. Both cable and open wire facilities are employed for this service. Recently a new program transmission system for use on open wire lines has been developed which has highly satisfactory characteristics. A description of this open wire system and test results obtained with it are given in this paper.

By
H. S. HAMILTON
MEMBER A.I.E.E.

Am. Tel. and Tel. Co.
New York, N. Y.

THE SIMULTANEOUS broadcasting of the same radio program from a large number of broadcasting stations, in different sections of the United States, has become of such every-day occurrence that the radio listening public takes it as an accepted fact and in many cases does not know whether the program is originating in the studio of a local broadcasting station or in a broadcasting studio in some distant city. The wire line facilities furnished by the Bell System for the interconnection of the radio stations, particularly the wire line facilities in cable, have such transmission characteristics that little detectable quality impairment is introduced even when programs are transmitted over very long distances.

This cable program system was described in a recent paper. (See "Long Distance Cable Circuit for Program Transmission," by A. B. Clark and C. W. Green, A.I.E.E., TRANS., v. 49, 1930, p. 1,514–23.) More recently a new program system for use on open-wire lines, which possesses transmission characteristics comparable with the cable system, was developed and an extensive field trial made involving 2 circuits between Chicago and San Francisco. This paper describes this new open-wire program system and gives the principal results of the tests made on the 2 transcontinental circuits.

In the paper referred to describing the cable system, the various factors and considerations involved dictating the grade of transmission performance that is desired for program circuits were discussed in considerable detail so they will not be reviewed here. The transmission requirements chosen as objectives are as follows:

Frequency Range. Frequency range to be transmitted without material distortion: about 50 to 8,000 cycles.

Volume Range. Volume range to be transmitted without dis-

Full text of a paper recommended for publication by the A.I.E.E. committee on communication and scheduled for discussion at either the A.I.E.E. 1934 summer convention or the A.I.E.E. 1934 Pacific Coast convention. Manuscript submitted Jan. 24, 1934; released for publication March 8, 1934. *Not published in pamphlet form.*

tortion or material interference from extraneous line noise: about 40 db, which corresponds to an energy range of 10,000 to 1.

Nonlinear and Phase Distortion. Nonlinear distortion with different current strengths and phase distortion to be kept at such low values as to have negligible effect on quality of transmission even on the very long circuits.

The frequency range afforded by the new open-wire program circuits extends about 3,000 cycles higher and more than 50 cycles lower than the frequency range available with the open-wire program circuits previously used. (See papers: "Wire Line Systems for National Broadcasting," by A. B. Clark, presented before the World Engineering Congress at Tokio, Japan, October 1929, and published in I.R.E., *Proc.*, v. 17, 1929, p. 1,998–2,005; and "Telephone Circuits for Program Transmission," by F. A. Cowan, A.I.E.E. TRANS., v. 48, 1929, p. 1,045–9.) The extension of the frequency range at the upper end necessitates the sacrifice of one carrier telephone channel of carrier systems operating on the same wires with the program pair since the frequency band of the lowest carrier channel lies in this range. In order to minimize noise and the possibility of crosstalk, the phantoms of program-pairs are not utilized and, of course, d-c telegraph compositing equipment is removed in order that the proper low-frequency characteristics may be realized.

DESCRIPTION OF NEW OPEN-WIRE SYSTEM

In general, the amplifiers on the open-wire program circuits employ the same spacing as the telephone message circuit repeaters on the same pole lead. The average repeater spacing is about 150 miles but the repeaters may be located as close as 60 miles or may be as much as 300 miles apart depending upon the location of towns and cities on the open-wire route and the gauge of the wires used. The upper diagram of Fig. 1 shows a typical layout of the new wide-band open-wire program system. Three types of stations are shown, a terminal transmitting station, an intermediate station which may be either bridging or nonbridging, and a terminal receiving station.

The terminal transmitting station includes an equalizer for correcting for the attenuation distortion of the local loop from the broadcasting studio, an attenuator for adjusting the transmission level received from the local loop to the proper value, an amplifier for inserting the required gain, filters for separating the program and carrier channels, monitoring amplifier, loudspeaker and volume indicator for making the necessary operating observations, and a predistorting network and associated amplifier.

At the intermediate station are included line filters for separating the carrier currents and program currents and directing them to their proper channels, 2 adjustable attenuation equalizers for correcting for the attenuation distortion of the line wires and associated apparatus, gain control attenuator, line amplifier, and associated monitoring equipment. At intermediate stations where it is necessary to provide branches to radio stations or to other program circuits an amplifier of a special type having several outlets is inserted immediately in front of the line amplifier.

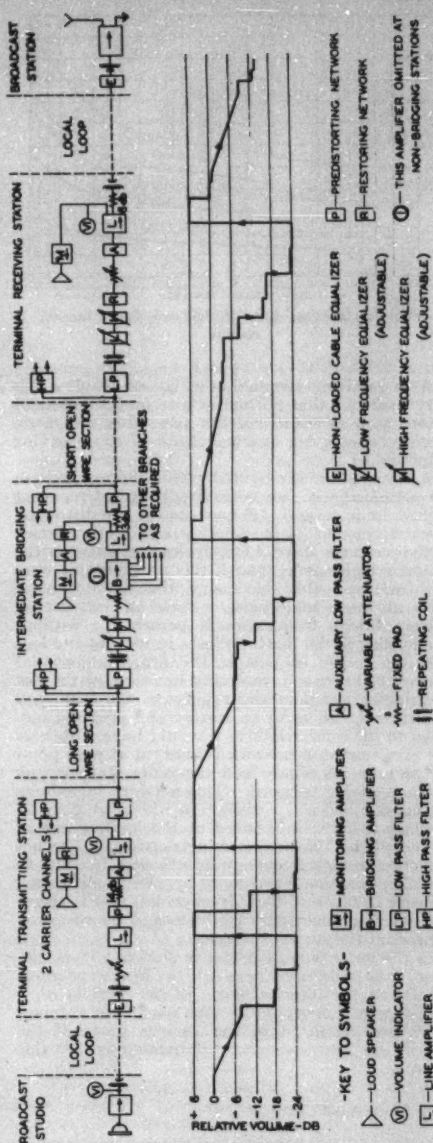


Fig. 1. Typical circuit layout and level diagram of the new wide-band open-wire program system

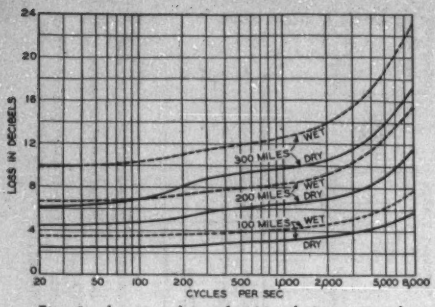


Fig. 2. Insertion loss of 165-mil 8-in. spaced circuits

At a receiving terminal, the layout employed is very similar to that utilized at intermediate stations except that an additional low pass filter and a restoring network are inserted ahead of the receiving amplifier.

A novel feature is provided in this program system for minimizing its susceptibility to interference at higher frequencies. It consists in predistorting the transmission at the sending end of the circuit so that currents above 1,000 cycles are sent over the line at a higher level than if this arrangement were not employed, thus increasing the signal-to-noise ratio at these frequencies. Such an increase in power at high frequencies is permissible without overloading in the line amplifiers in view of the fact that the energy content of the program material above 1,000 cycles is materially less than at the low frequencies, and decreases rapidly as the frequency is increased. In order to restore the program material to the same relations it would have if it were not predistorted, a network is inserted at each point in the branches which feed the radio stations and at the receiving terminal. This network introduces attenuation and phase distortion which are complementary to those introduced at the sending end of the circuit by the predistorting network. The net reduction in high frequency interference is equal to the discrimination introduced by the predistorting network in favor of these frequencies, and is therefore equal approximately to the loss of the restoring network at the same frequencies.

In the lower part of Fig. 1 is shown a level diagram, from which may be noted the losses and gains introduced by different parts of the system at a frequency of 1,000 cycles. The maximum volumes which are permitted in the various parts of the system are also indicated approximately by this diagram.

Line Facilities

As is well known the open-wire lines employed in telephone and program service do not have uniform attenuation for all frequencies, the low frequencies being transmitted with much less loss than the high frequencies. Since the program circuits employ the same type of open-wire facilities that is used in the message circuits, 3 different gauges of wire with either of 2 pin spacings between wires may be used and the repeater sections may vary in length from 60 to 300 miles. This means that the attenuation frequency characteristic of a repeater section not only varies with frequency but also varies considerably in magnitude of attenuation depending upon gauge and length of repeater section.

On Fig. 2 are shown 3 pairs of characteristics which illustrate the loss-frequency characteristics of 3 lengths of 165-mil, 8-in. spaced circuits. The lengths chosen for purposes of illustration are 100, 200, and 300 miles, respectively. The solid line curves show the insertion loss-frequency characteristics of the circuits for average dry weather conditions when the circuits are connected between 600-ohm resistances. The dashed line curves indicate the wet weather insertion loss characteristics, that is, they indicate the loss-frequency characteristic which might obtain if the lines were very wet for the entire length of a repeater section.

For the purpose of comparing the attenuation-frequency characteristics of the different types of open wire lines, the curves shown on Fig. 3 have been prepared. These characteristics have been plotted so that all coincide at 1,000 cycles; thus a direct comparison of the difference in shape of the

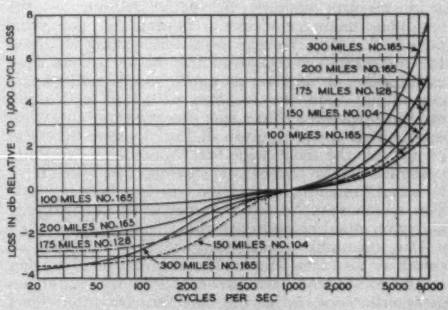


Fig. 3 (above). Attenuation-frequency characteristics of open-wire lines when inserted between 600-ohm resistances

8-in. spaced pairs

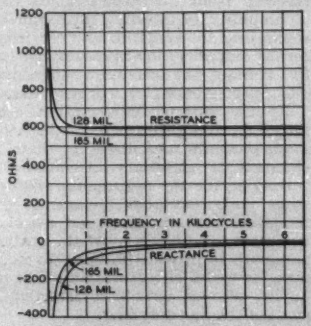


Fig. 4 (right). Impedance of 8-in. spaced pairs

attenuation frequency characteristics may readily be observed.

In Fig. 4 are shown resistance and reactance components of 165-mil and 128-mil 8-in. spaced open-wire lines. Note that, except at low frequencies, the impedances of the various open wire lines are quite uniform throughout the frequency range and do not depart greatly from 600 ohms. For this reason and in consideration that the majority of telephone apparatus is designed for 600-ohm impedance, all units of this new program system, except the carrier line filters, have been designed to have an impedance of 600 ohms. In order to reduce reflection losses, particularly in the carrier range, the line filters have been designed to have an impedance on the line side somewhat lower than 600 ohms although the drop or office side impedance is 600 ohms.

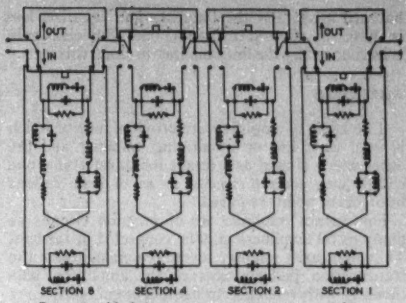


Fig. 7. High-frequency attenuation equalizer

Attenuation Equalizers

To furnish the necessary attenuation corrections for the 3 different gauges of lines, 4 adjustable attenuation correcting networks have been provided. One attenuation equalizer provides attenuation correction for high frequencies only and is common for all gauges. The 3 other equalizers provide low-frequency attenuation correction designed specifically for the particular gauge of circuit the equalizer is to be associated with and also include a fixed amount of high-frequency attenuation correction.

On Fig. 5 is shown a schematic diagram of one of the low-frequency attenuation equalizers. This consists of 4 sections of 600-ohm constant impedance type networks. One section referred to as a basic section introduces attenuation correction over the complete frequency range from 35 to 8,000 cycles for a particular minimum length of line, as for example, in the case of 165-mil circuits this is for 100 miles. The 3 other sections, on the other hand, furnish attenuation correction only for frequencies from approximately 1,000 cycles down to 35 cycles. Section 1 of the equalizer for 165-mil circuits puts in about 0.5 db more loss at low frequencies than it does at 1,000 cycles. Section 2 puts in double the amount of correction that is introduced by section 1 and section 4 introduces 4 times as much attenuation correction as section 1. These 3 sections are controlled by switches so that any one or all of them may be cut in tandem with the basic section. The attenuation corrections afforded for the various adjustments of this equalizer are shown on Fig. 6.

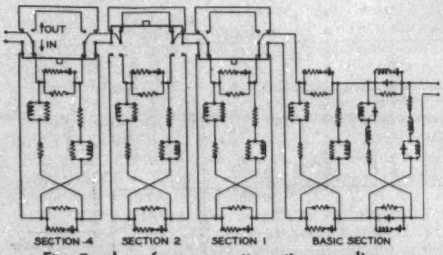


Fig. 5. Low-frequency attenuation equalizer

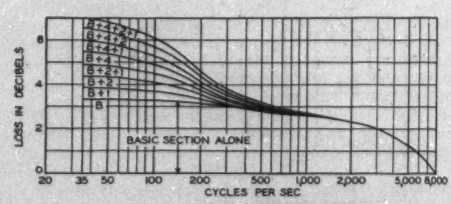


Fig. 6. Attenuation correction furnished by low-frequency equalizer for 165-mil circuits

The attenuation equalizers for 128-mil and 104-mil facilities are similar in construction to the one just described having different constants so as to furnish somewhat different attenuation correcting characteristics.

In Fig. 7 is shown a schematic diagram of the high-frequency attenuation equalizer. This consists of 4 600-ohm constant impedance type network sections which, as indicated, are controlled by switches so that any one or all of them may be cut in tandem with the program circuit as required. In Fig. 8 is shown the loss-frequency characteristics of these 4 sections. As may be noted, the loss of the various sections is practically constant over the frequency range up to 1,000 cycles, decreasing from there on to a minimum value at 8,000 cycles. Section 1, as may be noted, furnishes about 0.5-db attenuation correction. Section 2 is double that of section 1, section 4 is 4 times that of section 1, and section 8, 8 times that of section 1. These sections may be used in tandem so that attenuation correction for the high frequencies is, therefore, provided in steps of 0.5 db from zero to 7.5 db.

An illustration of how the equalizers introduce the necessary attenuation correction is given on Fig. 9. The lower curve on this figure shows the loss of a 300-mile section of 165-mil circuit. The losses introduced by the particular sections of low and high-frequency equalizers that would be required for this length of line are indicated by the cross-

hatched areas, and the total line and equalizer loss is shown by the top horizontal line. Sufficient gain is introduced by the line amplifier to annul this loss.

Amplifiers

Two types of amplifiers are provided, one of which is used as a line or monitoring amplifier and the other which is used as a means for transforming one circuit into several circuits so as to feed various branches at points required.

For certain combinations of program circuits as many as 50 amplifiers may be connected in tandem. This necessarily imposes severe requirements on the transmission performances of the amplifiers, particularly with reference to flatness of gain-frequency characteristics and phase distortion. By designing the coils used in the amplifiers so as to have very high inductances the desired phase distortion requirements were met while at the same time the necessary flatness of gain characteristic was obtained at the low frequencies.

In Fig. 10 is shown the transmission circuit of the line amplifier and monitoring amplifier. This device has a 600-ohm input and output impedance and consists of 2 stages of push-pull amplification. The potentiometer is a balanced slide wire having a continuous gain adjustment over a range of 6 db. A balanced input transformer serves to connect the potentiometer to the grids of the 2 push-pull vacuum tubes which function as the first stage of this amplifier. The first stage is connected to the second or power stage by means of resistance coupling which gives better results both as to phase distortion and low-frequency gain characteristics than if transformer or retard coil coupling were used. Resistances are provided in the grid circuits of the second stage so that the high frequency characteristic may be adjusted as required. The power tubes are connected to an output transformer which has the unique feature of providing a monitoring outlet which is not materially affected by voltages produced at or beyond the line terminals. The transformer, as may be observed, consists of 3 balanced windings arranged as in the form of the well-known hybrid coil used in 2-wire telephone repeaters, with the exception that the 2 low impedance windings are of unequal ratio, the line windings having many

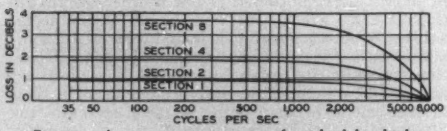


Fig. 8. Attenuation correction furnished by high-frequency equalizer

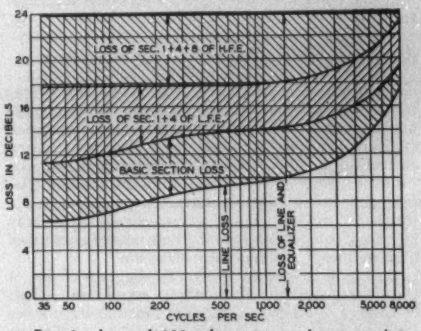


Fig. 9. Loss of 300-mile section and associated equalizers

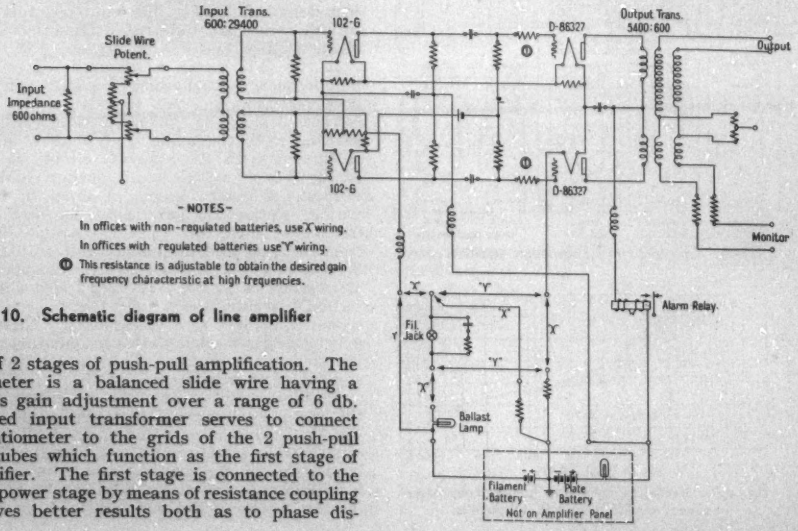


Fig. 10. Schematic diagram of line amplifier

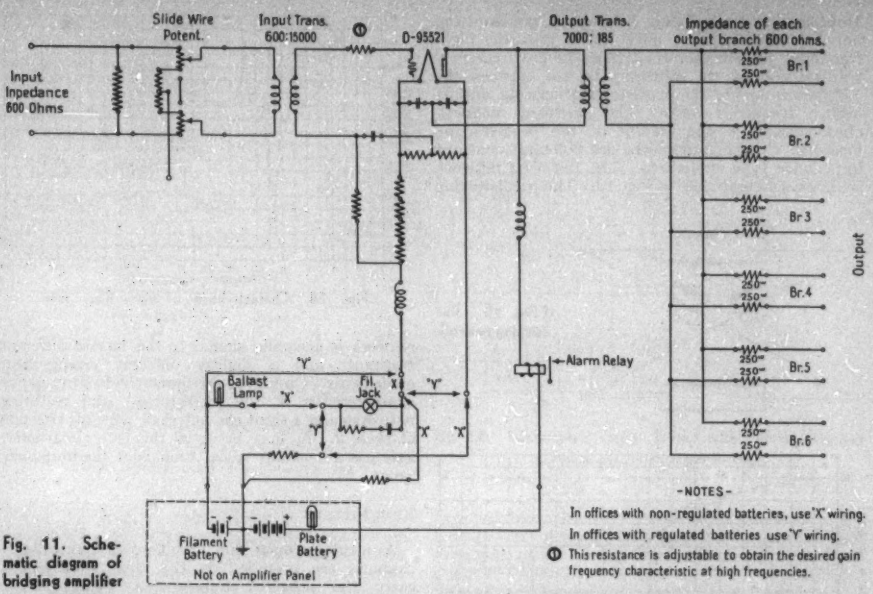


Fig. 11. Schematic diagram of bridging amplifier

more turns than the monitoring windings. The ratio of the windings is such that the voltage at the monitoring terminals when said terminals are closed through 600 ohms is 30 db below the voltage at the line terminals. Resistances are inserted in series with the monitoring winding so that an impedance of 600 ohms will be presented at the monitoring terminals.

The average gain of the amplifier with the potentiometer set at its maximum position is 33 db. Of 100 amplifiers measured, the gain at 35 cycles averaged 0.10 db less than the gain at 1,000 cycles, while from 100 to 8,000 cycles the gain was constant within 0.05 db. The delay at 50 cycles is approximately 0.6 millisec greater than it is at 1,000 cycles. From 150 to 8,000 cycles the delay is substantially constant and is only a small fraction of a millisecond. The amplifier is capable of handling an output power 9 db above reference volume without noticeable distortion.

At several points along a program circuit taps or branches are provided so as to connect various broadcasting stations to the program circuit and also to connect to other program circuits which form part of a broadcasting network. Points where such connections or branches are made are commonly called bridging stations. At some points as many as 6 branches are supplied but generally only 2 or 3 taps are utilized.

To accomplish this branching out at a bridging station a resistance network multiple is provided having 6 outlets. This network multiple is shown on Fig. 11. To annul the loss of the network a single stage amplifier is connected in front of it. This network multiple and amplifier are mounted on the same panel forming a single integral unit. The network multiple is so proportioned that if any one of the branches is accidentally opened or short-circuited the other branches are affected to only a minor degree. The amplifier is adjusted so that the gain from the input terminals to any of the output branches is zero. The bridging amplifier is normally inserted immediately in front of the line amplifier. As in the case of the line amplifier mentioned above, high inductance coils are utilized in order to keep phase distortion at a minimum. A resistance adjustment is provided in the grid circuit in order to adjust the high frequency characteristic of this amplifier to the desired value.

The gain-frequency characteristic of the bridging amplifier is practically identical with the corresponding characteristic just described for the line amplifier, while the delay is even less.

Predistortion

The means utilized to accomplish the predistorted transmission referred to earlier includes the provision of a so-called predistorting network at the sending end of a program circuit and a restoring network in each branch which supplies a broadcasting station. The predistorting network introduces a large loss at low frequencies with a decreasing loss as the frequency is increased. By introducing suitable

amplification immediately behind the predistorting network the resultant effect is to raise the high-frequency transmission relative to the low frequency transmission by the difference in loss between the 1,000-cycle loss of the predistorting network and its higher frequency loss. The restoring network characteristic is the inverse of the predistorting network. These 2 networks are 600-ohm constant impedance type structures. The restoring network is shown schematically in Fig. 12. The predistorting network is generally similar to this having different constants and a slightly different arrangement of elements. On Fig. 13 are shown the loss-frequency characteristics of the predistorting and restoring networks and a third characteristic which is the sum of these 2. As may be noted this latter characteristic has a constant value throughout the frequency range.

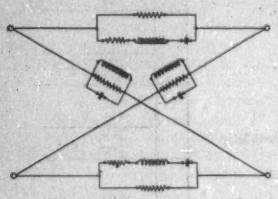


Fig. 12. Restoring network

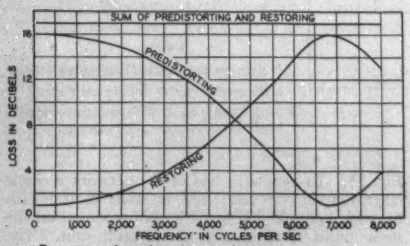


Fig. 13. Loss-frequency characteristics of predistorting and restoring networks

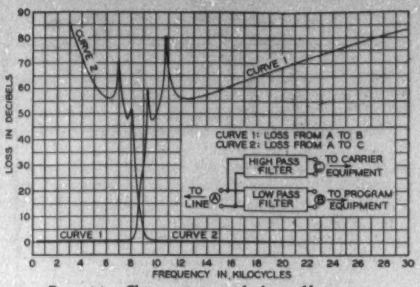


Fig. 14. Characteristics of line filter sets

Line Filters

As a rule on open-wire circuits other transmission channels are provided on the same wires which carry the program transmission. These other channels operate at frequencies above the program range and in order to direct the various currents to their proper channels at a terminal or repeater station, carrier line filter sets are inserted at the ends of the line wires. The carrier line filter sets include a low pass and a high pass filter. The low pass filter, cutting off somewhat above 8,000 cycles,

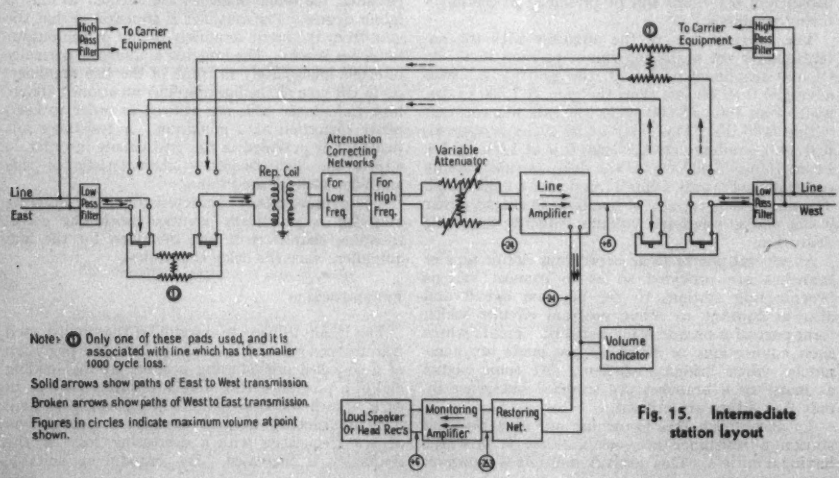


Fig. 15. Intermediate station layout

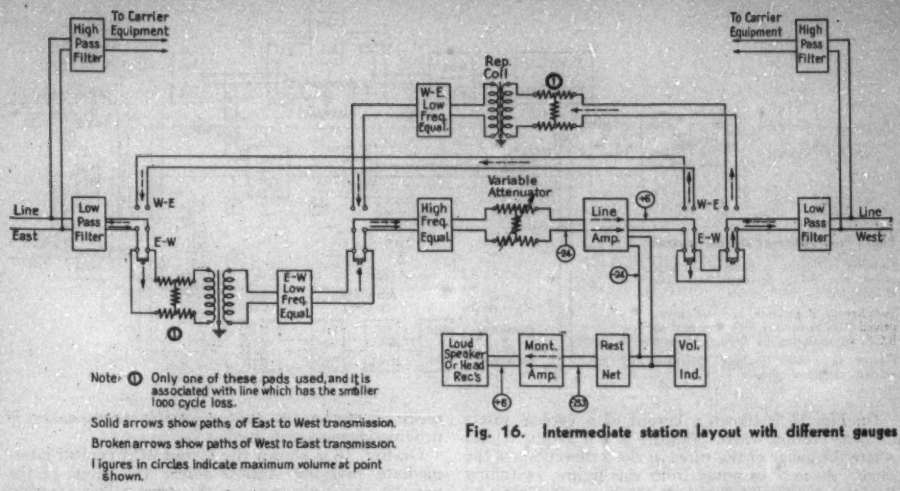


Fig. 16. Intermediate station layout with different gauges

directs the program transmission to the program apparatus and the high pass filter, which has a low end cutoff around 9,000 cycles, directs the carrier transmission to its associated carrier equipment. Attenuation frequency characteristics of these filters are shown on Fig. 14. The low pass filter is of unusual design and is described at some length in a companion paper. (See "Line Filter for Program System," by A. W. Clement, p. 562–6 this issue.)

Monitoring Features

A very important factor in the satisfactory operation of a program system is the provision of monitoring arrangements by which the operating forces are enabled to observe the quality of transmission, listen for extraneous interferences, and observe indicating devices in order to make certain that the program is maintained at its proper volume.

Three types of aural monitoring facilities were provided on a trial basis for the new program system. The first type consists of a single unit loudspeaker operated by a suitable amplifier. With this loudspeaker system a good response characteristic from approximately 100 to 5,000 cycles is obtained, the low-frequency response depending, of course, upon the size of the baffle used with the loudspeaker.

The second type of monitoring consists of 2 headset receivers arranged with a proper equalizing network circuit. This type of monitoring provides good response characteristics from approximately 50 cycles to 8,000 cycles, enabling the observer to cover the entire program frequency range and thus permitting him to detect any extraneous interference which may be introduced even though this occurs at very low or very high frequencies.

The third type of monitoring consists of 2 loudspeakers and associated equalizing network with the loudspeakers mounted in a large baffle board. This arrangement affords a fairly uniform response from about 40 cycles to above 8,000 cycles. The particular type of monitoring which might be provided at the various stations would be governed by the service requirements involved.

To observe the volume on the program circuit, volume indicators are used. A new type of volume indicator was made available along with the new program system. This new device utilizes a full-wave copper oxide rectifier and has a much greater sensitivity range and materially improved indicating characteristics than the devices formerly used. The volume indicator is connected across the monitoring terminals of the line amplifier in which position it is bridged across a practically nonreactive 600-ohm impedance. Located thus it is also independent of line impedance affording more accurate results and obviating the necessity of correcting volume readings on account of line impedances. Also at this location it introduces no loss or phase distortion to the through program circuit.

The above constitutes a description of the major items employed in this program system. There are a number of other units, such as attenuators, repeating coils, etc., which will not be described in detail here but will be referred to as the need arises.

Typical Station Layouts

Due to the various requirements for different types of service and due in part to the different type of facilities, the general apparatus layouts and arrangements at different repeater stations are not always the same. Several of the more important general or typical layouts will be briefly discussed, however.

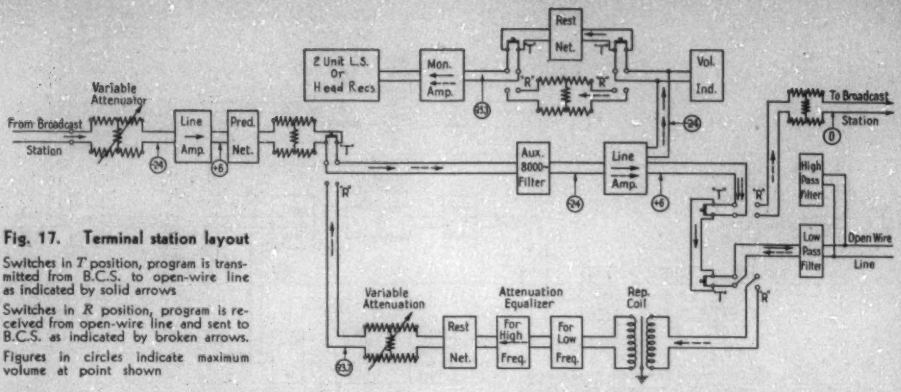


Fig. 17. Terminal station layout

Switches in *T* position, program is transmitted from B.C.S. to open-wire line as indicated by solid arrows

Switches in *R* position, program is received from open-wire line and sent to B.C.S. as indicated by broken arrows.

Figures in circles indicate maximum volume at point shown

On Fig. 15 is shown a layout of a typical intermediate station where bridging is not required and where the gauge of the wires in the 2 directions is the same. As may be noted from this figure, switching facilities are provided so that the apparatus may be connected into the circuit so as to properly take care of either the east-west or west-east transmission. For this type of layout most of the apparatus is common to both directions of transmission. The fixed artificial lines or pads indicated by Note 1 on Fig. 15 are for the purpose of building out whichever line has the lower 1,000-cycle attenuation so that this line and associated pad will have the same 1,000-cycle loss as the other line. As indicated, only one of these pads is required. This building out of the shorter line minimizes attenuator adjustment when the direction of transmission is reversed. The line amplifier in this as well as the other layouts to be discussed is always set for a gain of 30 db.

On Fig. 16 is shown the layout of a typical intermediate nonbridging station where the gauges of the wires on the 2 sides of the repeater station are different. As mentioned earlier each gauge of wire has its own particular low-frequency attenuation equalizer. Consequently, where the gauges of the wires on the 2 sides of the repeater station are not alike, it is necessary to arrange the station layout so that the proper low-frequency equalizer will be associated with the proper direction of transmission. This association of apparatus may be readily observed from Fig. 16.

On Fig. 17 is shown the layout of a typical terminal station. This layout differs from the intermediate station layout largely in the fact that provision must be made for the introduction of predistortion when the terminal station is transmitting a program to the open-wire line and in the provision of a restoring network when the terminal station is receiving a program from the open-wire line. The general layout of the apparatus may readily be observed by reference to the figure. The monitoring facilities at this type of station, in general, differ from those provided at the normal intermediate station in that a 2-unit loudspeaker is provided for use as desired.

On Fig. 18 is shown the layout of a typical intermediate bridging station where the gauge of the wires in the 2 directions is the same. This arrangement differs largely from the arrangement shown on Fig. 15 in that the bridging amplifier is inserted immediately ahead of the line amplifier so as to provide the necessary additional branches as required. The general circuit arrangements involved to take care of the different types of branches which may be encountered are indicated on this figure. The photograph, Fig. 19, shows the program equipment layout at an intermediate bridging station, which is of the type just discussed in Fig. 18, utilizing, however, only one branch circuit which is connected to a local broadcasting station.

In certain of the layouts just discussed, one apparatus unit designated as "aux filter" is shown which has not previously been mentioned. This is an 8,000-cycle low-pass filter somewhat similar to the low-pass line filter, except that it is not designed to operate in parallel with any high-pass filter. This filter is required at the transmitting and receiving terminals, in the branches feeding the radio station, and also in the high quality monitoring circuit to afford additional discrimination against unwanted high frequency interference as, for example, interference from the carrier channels. This arrangement of splitting the filter requirements enables a less expensive type of line filter set to be employed.

Over-All Performance

The initial application of this new program system was made on 2 transcontinental circuits between Chicago and San Francisco. One circuit, referred to as circuit 1, was routed through Omaha and Denver over the central transcontinental line. The other circuit, referred to as circuit 2, was routed via St. Louis and Kansas City to Denver and thence over the same pole lead as circuit 1. Circuit 1 was

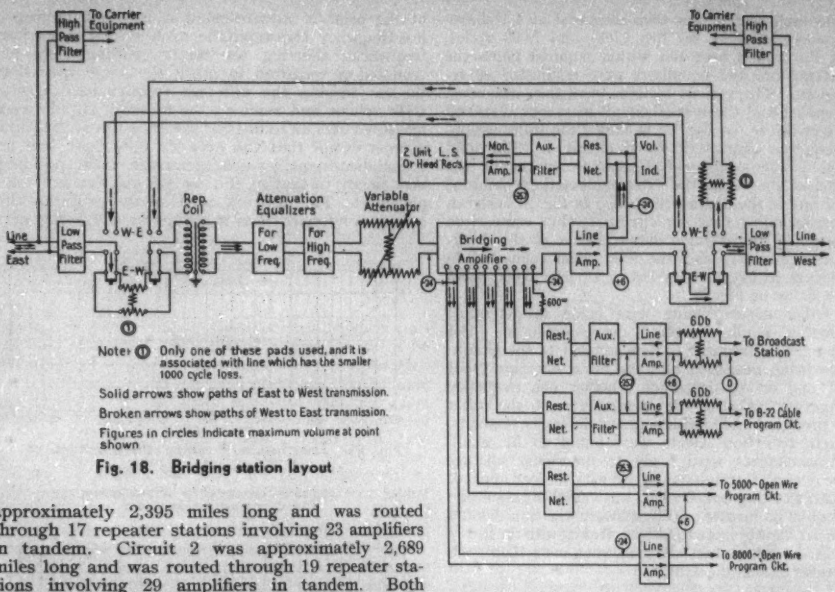


Fig. 18. Bridging station layout

approximately 2,395 miles long and was routed through 17 repeater stations involving 23 amplifiers in tandem. Circuit 2 was approximately 2,689 miles long and was routed through 19 repeater stations involving 29 amplifiers in tandem. Both circuits were routed through *B*-22 cable facilities between Sacramento and Oakland, Calif., and non-loaded cable facilities in the transbay submarine cable between Oakland and San Francisco.

At San Francisco a listening studio was set up in the Grant Avenue office where the program circuits terminated. A 2-unit loudspeaker with suitable connecting networks was set in a 7 x 7-ft baffle, the response of this loudspeaking system being practically uniform from about 40 cycles to above 8,000 cycles. The room in which the loudspeakers were located was acoustically treated so as to obtain the proper reverberation time. A powerful amplifier having a flat gain-frequency characteristic from 35 cycles to well above 8,000 cycles supplied the loudspeaker system. A high quality phonograph system for furnishing test programs was also installed at the Grant Avenue office. The records used were of the vertical cut type and included several recordings of a 75-piece orchestra as well as various solo and instrumental recordings. Two outside pickup points were used, one at the studios of one of the broadcasting companies at San Francisco and the other at a hotel. At both of these places the moving coil type of microphones was used and the latest type of high quality pickup amplifiers. The pickup system used at both these places had a response characteristic within about 2 db of being flat over the range of 35 to 10,000 cycles. At the Grant Avenue office, loud speaking equipment and considerable associated apparatus was installed for carrying out the various over-all tests.

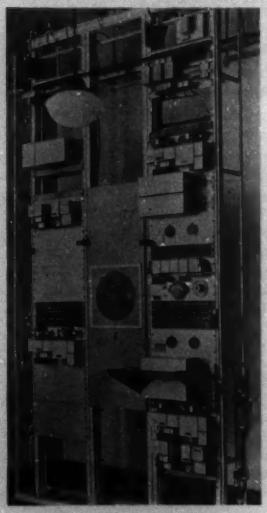


Fig. 19. Program equipment layout at an intermediate bridging station

Transmission and Other Measurements

In making transmission measurements, the circuit under test was first split up in a number of sections

and each section was then measured at 4 test frequencies, namely, 50, 100, 1,000, and 7,000 cycles. If the results were not within required limits the attenuators and equalizers were readjusted as required. The various sections were then connected together and the over-all circuit measured at several frequencies. In Fig. 20 is shown the transmission-frequency characteristics of circuit 1. The solid line is the average of 9 measurements while the dashed lines show the extreme deviations obtained for any of the 9 measurements. In Fig. 21 is shown corresponding data for circuit 2. For comparison purposes the average characteristics of the 2 circuits separately and the 2 of them connected in tandem making a loop circuit of over 5,000 miles are shown on Fig. 22.

Other measurements were made to determine whether nonlinear effects were produced. For example, 2 frequencies were applied to the circuit, one being measured and the other alternately cut off and on to determine whether one frequency adversely affected the transmission of the other or produced undesirable sum and difference products. Such distortion effects were found to be small. Measurements were made to determine whether the over-all transmission varied with the load applied. With a testing power which was varied in magnitude from 50 milliwatts to 0.1 milliwatt, the transmission varied slightly more than 1 db, that is, with the heavy load the circuit loss was somewhat more than 1 db greater than at the light load.

Noise and Crosstalk Survey

A noise and crosstalk survey was made on these program circuits and on message circuits on the same pole lead. Observations were made at the terminals of the message circuits while program was being transmitted on the program circuits to determine the amount of interference introduced into the message

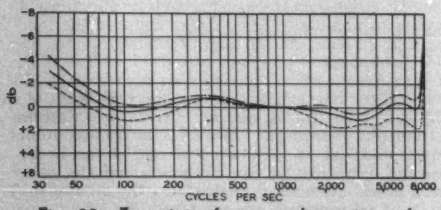


Fig. 20. Transmission-frequency characteristics of circuit 1, Chicago to San Francisco

Solid curves, average of 9 measurements
Dash curves, extreme deviations

circuits from the program circuits, and, conversely, observations were made on the program circuits while various paralleling message circuits were in use, and the resulting interference was recorded.

The noise or crosstalk volume on the program circuits was measured by means of a volume indicator, which had inserted between it and the circuit at the point of measurement a network having a loss-frequency characteristic such that the various frequencies affecting the meter reading were attenuated or weighted in much the same way that the ear weights the different frequencies. Crosstalk volume and noise on the message circuit were measured with an indicating meter in much the same manner except that the network used here had an attenuation-frequency characteristic corresponding very nearly to that of the ear and an average telephone set. The network used on the program circuits was referred to as a "program weighting network," while that used with the message circuit was the ordinary "message weighting network." The noise and crosstalk volume was then recorded in decibels referred to reference noise with either program weighting or message weighting. Reference noise is that amount of interference which will produce the same meter reading as 10^{-12} watt of 1,000-cycle power, which is 90 db below 1 milliwatt.

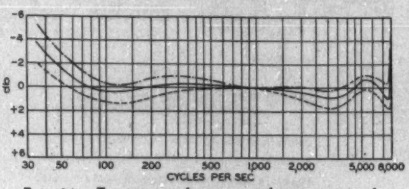


Fig. 21. Transmission-frequency characteristics of circuit 2, San Francisco to Chicago

Solid curve, average of 14 measurements
Dash curves, extreme deviations

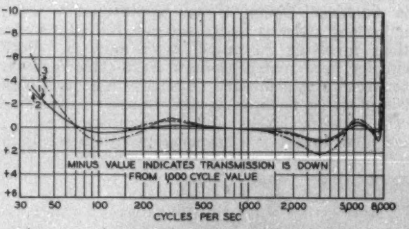


Fig. 22. Average characteristics of the 2 circuits separately and in tandem

Curve 1. San Francisco to Chicago on circuit 2, west to east
Curve 2. Chicago to San Francisco on circuit 1, east to west
Curve 3. San Francisco-Chicago-San Francisco loop (circuit 2, west to east, and circuit 1, east to west)
Circuit 2—2,689 miles, 29 amplifiers
Circuit 2—2,395 miles, 23 amplifiers
Loop—5,084 miles, 52 amplifiers

The results of this survey indicated that in consideration of the layout and levels of the existing message circuits and of the noise existent on these circuits and on the program circuits, the value for maximum program volume, should, under normal conditions, be +3 referred to reference volume;

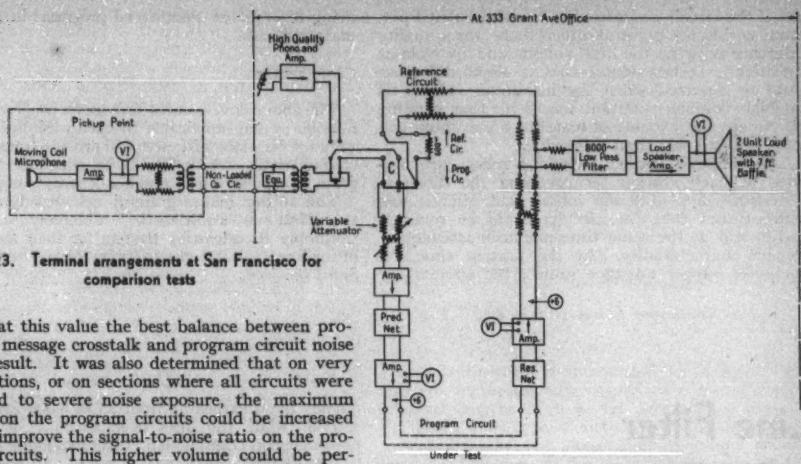


Fig. 23. Terminal arrangements at San Francisco for comparison tests

that is, at this value the best balance between program to message crosstalk and program circuit noise would result. It was also determined that on very long sections, or on sections where all circuits were subjected to severe noise exposure, the maximum volume on the program circuits could be increased 3 db to improve the signal-to-noise ratio on the program circuits. This higher volume could be permitted in these cases since on the longer sections the message circuits also usually operate at higher levels, and on the especially noisy short sections the increased crosstalk to the message circuits will ordinarily be masked by the greater noise.

The average noise measured at San Francisco or Chicago at the circuit terminals at the reference volume point was 49 db above reference noise "program weighting" when the restoring network was included at the receiving terminal. The noise averaged 5 db higher than this with the restoring network removed. This value of noise is about 43 db below the maximum power of the program measured at the same point with the same measuring instrument. This, therefore, establishes a signal-to-noise ratio of about 43 db, thus permitting a volume range of approximately 40 db.

Critical Listening Tests

The various tests referred to gave statistical data concerning the transmission performance of the circuits from which it could readily be predicted that the circuits would transmit programs with very little impairment to quality. To substantiate this, very critical listening tests were made comparing the quality of a program after it had been transmitted over various length circuits with the same program transmitted over a reference circuit which was distortionless over the frequency range for which the circuits were designed, namely, to 8,000 cycles. In Fig. 23 is shown schematically the terminal arrangements employed at San Francisco for these listening, or, as they are more commonly called, comparison tests.

Various types of programs were used, such as speech, vocal and instrumental selections, and orchestral renditions, both classical and jazz. Quite a number of observers were used, some of whom were present on several tests and a few on all tests. On tests made on a San Francisco-Denver-San Francisco loop involving 2,600 miles of circuit, no observer was able to consistently differentiate between the quality over the reference circuit and that over the program circuit. On tests made on the San Francisco-Chicago-San Francisco loop certain of the more experienced observers were able to differentiate between the circuits somewhat more than 50 per cent of the time, but this, it must be remembered, was on a direct comparison test. None of the observers could tell with any assurance which was the program circuit and which was the reference circuit if a few minutes were allowed to elapse between switches. On the Chicago loop 264 observations were made on direct comparison tests on which 60 per cent of the observations favored the reference circuit and 40 per cent favored the program circuit.

Other Tests of Over-All Performance

Included as part of the over-all program, were tests to determine the volume range, maximum volume obtainable, and speed with which the circuits could be reversed.

On the volume range tests a source of program was obtained and so regulated that it had a very narrow volume range. This was then applied to the circuit with the sending end gain adjusted so that the maximum volume applied at the repeater outputs was +6. The sending end gain was then gradually decreased so as to apply a gradually decreasing volume to the circuit. This process was continued until the program volume was so weak that the line noise interfered with its satisfactory reception. The amount that the sending end gain was adjusted determined the volume range. The average value for several tests was slightly in excess of 40 db. The maximum volume was determined by switching a 10-db pad from the sending end to the receiving

end of the circuit and listening to a transmitted program, noting the point at which there was a quality difference between the high volume and low volume condition. It was found that a slight difference could be detected when the maximum volume on the high volume condition was +10, thus showing the circuit was capable of handling a maximum volume slightly lower than this value.

As mentioned earlier, switching means are provided at each station for reversing the direction of transmission. On the initial field tests it was demonstrated that the circuits could be reversed readily and at the same time maintain satisfactory over-all characteristics. At the present time, on receipt of proper advance notice, the circuits are being reversed on commercial programs in approximately 30 secs.

Conclusion

The above development provides a program transmission system applicable to open-wire lines which even for very long distances will provide transmission characteristics which should be adequate for program transmission for a number of years to come.

The author makes grateful acknowledgment to the National Broadcasting Company and the Columbia Broadcasting System for their assistance in making available the program pickup sources at San Francisco.

Line Filter for Program System

Open wire circuits recently have been developed for transmitting radio broadcast programs with greater naturalness and over greater distances than heretofore (see companion paper "Wide-Band Open-Wire Program System" in this issue). The simultaneous utilization of these circuits for the transmission of broadcast programs and carrier telephone messages requires the use of line filters to restrict the program and carrier currents to the proper circuits. The low pass line filter developed for the program circuits and its contribution to the maintenance of good quality in the programs transmitted are described in this paper.

By
A. W. CLEMENT
ASSOCIATE A.I.E.E.

Bell Telephone Labs.
New York, N. Y.

PROGRAM transmission systems operated on open wire telephone lines ordinarily are not assigned the exclusive use of the lines, but usually share them with other communication facilities. The wide band system described in an accompanying paper[1] transmits currents in the frequency band extending from 35 to 8,000 cycles per second, while the lines over which it is routed possess useful transmission ranges extending from 35 to considerably above 30,000 cycles. In order that the range above 8,000 cycles shall not be wasted, carrier telephone systems utilizing these frequencies usually are operated on the same wires with the program systems.

Line filters are used at each terminal and repeater point in the program system to separate the program currents from the carrier currents and to guide each to the proper channel. They are operated in sets consisting of a low pass filter and a high pass filter connected in parallel at one end, the end that faces the line. The low pass filter transmits the program currents freely while effectively excluding the carrier currents, and the high pass filter transmits the carrier currents while excluding the program currents.[2]

The line filters are located in the open wire program systems as shown in Figs. 1, 15, 16, 17, 18, and 20 of the accompanying paper by H. S. Hamilton.[1] The low pass filter is in the direct path of the program currents and therefore has a number of features of special interest. It is the object of this paper to describe this filter and its contribution to the maintenance of good quality in the programs transmitted over the system.

This low pass line filter, with its associated high pass filter, makes it possible to use the open wire lines simultaneously for wide band program service and for commercial carrier telephone service, without impairing the quality of the program. It represents an improvement over older types of line filters, as well as an advance in the technique of equalization in filters. In cases requiring careful delay and loss equalization, it has been the usual practice to design the filter first to supply the required discrimination or filtering action, and then design a delay corrector

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and tentatively scheduled for discussion at either the A.I.E.E. 1934 summer convention or the A.I.E.E. 1934 Pacific Coast convention. Manuscript submitted Jan. 24, 1934; released for publication March 8, 1934. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

to correct for the delay distortion in the filter, after which a loss equalizer is designed to correct for the amplitude distortion in both the filter and the delay corrector. The loss equalizer introduces a small delay distortion which usually can be anticipated and corrected in the delay corrector. In the wide band program filter the functions usually performed by these 3 separate types of networks have been combined, with a consequent saving in cost and space.

Requirements to Be Met by Program Filter

To function effectively as a line filter, the low pass filter must provide sufficient discrimination against carrier currents to make their effect completely inaudible in all the receivers connected to the program system. Discrimination varying from 46 to about 90 db is necessary to accomplish this end. Because of the presence of an auxiliary low pass filter[1] which supplies considerable loss in the frequency ranges where the requirement is unusually severe, each line filter need furnish discrimination varying only from 40 to about 60 db.

From the standpoint of program quality, it is essential that the line filter, while furnishing the foregoing discrimination, shall not introduce any appreciable distortion into the program. This requirement would call for nothing unusual in the way of filter design if there were only a few filters in the system. Long open wire program systems, however, may extend as far as 3,000 or 4,000 miles, and may contain as many as 50 low pass line filters. A program that has traversed such a circuit still must be comparable in quality to a program that is broadcast from the point at which it originated. Since the system contains much other apparatus, such as equalizers and amplifiers, each low pass line filter can be permitted to introduce not more than about 1/100 of the distortion that can be tolerated in the whole system, assuming 50 filters in the system.

There are 2 types of distortion that must be controlled very carefully in the program filter: these are (1) amplitude distortion, and (2) delay, or phase, distortion. Amplitude distortion is introduced by a filter when its loss is not the same at all frequencies in the transmitted band, currents of

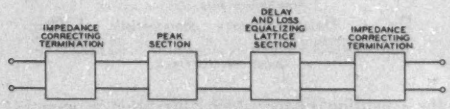


Fig. 1. Block schematic diagram of filter

some frequencies being attenuated more than others. The effect of amplitude distortion on the program is to change the relative intensities, or volumes, of tones of the frequencies at which distortion occurs, thus impairing the naturalness of the program. Amplitude distortion ordinarily can be corrected without much difficulty by means of suitable attenuation equalizers.

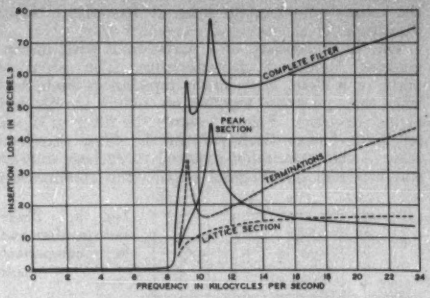


Fig. 2. Loss in filter and in component sections

Delay distortion is introduced by a filter when different frequency components of a signal require different lengths of time for propagation through the filter. This type of distortion is related directly to the shape of the phase shift-frequency characteristic. The slope of this phase shift curve usually is taken as a measure of the delay introduced by the filter. Stated mathematically, the delay in seconds is taken as $\frac{\partial B}{\partial \omega}$, where B is the phase shift in radians and ω is $2\pi f$, f being the frequency in cycles per second. Thus if the phase shift of the filter is proportional to frequency, $\frac{\partial B}{\partial \omega}$, or the delay, is constant and there is no delay distortion. In this case the wave form of a signal transmitted through the filter remains unchanged, the signal being delayed in transmission an interval of time corresponding to the slope of the phase shift curve. If the slope of this curve is not constant over the transmitting band of the filter, however, delay distortion is introduced. In low pass filters, the difference between the slope of the phase shift curve at a given frequency and the minimum slope of the curve is a measure of the delay distortion at that frequency.

A discussion of delay distortion in telephone apparatus, including filters, as well as a discussion of the effect of delay distortion on telephone quality, may be found in 2 recent articles on these subjects.[3,4] Whereas the effect of amplitude distortion is to weaken or strengthen some of the tones in the sound being transmitted with respect to the other component tones, the effect of delay distortion is to introduce unnatural audible effects which may become so pronounced as to be annoying if the delay distortion be great enough.

Delay distortion is present in most filters used in communication work, but ordinarily not in such magnitude that its effect is noticeable. As a rule, it need be considered only when a large number of filters is used in a single circuit, as in the case of the program systems. Delay distortion is in general more difficult to correct than amplitude distortion. One of the unusual features of the low pass line filter used in the wide band program circuits is

the means employed to keep it free from delay distortion.

The filter consists of 4 parts, each with distinguishing functional characteristics. The separate parts, or sections, have image impedances such that when they are joined together no current is reflected at the junctions. Figure 1 shows the filter in block schematic form. Each part of the filter provides some of the attenuation required to exclude carrier currents from the program circuit, the attenuation

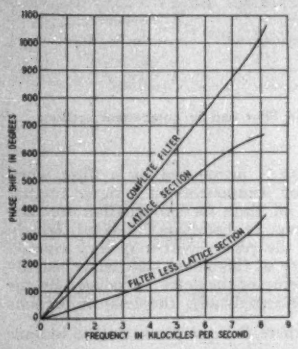


Fig. 3. Phase shift in filter and in component parts

of the complete filter being the sum of the attenuations of all parts. On Fig. 2 are shown the loss-frequency characteristics of the various sections and of the complete filter.

Delay Equalization

Likewise, the phase shift of the complete filter is the algebraic sum of the phase shifts of all sections. The phase shift of the filter exclusive of the delay and loss equalizing section is similar to that of the usual ladder type low pass filter. Over the lower frequencies of the transmitting band the phase shift-frequency characteristic is practically linear with frequency, but at the higher frequencies the slope of this curve increases gradually with frequency and becomes very large near the upper edge of the band. Phase shift varying in this manner introduces much more delay distortion than can be tolerated, and therefore has to be corrected. It is one of the functions of the delay and loss equalizing section, which is of the lattice type, to correct for this distortion. The phase shift of this lattice section is such that when it is added to that of the rest of the filter the total phase shift is very nearly proportional to frequency over the whole program band, and delay distortion thus is almost entirely eliminated.

The property of the lattice section by which its phase shift can be made to vary with frequency in the desired manner is expressed in the following characteristic equation, which holds only in the transmitting band and when the section is terminated in its image impedances[8]:

$$\tan\frac{B}{2} = \frac{Kf\left(1-\frac{f^2}{f_1^2}\right)\sqrt{1-\frac{f^2}{f_c^2}}}{\left(1-\frac{f^2}{f_2^2}\right)\left(1-\frac{f^2}{f_3^2}\right)} \qquad (1)$$

In this equation, B is the phase shift in radians; f is the frequency in cycles per second; f_1, f_2, f_3, and f_c are frequencies at which the phase shift of the section is successive multiples of π radians or 180 deg, f_c being also the cut-off frequency of the filter; and K is a constant controllable by assigning the proper values to the coils and condensers of the section. By assigning to f_1, f_2, and f_3 the values of frequency at which it is desired that the phase shift of the section shall be π, 2π, and 3π radians, respectively, and by giving K the proper value, the phase shift-frequency curve is made to approximate the ideal one which completely would correct the delay distortion of the filter. Figure 3 illustrates the building up of the phase shift characteristic.

The delay corresponding to the rate of change of the phase shift with frequency is plotted in Fig. 4. The average delay introduced by the filter is about 0.00033 sec. It may be noted that for frequencies below 7,500 cycles per second, the variation from this average does not exceed 0.000025 sec. Thus the delay due to 50 filters in a long program circuit does not deviate from the average in this frequency range by more than 0.00125 sec. Distortion of this amount ordinarily would not be detected by the average listener. Above 7,500 cycles per second the delay gradually increases with frequency, rising quite rapidly outside the program band. The high attenuation at frequencies above the program range, however, eliminates any effect this distortion otherwise might have on the program.

Loss Equalization

Another function of the lattice section is to make the loss of the filter constant in the program frequency band. In a dissipationless filter terminated in its image impedances (which is substantially

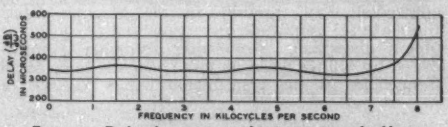


Fig. 4. Delay-frequency characteristic of filter

The ordinates of this curve are proportional to the slope of the upper curve of Fig. 3

the condition under which this filter is operated) the loss in the transmitting band is zero. The effect of dissipation is to introduce a loss which is given approximately in this band by the equation:

$$A_d = \frac{\omega}{2Q}\frac{\partial B}{\partial \omega} \qquad (2)$$

where A_d is the loss due to dissipation, B is the phase shift of the nondissipative filter, and Q is the average dissipation factor of the coils (dissipation in the condensers being negligible, ordinarily). The factor Q

is equal to the average of the ratios $\frac{\omega L_s}{R_s}$, and $\frac{\omega}{2Q}$ in eq 2 therefore may be written $\frac{R_s}{2L_s}$, where R_s and L_s are the effective resistance and effective inductance, respectively, of the coils.

In the coils of the program filter, Q is about proportional to frequency over the lower portion of the program band, but above this range the factor $\frac{\omega}{2Q}$ increases with frequency. For the filter exclusive of the lattice section, the factor $\frac{\partial B}{\partial \omega}$ is also greatest at the higher frequencies, as may be seen from the lower curve in Fig. 3; hence this part of the filter introduces much more amplitude distortion than is permissible. For the lattice section alone, however, the factor $\frac{\partial B}{\partial \omega}$ is greatest at the lower frequencies, as is apparent from the middle curve of Fig. 3. Thus the natural tendency of dissipation in the lattice section is to compensate for the distortion in the other sections of the filter. This compensating tendency can be controlled to a considerable degree, since by eq 2 A_d is proportional to R_s. By proper adjustment of the effective resistance of the coils of the lattice section, its loss is made practically complementary to that of the rest of the filter, so that the loss of the complete filter is substantially constant throughout the program range.

The loss of the filter in the transmitting frequency band is shown in Fig. 5. The average loss below 7,000 cycles per second is about 0.53 db and the deviation from this average does not exceed 0.03 db. Considering again a circuit containing 50 filters, the deviation from the average loss introduced by the filters does not exceed 1.5 db in this range. Between 7,000 and 7,500 cycles per second the amplitude distortion per filter is about 0.10

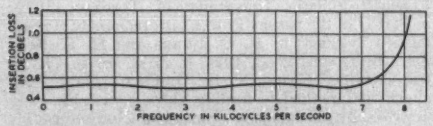


Fig. 5. Loss of filter in program frequency band

db, and above 7,500 cycles the loss increases in such a way as to tend to mask the small delay distortion in this range.

Impedance Correction

In the discussion of the lattice section it was stated that its phase shift is given by eq 1 only when the section is terminated in its image impedance. To facilitate the design and simplify the filter structure, this section has been given an image impedance of the simplest type. This impedance, Z_I, varies with frequency according to the following equation:

$$Z_I = \frac{Z_o}{\sqrt{1 - \frac{f^2}{f_c^2}}} \tag{3}$$

where Z_o is the "nominal impedance" of the filter, a constant equal approximately to the average impedance of the open wire lines in the program

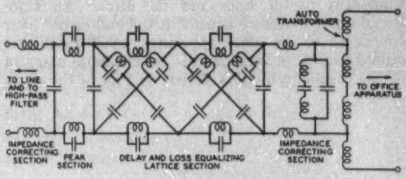


Fig. 6. Schematic diagram of filter

band; and f_c is the theoretical cut-off frequency. Thus the image impedance rises with increasing frequency to a very high value near the cut-off; and, since the line impedance is practically constant except at very low frequencies, a large mismatch would result at the upper edge of the transmitted band if the lattice section were connected directly to the line. The impedance correcting sections at the ends of the filter are employed to avoid this mismatch. The properties of these sections are such that when they are inserted between the lattice section and the line or the office terminating apparatus, the impedance of the filter matches that of the line and the office apparatus, and the lattice section faces its own image impedance. In this manner, both internal and external reflections largely are avoided; and the phase shift of the lattice section has the proper value.[6]

The general theory on which the design of the impedance correcting sections is based is discussed at length in a recently published article.[7] In brief, the sections consist of 2 parts: a 4-terminal network to make the resistance of the filter approximately constant over the program band, and a 2-terminal network placed in shunt at the end to cancel the reactance of the filter in this band. The inductance and capacitance of the coils and condensers of the 4-terminal network are related to the coefficients of a power series expansion of the right-hand part of eq 3 in the manner explained in the article by H. W. Bode.[7] The 2-terminal shunt network at the apparatus end is designed so that, while canceling the reactance of the filter in the program band, it resonates just above the band to produce a peak or sharp maximum of attenuation. It thus supplies the sharp selectivity required to produce an abrupt change from free transmission of the program frequencies to high attenuation of the carrier frequencies.

At the line end, the impedance correcting section is designed for parallel connection with the high pass

line filter. The high pass filter itself acts as the shunt reactance-canceling network.

The peak section shown at the left of the delay and loss equalizing section in Fig. 1 provides attenuation which rises rapidly with frequency above the program band in such a way as to add to the selectivity of the filter. It is a ladder section of a type often employed in filters for its selectivity.

The filter is designed to match the average impedance of the open wire lines. The impedance of the office apparatus, however, is slightly higher than that of the lines and the filter. An auto-transformer therefore is used at the end of the filter connected to the office apparatus, to effect the required change in impedance. A schematic diagram of the complete filter is shown on Fig. 6, the parts being marked for identification in accordance with the foregoing discussion.

References

1. Wide-Band Open-Wire Program System, H. S. Hamilton. Elec. Engg., v. 53, April 1934, p. 550–62.
2. Telephone Transmission Networks, T. E. Shea and C. E. Lane. A.I.E.E. Trans., v. 48, 1929, p. 1031–44.
3. Phase Distortion in Telephone Apparatus, C. E. Lane. *Bell System Tech. Jl.*, July 1930.
4. Effects of Phase Distortion on Telephone Quality, J. C. Steinberg. *Bell System Tech. Jl.*, July 1930.
5. U. S. Patent No. 1,828,454 to H. W. Bode.
6. Impedance Correction of Wave Filters, E. B. Payne. *Bell System Tech. Jl.*, Oct. 1930.
7. A Method of Impedance Correction, H. W. Bode. *Bell System Tech. Jl.* Oct. 1930.

A Graphical Solution of Steady State Stability

The steady state stability limit of a power system, and adjusted synchronous reactance, are considered in this paper. A graphical solution of the problems of the determination of the steady state power limits is described, based directly upon the use of the general circuit constants of the transmission line.

By
H. B. DWIGHT
FELLOW A.I.E.E.

Mass. Inst. of Tech., Cambridge

It is often desirable to determine the steady-state power limit of a system which, for simplicity, is represented by a generator, a transmission line, and a synchronous motor. The 2 synchronous machines may be represented each by a number of ohms of synchronous impedance and in the problem to be considered here, the voltages at the terminals of the machines are given.

A graphical solution is convenient for this problem, and has been presented in the paper "Steady State Stability in Transmission Systems" by Edith Clarke (A.I.E.E. Trans., v. 45, 1926, p. 24, Fig. 3) where the transmission line of the problem is represented by its equivalent π line. (See also the discussion by C. F. Wagner on p. 90 of the same volume.)

In the present paper, a graphical solution is described for the above problem, in which the general circuit constants of the long transmission line are used, instead of the equivalent π line.

Let Z_1 and Z_2 be the synchronous impedances of the generator and the synchronous motor indicated in Fig. 1 and let A, B, C, and D be the general constants of the complete system shown in Fig. 1.

Then $E_1 = DE_1 - BI_1$ (1)

and $I_1 = -CE_1 + AI_1$ (2)

where the voltages are from line to neutral.

These equations constitute definitions of the 4 general constants.

A description of the use of these general constants may be found in "The Calculation of Transmission Line Networks" by T. R. Rosebrugh, Engineering Research Bulletin, University of Toronto, 1919; in Part II of the paper "Power Limitations of Transmission Systems" by R. D. Evans and H. K. Sels, A.I.E.E. Trans., v. 43, 1924, p. 33–8; or in "Electric Circuits," Chap. IX, by O. G. C. Dahl. An alternative method of finding these constants was described by the author in "Electrical Characteristics of Transmission Systems," A.I.E.E. Trans., v. 41, 1922, p. 781–4.

From a point O on cross section paper plot the complex quantity Z_2A ohms, thus locating the point R, Fig. 2. From O also plot B ohms, locating the point P and then plot $B - \frac{Z_1}{A - CZ_1}$ ohms, locating the point S.

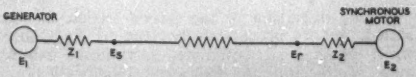


Fig. 1. Representation of power system

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery and scheduled for discussion at the A.I.E.E. North Eastern District meeting, Worcester, Mass., May 16–18, 1934. Manuscript submitted Jan. 15, 1934; released for publication March 13, 1934. *Not published in pamphlet form.*

If $A = a_1 + jb_1$
and $B = b_1 + jb_2$

find an angle ϕ such that

$$\tan \phi = \frac{a_1b_1 - a_2b_1}{a_1b_1 + a_2b_2} \tag{3}$$

If polar expressions are used, such that

$A = |A| \angle \lambda$
and $B = |B| \angle \mu$
then $\phi = \mu - \lambda$ (4)

Draw MC, Fig. 2, perpendicular to OP at its middle point M, and on the side shown. Make $MC = MP/\tan \phi$. With C as center describe

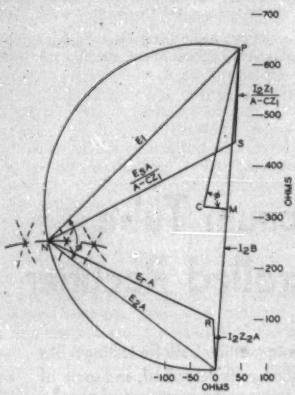


Fig. 2. Diagram for graphical solution

a circle passing through the points O and P. Any pair of lines drawn from O and P to a point on this circle will meet at an angle ϕ, which is a desired characteristic.

Now choose 2 arbitrary lengths which have the ratio of $|E_rA|$ to $|E_rA/(A - CZ_1)|$. On the left-hand side of OP draw an arc with center R and radius equal to the first of the above lengths and draw an arc to cut it, with center S and radius equal to the other length. Repeat this with 2 or more pairs of radii of the same ratio and draw a curve through the intersections of each pair of arcs. Let this curve cut the circle in N and draw lines from N to O, R, S, and P. These lines are proportional to voltages.

Measure NR. Its length is proportional to the known voltage $|E_rA|$, and this gives the voltage scale. From NP find E_1, using this scale, and from NO find $|E_2A|$ from which E_2 may be found.

The maximum power output of the synchronous motor is given by the well-known result,

$$\frac{3}{1{,}000}\left[\left|\frac{E_1E_2}{B}\right| - \left|\frac{E_2^2}{B^2}\right|(a_1b_1 + a_2b_2)\right] \text{kw} \tag{5}$$

or

$$\frac{3}{1{,}000}\left[\left|\frac{E_1E_2}{B}\right| - \left|\frac{E_2^2A}{B}\right|\cos(\mu - \lambda)\right] \text{kw} \tag{6}$$

The value of the current I_2 may be found from the fact that I_2B volts is equal to OP, Fig. 2, using the voltage scale previously found. Dividing by B gives I_2 from which the losses in the synchronous motor may be found, if desired. The phase angle of I_2 is a horizontal line in Fig. 2, since I_2 times resistance is a horizontal line in that diagram.

After the armature and field currents of the synchronous machines have been found, the values of synchronous reactance should be changed to correspond and the problem should be repeated, thus obtaining the "adjusted synchronous reactance." (See Appendix A.)

In deriving the expressions which have been used in this problem,

$$E_1 = E_2A + I_2B \tag{7}$$

from which OP is plotted.

$$E_rA = E_2A + I_2Z_2A \tag{8}$$

from which OR is plotted.

$$E_1 = E_s + I_1Z_1 \tag{9}$$

and directly from eq 2,

$$I_1 = \frac{CE_1}{A} + \frac{I_2}{A}$$

then $I_1 = \dfrac{CE_s}{A} + \dfrac{CI_1Z_1}{A} + \dfrac{I_2}{A}$

$$I_1Z_1(A - CZ_1) = CE_sZ_1 + I_2Z_1 \tag{10}$$

From eqs 9 and 10, $E_1 = E_s\left(\dfrac{A}{A - CZ_1}\right) + \dfrac{I_2Z_1}{A - CZ_1}$ (11)

from which PS is plotted.

The voltages OR, OP, and PS all involve I_2 which at first is unknown, but the coefficients in ohms can be plotted, as already described.

EXAMPLE (See Fig. 2.)

Let $A = 0.620 + j\,0.043$
$B = 50 + j\,630$
$C = -0.000021 + j\,0.00152$
$Z_1 = Z_2 = 4 + j\,160$
$E_r = E_s = 86{,}600$ volts to neutral

Then $Z_2A = OR = -4 + j\,99$
$B - Z_1/(A - CZ_1) = 37 + j\,445$
$\tan \phi = 6.70$
$|E_rA| = 53{,}800$
$|E_rA/(A - CZ_1)| = 62{,}200$

From Fig. 2,
$E_1 = 80{,}000$, $E_2 = 100{,}000$

and maximum power = 33,000 kw.

Appendix A—Adjusted Synchronous Reactance

In the calculations described in this paper, as well as in many other calculations, the number of ohms to be taken for the synchronous reactance of a machine is of importance. It should be such as to make the vector diagram of the machine of as nearly as possible the same proportions as the vector diagram drawn by more elaborate methods such as that involving the armature ampere-turns.

One value of synchronous reactance for a machine will not suit all load conditions, but different values are required for different load currents and for different field currents. Values of synchronous reactance obtained from zero power factor tests at strong field current, corresponding to generator load of lagging power factor, are found to be applicable, to a reasonable degree of accuracy, at loads of other power factors, when the machine is not under-excited, pro-

vided the armature and field currents are the same as those at which the zero power factor measurement was made.

Maximum Power With Given Field Currents

Let a synchronous motor with fixed field current giving excitation voltage E_m to neutral be supplied with current from a generator with fixed field current giving excitation voltage E_g. Let Z be the total impedance made up of the adjusted synchronous impedance

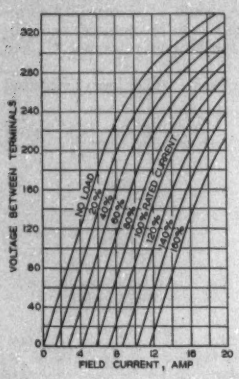


Fig. 3. Zero power factor curves of a 44-kva machine

of the generator and motor and the impedance of the circuit between them. Let letters without dots represent absolute values and let $Z = Z(\cos\gamma + j\sin\gamma) = Z\underline{/\gamma}$. Let E_m be reference vector and $\dot{E}_g = E_g\underline{/\alpha}$. Then, $\dot{I} = \dfrac{\dot{E}_g - E_m}{\dot{Z}} = \dfrac{E_g\underline{/\alpha} - E_m}{Z\underline{/\gamma}}$

According to well-known equations, the power which is the sum of the mechanical load on the motor and its losses except resistance loss, is equal to the real part of $3\,E_m\dot{I}$ and is

$$P_{motor} = \frac{3E_gE_m}{Z}\cos(\alpha - \gamma) - \frac{3E_m^2}{Z}\cos\gamma \quad \text{watts} \quad (12)$$

The maximum value of this power is when $\alpha = \gamma$ and is

$$P_{max} = \frac{3E_gE_m}{Z} - \frac{3E_m^2R}{Z^2} \quad \text{watts} \quad (13)$$

The current at pull-out is

$$I = \frac{1}{Z}\sqrt{(E_g^2 + E_m^2 - 2\,E_mE_gR/Z)} \quad (14)$$

If the resistance is negligible,

$$P_{max} = 3\,E_gE_m/X \text{ watts} \quad (15)$$

$$\text{and } I = \frac{1}{X}\sqrt{(E_g^2 + E_m^2)} \text{ at pull-out} \quad (16)$$

where the voltages are from terminal to neutral. (See "Adjusted Synchronous Reactance and Its Relation to Stability," by H. B. Dwight, *Gen. Elec. Rev.*, v. 35, 1932, p. 609–14.)

In calculating maximum power, a successive approximation must be made. A value of armature current is chosen and the synchronous reactance for that current and for the specified field current is taken from the zero power factor saturation curves, such as Fig. 3. The current for the maximum power condition is then computed, and if it is appreciably different from the value originally assumed, the calculation should be repeated with a better assumed value.

Example. (From thesis of W. J. O'Neill at Massachusetts Institute of Technology.)

Find the maximum power for 2 machines separated by 0.41 ohms reactance.

Generator, 44 kva, 230 volt, 110 amp, 1,200 rpm, 11.6 amp field current
Saturation curves, Fig. 3
Motor, 36 kva, 230 volt, 90 amp, 1200 rpm, 4.2 amp field current

After 2 or 3 trials, using eq 14, the current at pull-out was computed to be 107 amp.

This is 97 per cent of 110 amp, the rated generator current. From Fig. 3, for 11.6 amp field current, the generator synchronous reactance is:

$$X_g = \frac{281 - 134}{107\sqrt{3}} = 0.79 \text{ ohms}$$

A similar calculation for the motor gave 0.84 ohms and 248 volts excitation voltage between terminals.

$$X = 0.79 + 0.41 + 0.84 = 2.04 \text{ ohms}$$

$$P_{max} = \frac{3 \times 281 \times 248}{3 \times 2.04} = 34.1 \text{ kw}$$

The maximum power by test was 35.1 kw, the discrepancy being about 3 per cent.

For other examples of this method, see the paper, previously referred to, by the author in the *General Electric Review*, v. 35, 1932, p. 609–14.

A Vacuum Tube Controlled Rectifier

An electronic rectifier built for testing radio transmitting tubes is described, and some of the factors influencing precision of control are discussed briefly.

By
CALDWELL B. FOOS
ASSOCIATE A.I.E.E.

General Electric Co.
Schenectady, N. Y.

THE PURPOSE of this paper is to discuss a vacuum tube controlled rectifier, developed and built for testing experimental and semiproduction radio transmitting tubes. The set required had to supply filtered direct current at any voltage from 50 to 5,000 volts; had to hold voltage at any set point within 1 per cent, regardless of supply voltage fluctuations up to 15 per cent and load current variations up to 2 amperes full load; had to have a feature capable of limiting the current output to any value from 1 ampere up, even on short circuit, without affecting the voltage regulation up to the current limit; the operation of the set was to be as simple as possible; it was to have a high order of reliability

Full text of a paper recommended for publication by the A.I.E.E. committee on electrophysics and scheduled for discussion at the A.I.E.E. North Eastern District meeting, Worcester, Mass., May 16–18, 1934. Manuscript submitted Feb. 14, 1934; released for publication March 19, 1934. *Not published in pamphlet form.*

and be constantly available; and finally the completed unit was to fit into an existing space $4^1/_2$ by $2^1/_2$ by 3 ft. These severe specifications were completely met by a hot cathode mercury vapor rectifier set of conventional design, the primary voltage of which is controlled by saturable reactors with vacuum tube control. The system involved is unusual, and is capable of a wide variety of applications and high precision of control. The set built for this specific problem will be described, and the factors influencing precision of control by the system used will be discussed briefly.

The Rectifier Built

Reduced to its essentials, the set developed consisted of the components shown in Fig. 1. The main unit is a 10-kw full wave hot cathode rectifier, rated 220-volt 3-phase input, 6,000 volts d-c output. In the a-c input to the set are 3 reactors with d-c saturating windings. By means of these saturating windings, the impedance of the reactors may be varied, from a very high value (when no direct current flows in the saturating windings) to a low value (when full saturating direct current flows in the windings). Thus, the current supplied to the reactor saturating windings determines the voltage on the rectifier primary, and hence the output voltage of the rectifier.

The amount of this saturating current is controlled by a 3-element mercury vapor control tube T_1, and so the focal point of the whole control is the voltage applied between grid and cathode of this tube, which determines the amount of current it will pass; how, will be seen later. In this grid circuit are con-

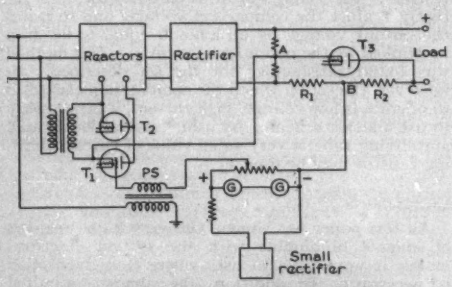


Fig. 1. Schematic diagram of component parts of vacuum tube controlled rectifier set

nected a phase-shift voltage *PS*, a standard voltage *G-G*, and a control, or comparison voltage. As may be seen, the control voltage is taken from the potentiometer, at points *A* and *B*. It is so connected that its polarity tends to act on the set to reduce the output voltage. In series with it, and opposing its effect, is the standard voltage; the difference between the 2 controls the set. This standard voltage is taken from a potentiometer across 2 glow tubes *G-G* connected in series. Each of these tubes maintains a constant voltage drop of about 90 volts over a considerable current range. They are supplied with a much higher d-c voltage, from a small rectifier through a high resistance, so that they will maintain 180 volts on the potentiometer over a large range of supply voltage. As the voltage regulation is obtained by the difference between the standard and control voltages only, it may be seen that the set will hold constant d-c output voltage regardless of line voltage fluctuations.

Resistor R_1 is the compound resistor. The voltage drop across it, due to the load current, acts against the control voltage, tending to raise the output voltage.

Resistor R_2 is the current-limiting control resistor. Point *C* is connected to point *A* through the rectifier tube, T_3. At no load, point *A* is the more positive, and current cannot flow through the rectifier from *A* to *C*. As the load current increases, the voltage drop across R_2 rises until point *C* becomes more positive than point *A;* current then flows through the rectifier from *C* to *A*, tending to raise the potential of point *A* and hence the control voltage, which acts to reduce the output voltage; thus the control is shifted from the voltage to the current at this point. Both R_1 and R_2 are variable, of course, because the current limit is adjustable, and it may be seen that at the current limit the IR drop in R_1 is approximately equal to the standard voltage. R_2 compensates for the drop in R_1.

As has been said, the 3-element mercury vapor tube controls the amount of rectified alternating current fed into the saturating windings of the reactors. The a-c supply for this circuit is taken through an insulating transformer, in this case, because the negative point of the load and the neutral point of the supply are both grounded; if no insulating transformer were used, supply-line-to-ground voltage would be impressed across the control voltage. A "trailing tube" rectifier is placed across the saturating windings, to allow a lower saturating voltage to be used. As may be seen, when the transformer voltage is no longer in such a direction as to push current through the windings through T_1, the voltage induced in the winding due to its electromagnetic energy storage causes the stored energy to flow through T_2. This maintains saturation while T_1 is off.

Factors Limiting Precision of Control

We now come to the discussion of the factors influencing the precision of control obtainable with this system. Of course, in order to obtain the regulation desired there must be two conditions fulfilled; first, the a-c input voltage must always be above the maximum required for the application; and second, the reactor must have a maximum impedance high enough to limit the a-c voltage on the set to the lowest value required for the regulation. Having these fundamentals, the precision of control obtainable comes down, in the final analysis, to the voltage change on the grid of T_1 which will produce a change in the current it controls from zero to maximum saturating current. Using the tube without phase

shift on the grid, this difference is quite small (perhaps $^1/_{10}$ volt, depending on the tube). But if the tube is used without phase shift, it will "hunt," that is, as the voltage changes by a small amount the tube will turn either full on or full off, giving an effect on the reactor like that of a vibrating reed voltage regulator. Depending on the time constant of the circuit, the set will turn on for a few cycles, overshoot the desired voltage, turn off, drop below the desired voltage, and repeat, causing a slow ripple in the d-c output which may be objectionable. To overcome this, an a-c voltage is superimposed on the grid, lagging the anode voltage by 90 electrical degrees. This has the effect of causing the tube, as the d-c grid bias is raised, to turn on at first at the very end of the supply voltage positive half-cycle, then earlier and earlier, until finally it is conducting over all of the positive half-cycle. (See Fig. 2.) The d-c saturating current can thus be smoothly varied in proportion to the d-c bias on the grid; this makes the restoring force proportional to the unbalance, which gives an antihunting characteristic. But the larger the value of the phase shift voltage, the larger the change in d-c grid bias necessary to completely control the tube (see Fig. 2); so this a-c voltage should be as small as possible consistent with good antihunt characteristics. At this point, as in so many engineering solutions, a balance must be struck, a compromise effected.

Let us say, then, that a desirable compromise has been made, and that a given d-c grid bias change, x volts, completely controls the tube. The precision of the control will then be limited by the value of the standard. This may be readily seen from Fig. 3. For simplicity in explanation, let us say that when voltage A equals the standard voltage, the

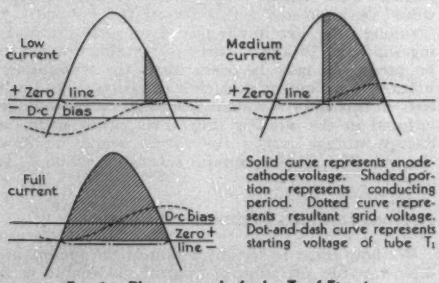


Fig. 2. Phase control of tube T_1 of Fig. 1

balance point or control point is established. Now suppose a variation of load occurs which requires that the conduction angle of the tube be shifted from almost full off to full on, requiring x volts change in the value of the voltage across A. This means a change in the voltage across B of $(B/A)x$. Thus the larger the voltage across A (set by the standard voltage) the smaller the resultant change in B and the higher precision of control obtainable. Ordinarily a good precision of control is possible without going to high standard voltages; for example, in the set described here the regulation was 1 per cent, no load to full load, without compounding or compensation, using a standard of 180 volts. With compounding, this was reduced to $^1/_{10}$ or $^2/_{10}$ per cent over the whole range (without current limiting control). Even finer precision can be, and has been, easily obtained by amplifying the voltage difference between the standard and comparison voltages by a small vacuum tube before it is applied to the control tube grid.

The preceding discussion applies both to current regulation and voltage regulation, when applied singly; when both are applied together, the prob-

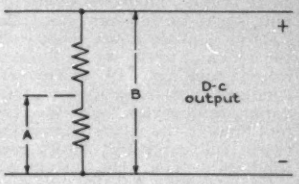


Fig. 3. Schematic diagram of method of precision control

lem becomes a bit more complex. With the system used in the set described here, it may be seen that the load voltage is equal to the voltage across the potentiometer minus the voltage drop across the current limiting control resistor. At high voltages this drop is small compared to the total voltage, and can be compensated for by increasing the compounding resistor; the voltage drop of this resistor adds directly against the comparison voltage, and so raises the output voltage by an amount equal to its drop multiplied by the potentiometer ratio. This method was found satisfactory for the set described. If, however, the set on which the combination control is to operate is low voltage, high current, it is necessary to use another scheme; by using an additional small amplifying tube, a very small value of current-limiting resistor may be used.

Conclusion

As this paper has shown, the very high precision of control obtainable with the system described makes it applicable to uses where close regulation is necessary. In addition, the almost unlimited range of current and voltage to which it may be applied, and the ease with which it works into an automatic control system, makes it seem likely that it will be used on a large variety of applications.

References

Principles of Mercury Arc Rectifiers and Their Circuits, D. C. Prince and F. B. Vodges. McGraw-Hill Publishing Co.

Characteristics and Functions of Thyratrons, Dr. A. W. Hull. Physics, Feb. 1933.

Engineering Features of Gas-Filled Tubes, H. C. Steiner, A. C. Gable, and H. T. Maser. Elec. Engg., May 1932.

Theory of D-C Excited Iron Core Reactors and Regulators, A. Boyajian. A.I.E.E. Jl., October 1924, Vol. 43.

The Theory of Incremental Rates and Their Practical Application to Load Division—Part II

Part I of this paper on incremental rates was published in ELECTRICAL ENGINEERING for March 1934, p. 432–45. The second and concluding part is presented herewith.

By
M. J. STEINBERG
MEMBER A.I.E.E.

THEODORE H. SMITH
NONMEMBER

Both of the Brooklyn Edison Co., Brooklyn, N. Y.

Application to the Generating Station

IN the discussion so far, the operation of the boiler room and turbine room have been treated independently. It has been shown that in the usual case, the maximum turbine room efficiency is obtained when the turbine-generators are loaded incrementally and the maximum over-all boiler room efficiency when the boilers are loaded incrementally.

If the design of the station piping is such that all boilers feed into a common header, so that any boiler or group of boilers can supply steam to any turbine, then the maximum station efficiency will be obtained when the boilers and turbines are independently loaded so that all the turbines are operating at loads which correspond to the same turbine incremental rate and similarly all the boilers are operating at outputs which correspond to the same boiler incremental rate.

The mathematical proof of this statement is contained in Appendix B for the simple case consisting of only 2 boilers and turbines; the proof can easily be extended to include any number of turbines or boilers.

When the station design does not permit the flexibility of steam supply as stated above, the procedure should be modified depending upon the nature of the limitation. Three conditions of common occurrence are discussed below.

First Condition. If certain groups of turbines can be supplied with steam only by certain boilers, then the independent treatment of the entire boiler room and turbine room is not possible. In such a case it is necessary to compute the combined performance of each section of the station, consisting of a group of turbines and the particular group of boilers which supply them with steam. Each section is treated as an independent station and the turbine and boilers of that section loaded independently. The over-all station performance is obtained by dividing the total station load incrementally between the sections. It then becomes relatively a simple matter to compute the heat rate and incremental heat rate curves for the station.

Second Condition. Sometimes sections of a station are connected by a steam tie line of limited capacity. Appendix B shows that in such a case the boiler and turbine rooms may be treated independently until the limit of the tie line capacity is reached. Beyond this point, load division should be between sections until the capacity of either the boilers or turbines of one of the sections is reached.

To illustrate the procedure, consider the hypothetical set-up shown in Fig. 23*A* consisting of 2 turbines, each supplied by a group of boilers which are in parallel through a tie line of limited capacity. For the purposes of simplicity, the boiler outputs are expressed in megawatts referred to the generator terminals. Turbine-generators of 100 megawatts capacity each, with minimum operating loads of 25 megawatts, were assumed. Each group of boilers was assumed to have a capacity of 100 megawatts with a minimum operating load of 5 megawatts. The steam tie line was assumed to have

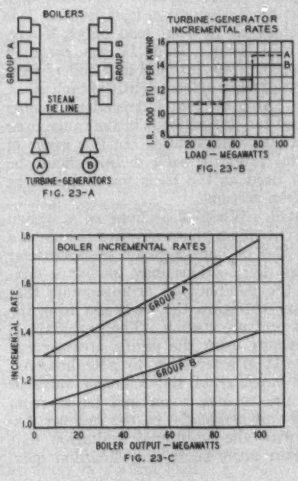


Fig. 23. Performance curves of 2 groups of boilers connected by a steam tie line of limited capacity. (Used to illustrate method of loading turbine-generators and boilers)

Part II of a paper recommended for publication by the A.I.E.E. committee on power generation. Manuscript submitted July 11, 1933; released for publication Sept. 7, 1933. *Not published in pamphlet form.*

a limited capacity of 20 megawatts. The incremental rates for the turbine-generators and the corresponding groups of boilers are shown in Figs. 23*B* and Fig. 23*C*, respectively.

Table IV—Turbine and Boiler Load Division for Set-Up of Fig. 23A

Station Load	Turbine Loads: Unit A	Turbine Loads: Unit B	Boiler Output: Group A	Boiler Output: Group B	Steam Tie Line Load
50	25	25	5	45	20
55	25	30	5	50	20
60	25	35	5	55	20
65	25	40	5	60	20
70	25	45	5	65	20
75	25	50	5	70	20
80	30	50	7	73	23
85	35	50	9	76	26
90	40	50	11	79	29
95	45	50	13	82	32
100	50	50	15	85	35
105	50	55	17	88	33
110	50	60	19	91	31
115	50	65	21	94	29
120	50	70	23	97	27
125	50	75	25	100	25
130	55	75	30	100	25
135	60	75	35	100	25
140	65	75	40	100	25
145	70	75	45	100	25
150	75	75	50	100	25
155	75	80	55	100	20
160	75	85	60	100	15
165	75	90	65	100	10
170	75	95	70	100	5
175	75	100	75	100	0
180	80	100	80	100	0
185	85	100	85	100	0
190	90	100	90	100	0
195	95	100	95	100	0
200	100	100	100	100	0

All values in megawatts

Since the capacity of the steam tie line may be a limitation to the most economical load division, it is necessary to determine in what load range, if any, this limitation will occur. Table IV was prepared for the set-up used. The turbines and boilers were loaded incrementally and independently of each other. It is seen from Table IV that independent loading cannot be applied for station loads in the range from 75 megawatts to 155 megawatts. In this range of load, incremental rates for each section should be established and used as the basis for dividing the total load between sections.

Third Condition. Where 2 sections of a station operate at different steam pressures, then the use of a reducing valve and perhaps a steam desuperheater as a tie between the sections may introduce difficulties due to the complicated arrangements that may be necessary to return the feedwater from the low to the high pressure station. The procedure in such a case depends upon the piping arrangement of the station. It is interesting to note however, that up to the capacity of the reducing valve or desuperheater, the turbine room and boiler room may be treated independently in the manner discussed above, with the additional limitation that the flow of steam must be in one direction only. With capacity flow through the pressure-reducing device, each section should be considered as a unit and the total load divided between sections.

Corrections to Station Performance

Although the turbine heat rate and boiler efficiency are the 2 most important factors which determine station performance, there are several others which may have a considerable effect. The most important of these factors are auxiliary power, change in superheat and feedwater temperature with load, and seasonal variation in vacuum; sometimes heating steam or process steam must be considered. Allowance for these may be made by 1 of 2 methods: First, to correct the performance curves of the individual apparatus; and second, to make the correction on the station performance curves only. The first method is a laborious one which is perhaps justified only when the data available for computation purposes are adequate and

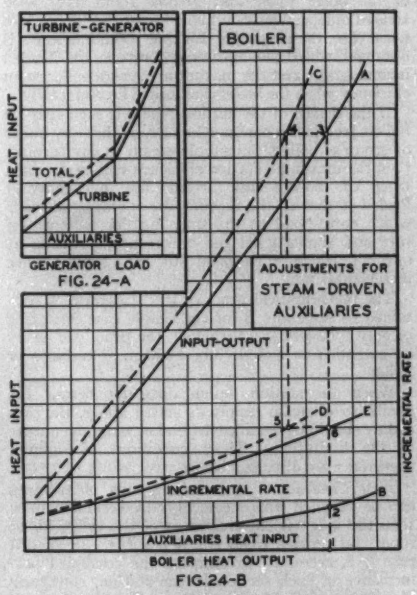


Fig. 24. Method of adjusting turbine-generator and boiler input-output curves for input to steam-driven auxiliaries

accurate, and when the performance for a great many different combinations of units is required. The second method requires less computation and can be used when a factor affects all of the equipment equally.

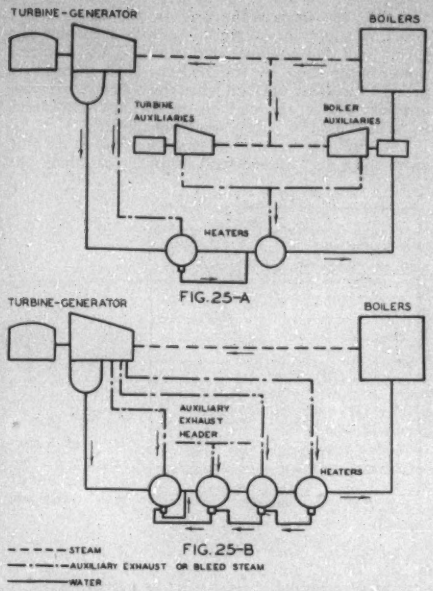


Fig. 25. Diagrams of typical heat balance cycles

Steam Auxiliaries

The auxiliary steam consumption varies with the load on the station and with the combination of boilers and turbines in operation. For load division purposes it usually is sufficiently accurate to group together the heat consumption of all steam auxiliaries and determine an average curve for the station. Then, for any station load, the boiler output would be the sum of the input to the turbines and the heat consumption of all the station steam auxiliaries. The boiler input for this value of boiler output would be found from the boiler input-output curve. Having determined the boiler inputs corresponding to the station loads, the station incremental rates and heat rates can be calculated.

Since the heat consumption chargeable against the auxiliaries is the heat input to the throttles of the auxiliary turbines less the heat recovered from the exhaust steam, the amount will vary depending upon the type and efficiency of the equipment utilizing the heat in the exhaust.

If the auxiliary steam requirements of different types of boilers or turbines in a station are radically different, use of one average auxiliary input curve for all combinations may not be desirable. When sufficient reasonably accurate data on individual auxiliary requirements are available, it is a simple matter to adjust the individual boiler and turbine input-output curves to include the auxiliary heat inputs.

For each turbine, the input for any given load is increased by the corresponding amount of the auxiliary heat consumption to give the equivalent turbine input required from the boilers. For each boiler the output for any given load is decreased by the corresponding auxiliary input, to give equivalent output available for use in the turbine room. The boiler incremental rate to be used in dividing load among the boilers will then be the slope of the curve showing the boiler input plotted against equivalent boiler output. The turbine incremental heat rate will be the slope of the curve of the combined heat input of the turbine and its auxiliaries plotted against turbine load.

The manner in which the input-output curves of the individual turbines and boilers are adjusted for the corresponding steam auxiliary heat consumptions is illustrated in Fig. 24*A* and *B*.

The foregoing method of correcting the individual turbine and boiler performance curves for their respective auxiliary heat consumptions can be correctly applied only if the exhaust steam is utilized after the turbine cycle is complete. A typical heat balance cycle which satisfies these conditions is illustrated in Fig. 25*A*.

In Fig. 25*B* is shown a heat balance diagram in which the exhaust steam enters the turbine cycle before a heater in which extracted steam is used. For a cycle of this kind, the heat consumption of the turbine from which extraction is made is affected by the amount and quality of the exhaust steam since these control the feedwater temperature entering the extraction heater thereby determining the amount of extracted steam. Hence, resort would have to be made to cut-and-try methods if it were desired to compensate for the variations in heat demand of auxiliaries of various units. The performance of any turbine would be affected by the number and loading of other turbines, and by the number and loading of the boilers in service.

An approximate solution could be made by establishing for each turbine 2 curves, both plotted against turbine-generator load. One would show the heat available for feedwater heating in the exhaust steam of the turbine auxiliaries; the other, the heat available in the exhaust of the boiler auxiliaries. The latter curve would be an approximate one, empirically determined by dividing the heat consumption of the boiler auxiliaries among the individual turbine-generators, so that for the normal sequence of operation, the sum of the quantities so assigned would equal the total heat consumption of the boiler auxiliaries through all ranges of station load. The 2 curves would be used to determine the input-output curve for each turbine. Once these were derived, the equivalent input-output curves of boilers and turbines would be computed in the manner already described.

Electric Auxiliaries

As in the case of steam auxiliaries, it is often most practical to group all of the electric auxiliaries together and determine an average total curve over the range of station load. A typical set of curves

for which an average was determined is shown in Fig. 26. Values from the total curve may be subtracted from the gross station output for any combination of units and the net station output be used to determine the station net heat rate and net incremental heat rate. If the load on the system is divided on the basis of gross station load, as is often the case, the station net heat rates and incremental rates should be plotted against gross station load.

If the auxiliary power requirements of the individual boilers and turbines are known, the input-output curves can be adjusted in a manner similar to that described for steam auxiliaries. Since the method to be used differs slightly with the different sources of auxiliary power, a solution for 3 cases commonly met with will be given below.

House Transformers

The effect of the station auxiliaries, when house transformers are used, is to reduce the station net output for a given total load on the main turbines. To obtain the maximum station efficiency it is necessary to make the station input a minimum for any given station *net* output. This requires that net rather than gross incremental rates be used in dividing load among the boilers and turbines.

For each turbine the net incremental heat rate is derived by subtracting from the generator output the corresponding amount of turbine auxiliary power, and determining the slope of the resulting net input-output curve. The turbine net incremental heat

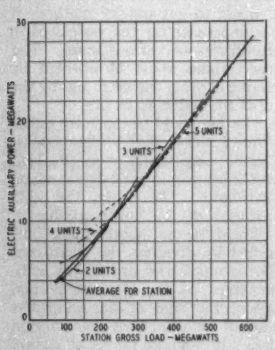


Fig. 26. Determination of average curve for station electric auxiliary power

rate should be plotted against the generator load for use in dividing load among the turbines.

For each boiler, the net incremental rate is derived by subtracting from the boiler output the equivalent *heat input* corresponding to the boiler auxiliary power and determining the slope of the resultant equivalent input-output curve. It will be noted, however, that the proper conversion factor to be used in reducing the kilowatt input to the boiler auxiliaries to Btu per hour input is the prevailing turbine incremental heat rate. In order to visualize the steps in the process, consider a boiler which is supplying steam to operate a turbine at a given load and assume that there is no auxiliary power being used by the boiler. Then, in order to produce the same net load when the boiler does require auxiliary power, the load on the turbine would have to be increased by a corresponding amount.

This increase in turbine-generator load is nothing more than an "incremental output" for which the

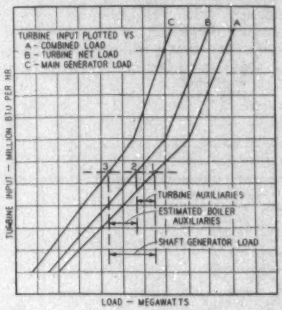


Fig. 27. Adjustment of turbine input-output curve for load on shaft generator

corresponding "incremental input" is the product of the boiler auxiliary power and the turbine-generator incremental heat rate. Since the turbine-generator incremental heat rate is not a function of the boiler load, but depends upon the number and loading of the turbine-generators in service, it would be difficult to ascertain the prevailing turbine-generator incremental heat rate for converting the boiler auxiliary power into equivalent heat units. The use of an average value of turbine-generator incremental heat rate in place of the prevailing value is recommended as being simple, without introducing great error.

House Generators

When station auxiliary power is obtained from house generators on the shafts of the main turbines, it may be difficult to establish an exact relation between the outputs of the house and main generators. Since the output of the house generator is small compared to that of the main generator, the error in assuming its efficiency to equal that of the main generator is negligible. Thus it may be assumed that the heat input to the turbine is a function of the total load on the 2 generators and is independent of the division of load between them.

The net turbine-generator load which is the combined load less the electric power consumption of the turbine auxiliaries, should be used in finding the turbine incremental rate. Since the actual assignment of load to a turbine is usually made in terms of load on the main generator, the division of load between the main and shaft generators must be estimated. This can be done by assuming average conditions in the boiler room and allocating

to each turbine a share of the boiler room electric auxiliary power which, added to the turbine-generator auxiliary power, gives the shaft generator load. Referring to Fig. 27, curves *A*, *B*, and *C* represent the input to the turbine plotted, respectively, against the combined load, turbine-generator net load, and main generator load. For purposes of load division in the turbine room, the incremental rates of curve *B* should be plotted against the corresponding load values of curve *C*. Thus the incremental rate at point 2 will be plotted against the load at point 3. The resulting curve would then show the turbine-generator net incremental rate plotted against the main generator load, and should be used in conjunction with the incremental curves of other turbine-generators to determine the turbine loading.

House Turbine-Generators, Noncondensing Type

Where house turbine-generators of the noncondensing type are used to supply electrically driven auxiliaries, the output of the house generator should be divided between the boilers and turbines. The electric power consumption of the auxiliaries should be converted into equivalent heat values and added to the turbine inputs and subtracted from the boiler outputs in the manner indicated in the discussion for steam driven auxiliaries. The conversion factor in this case, however, should be the corresponding value of the house turbine heat rate. An average value of house turbine-generator heat rate may be used if it is difficult to ascertain the instantaneous values.

In computing the heat rate of the house turbines when the exhaust steam is used to heat the feedwater, the heat reclaimed in the feedwater must not be charged against the auxiliaries. Furthermore, if the exhaust steam enters the turbine cycle, and affects the amount of steam extracted for feedheating, it will be necessary to make computations similar to those described for the same conditions in the discussion of steam auxiliaries.

House Turbine-Generators, Condensing Type

If the house turbines are of the condensing type the condensate from the main turbines is often used circulating water in the house turbine condenser; the house turbine condensate will be mixed with the main condensate, and go through the heaters of the main turbine. Thus, the heat consumption of the main turbines at any given load will be affected by the amount of auxiliary power required by the boilers and turbines. This introduces the same complication that was described for the case in which the exhaust steam from auxiliaries entered the turbine cycle; similar methods of solution are necessary.

Superheat and Feedwater Temperature

It is rarely that boilers give a constant superheat throughout their full load ranges. The superheat is usually affected by the percentage rating at which the boiler is run, the fire conditions, and the temperature of the feedwater into the boiler. The feedwater temperature into the boiler may be partially or wholly dependent upon the total station load and the number and loading of the turbines on the line. It is sometimes, however, kept constant by means of thermostatically operated pressure-reducing valves on the highest pressure heaters, or by the use of exhaust steam in an open heater to bring it to the final temperature.

Correction of station performance for the effect of feedwater temperature is rather an involved and complicated matter. A change in feedwater temperature will result in a change in the superheat of the steam delivered by the boiler to the turbine, which in turn will affect the performance of the latter. Thus it becomes necessary to correct not only the boiler performance but also the turbine performance for the effect of a change in feedwater temperature supplied to the boiler.

Superheat Correction, Feedwater Temperature Constant

When the station feedwater temperature is constant, the correction for the effect of variation of superheat on turbine performance need be applied only to the boiler performance curves.

The economy of operation of a turbine is affected by the temperature of the steam supplied to the throttle. For a given quantity of steam supplied per hour, a decrease in temperature results in a decrease in turbine output, and an increase in temperature results in an increase in output. Consequently, although 2 boilers are operating in parallel with equal efficiencies, if their steam temperatures are not the same, the steam at the lower temperature is used less efficiently in the turbine than the steam at the higher temperature. It is evident that some adjustment is necessary for the better economy obtained in the turbine from steam at the higher temperature. This can be done by calculating the turbine performance for a fixed steam temperature at the throttle and then adjusting the individual boiler efficiency curves for the variation of their steam temperatures from this fixed value. If there are large drops in steam temperature and pressure between the boiler outlet and turbine throttle, these should be allowed for in selecting the fixed temperatures used as the basis for adjusting the turbine and boiler performance curves.

The turbine performance correction factor may be given as a correction to the heat rate or to the water rate. It is much simpler to apply to the heat rate but for many of the older turbines only the water rate correction is available. It must be remembered that an increase in steam temperature which gives one per cent decrease in water rate does not give the same decrease in heat rate, since the heat content per pound of steam at the throttle is substantially increased, so that the total decrease in heat rate may be less than 0.5 per cent. If the superheat correction factors vary but slightly for the different machines an average factor may be used. If there is considerable variation, a better

method is to determine for each turbine the group of boilers which normally supply it with steam, using the superheat correction factor of each turbine for adjustment of the performance curves of the corresponding group of boilers.

To illustrate the method of adjusting the boiler performance curve, consider a boiler which is furnishing steam to a turbine at constant pressure and is receiving feedwater at a constant temperature. Let

T_s = standard steam temperature to which turbine and boiler performances are corrected, degrees Fahrenheit
T_a = actual steam temperature at turbine throttle, degrees Fahrenheit
W_s = turbine steam consumption at standard temperature corresponding to some given load, pounds per hour
W_a = turbine steam consumption at actual steam temperature and same load, pounds per hour
B_a = actual boiler output required when steam is at temperature T_a, Btu per hour
B_s = equivalent boiler output which would be required if steam were at the temperature T_s, Btu per hour
H_s = total heat of steam at temperature T_s, Btu per pound
H_a = total heat of steam at temperature T_a, Btu per pound
q = heat of liquid of feedwater into boiler, Btu per pound
k = turbine steam consumption correction factor for variation of superheat at throttle

Then

$$B_s = W_s(H_s - q)$$

$$B_a = W_a(H_a - q)$$

$$= W_s[1 + k(T_s - T_a)](H_a - q)$$

and

$$\frac{B_s}{B_a} = \frac{(H_s - q)}{[1 + k(T_s - T_a)](H_a - q)}$$

Since B_s is the boiler output at the standard temperature T_s which would do the same work in the turbine as the actual output B_a, the equivalent efficiency of the boiler may be defined as the ratio of B_s to the actual boiler input. Let E_a and E_s be the actual and equivalent boiler efficiencies, respectively.

Then

$$E_s = \frac{B_s \times E_a}{B_a} = \frac{E_a(H_s - q)}{[1 + k(T_s - T_a)](H_a - q)}$$

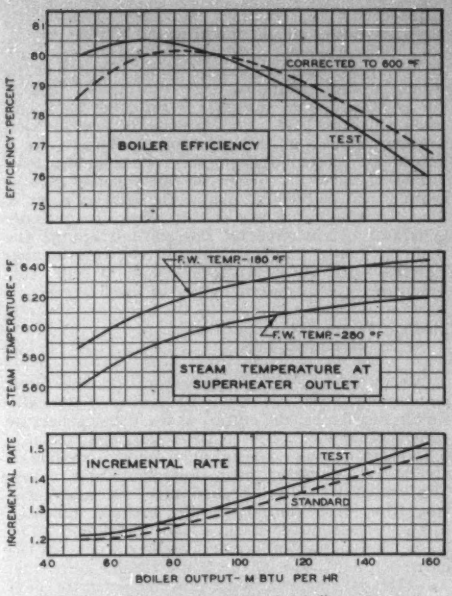


Fig. 28. Adjustment of boiler efficiency and incremental rate curves for feedwater temperature variation

M Btu indicates million Btu

When several boilers supply steam at different temperatures to a common header, the resultant temperature of the steam entering the turbine may be different from that at any boiler outlet. Adjustment of the boiler curves for variation in superheat is made as if the temperature of the steam entering the turbine is the same as that leaving the boiler. This is equivalent to assuming that when several quantities of steam having the same pres-

Table V—Superheat Adjustment of Boiler Performance

B_a	T_i	T_a	$T_s - T_a$	$1 + k(T_s - T_a)$	H_a	$H_a - q_s$	B_s/B_a	B_s	E_a	E_s
50	585	560	40	1.040	1291.2	1042.2	0.9819	49.1	80.00	78.55
60	599	574	26	1.026	1299.0	1050.0	0.9879	59.3	80.35	79.38
70	610	585	15	1.015	1305.0	1056.0	0.9930	69.5	80.50	79.94
80	618	593	7	1.007	1309.4	1060.4	0.9967	79.7	80.42	80.15
90	624	599	1	1.001	1312.7	1063.7	0.9995	90.0	80.14	80.10
100	629	604	−4	0.996	1315.5	1066.5	1.0020	100.2	79.74	79.90
110	633	608	−8	0.992	1317.7	1068.7	1.0039	110.4	79.23	79.54
120	636	611	−11	0.989	1319.3	1070.3	1.0055	120.7	78.66	79.09
130	639	614	−14	0.986	1320.9	1071.9	1.0070	130.9	78.00	78.55
140	641	616	−16	0.984	1322.0	1073.0	1.0080	141.1	77.39	78.01
150	643	618	−18	0.982	1323.1	1074.1	1.0090	151.4	76.71	77.40
160	645	620	−20	0.980	1324.2	1075.2	1.0101	161.6	75.99	76.76

T_s = 600 deg F
t_s = 280 deg F
t_i = 180 deg F
Pressure = 300 lb abs.

H_s = 1313.3 Btu/lb
q_s = 249.0 Btu/lb
$H_s - q_s$ = 1064.3 Btu/lb
k = 1 per cent for 10 deg F

$T_i - T_s = 0.25(t_s - t_i) = 0.25(280 - 180) = 25$ deg F

$$B_s/B_a = \frac{H_s - q_s}{[1 + k(T_s - T_a)](H_a - q_s)} = E_a/E_s$$

T_i is the steam temperature obtained on boiler test with a feedwater temperature t_i; t_s is the standard feedwater temperature to which boiler performance is adjusted

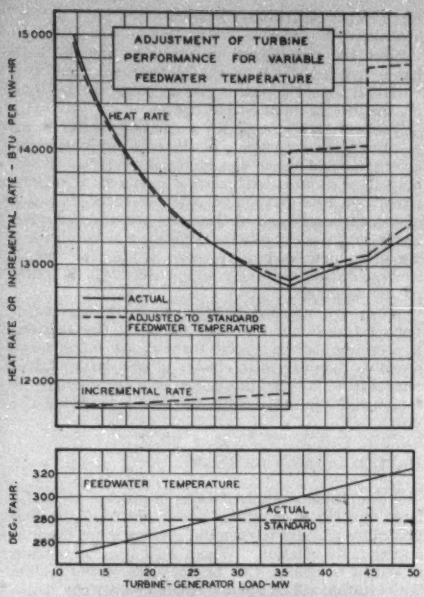


Fig. 29. Adjustment of turbine-generator heat and incremental heat rate curves for variation of feedwater temperature supplied to boilers

Mw indicates megawatts

sure but different temperatures are mixed, the resultant temperature may be obtained by taking the average, weighted according to the amount of heat contained in each quantity of steam. The error introduced by adjusting the boiler curves in the manner described here is within the accuracy with which the superheat curves of individual boilers can be determined.

Superheat Correction, Feedwater Temperature Variable

When the boiler is called upon to evaporate feedwater at variable temperatures, the fact that at a given load the steam will not always be delivered with the same superheat makes it difficult to determine a characteristic curve of superheat against heat output.

The effect of feedwater temperature on boiler performance is further complicated when economizers are used on the boilers. The hotter the feedwater entering the economizer the less heat is recovered from the flue gases. The loss in economizer efficiency is cumulative with the loss due to lowering the superheat, and may be several times as great as the latter.

Thus there are 3 different conditions that might prevail in a station having variable feedwater temperature. It might be that:

1. None of the boilers were equipped with economizers.
2. All of the boilers were equipped with economizers.
3. Some of the boilers had economizers while others had none.

The cases are cited in the order of their relative simplicity of treatment.

Boilers Without Economizers

In case of a station having no economizers on the boilers, the change in superheat with change in feedwater temperature is the only consideration. Some knowledge of the relationship existing between the feedwater temperature and the superheat for the particular boilers is necessary. This will depend upon the type and size of the superheaters installed; it may differ somewhat among the boilers, in which case a weighted average can be taken.

The boiler superheat characteristic should be corrected to a condition of constant feedwater temperature; the input-output curve and incremental rate should then be adjusted to compensate for the deviation of the new superheat characteristic from the standard superheat.

In the same way, the turbine performance will be

Table VI—The Adjustment of Turbine Performance for Feedwater Temperature

Load, Megawatts	t_a	$t_s - t_a$	$T_s - T'_a$	T'_a	$1 + k(T_s - T'_a)$	H'_a	q_a	$H'_a - q_a$	$H_s - q_a$	HR'_a/HR_s	HR_s	HR'_a
12	251	+29	− 7.3	607.3	0.9927	1317.3	219.4	1097.9	1093.9	0.9963	15000	14945
18	263	+17	− 4.3	604.3	0.9957	1315.6	231.6	1084.0	1081.7	0.9978	13923	13892
24	275	+ 5	− 1.3	601.3	0.9987	1314.0	243.8	1070.2	1069.5	0.9994	13385	13377
30	286	− 6	+ 1.5	598.5	1.0015	1312.5	255.1	1057.4	1058.2	1.0007	13063	13072
36	298	−18	+ 4.5	595.5	1.0045	1310.8	267.4	1043.4	1045.9	1.0021	12847	12874
40	306	−26	+ 6.5	593.5	1.0065	1309.7	275.7	1034.0	1037.6	1.0030	12949	12988
45	316	−36	+ 9.0	591.0	1.0090	1308.3	286.0	1022.3	1027.3	1.0041	13051	13105
47	320	−40	+10.0	590.0	1.0100	1307.8	290.2	1017.6	1023.1	1.0046	13157	13218
50	326	−46	+11.5	588.5	1.0115	1307.0	296.4	1010.6	1016.9	1.0052	13300	13389

T_s = 600 deg F
t_s = 280 deg F
k = 1 per cent for 10 deg F

H_s = 1,313.3 Btu/lb
Pressure = 300 lb abs
$T_s - T'_a = -0.25(t_s - t_a)$

$$HR'_a/HR_s = \frac{[1 + k(T_s - T'_a)](H'_a - q_a)}{H_s - q_s}$$

t_s and t_a are, respectively, the standard and the actual feedwater temperatures. If the boiler in Table V were supplying steam at the standard steam temperature, T_s with the standard feedwater t_s, changing the feedwater temperature to the actual turbine feedwater temperature t_a would cause the steam temperature to change to the adjusted value T'_a. HR_s and HR'_a are the turbine heat rates with steam at the temperature T_s and T'_a, respectively

corrected to the average superheat; it will be further corrected for the effect of its feedwater temperature characteristic on the superheat of the steam, generated in the boilers, and hence on its own economy.

In Table V are shown computations for adjusting the boiler performance curves of Fig. 28 from actual to standard conditions of steam and feedwater temperatures. Table VI shows computations for adjusting the turbine performance curves of Fig. 29 for the variation of the feedwater temperature from standard.

Economizers on All Boilers

The effect of varying feedwater temperature on the performance of boilers which are equipped with economizers may be several times as great as the effect on boilers without them. Since the amount of heat recovered in the economizer changes considerably with change in feedwater temperature, the boiler efficiency at any given heat input is dependent upon this temperature. The effect of change in feedwater temperature on the boiler superheat, however, is less when there is an economizer than when the feedwater goes directly into the boiler. The change in superheat and change in efficiency of the boiler unit per degree Fahrenheit change in feedwater temperature into the economizer should be determined for each type of installation. This is best done experimentally rather than by use of guarantee data.

Correction of the boiler performance curves to standard feedwater and steam temperatures is made in 3 steps:

1. Correction of the efficiency of the boiler unit for the effect on the heat recovery in the economizer caused by changing the feedwater temperature to standard.

2. Correction of the boiler superheat characteristic to a condition of standard feedwater temperature.

3. Adjustment of the efficiency curve obtained in (1) for variation of the superheat characteristic of (2) from the standard superheat.

Correction of the turbine performance curves is also made in 3 steps:

1. The turbine heat rate is corrected to the standard steam temperature.

2. Correction of the heat rate curve from (1) for the effect on the *turbine* efficiency, of the variation of the boiler superheat resulting from the difference of the actual turbine feedwater temperature from the standard.

3. Adjustment of the heat rate curve from (2) for the effect on the *boiler* efficiency, of the variation of the actual turbine feedwater temperature from the standard.

Some Boilers With Economizers, Some Without

In this case the performance curves of each individual boiler are adjusted as was described above, using the proper correction factors. In making the adjustment of the turbine performance curves the most feasible solution is to use the correction factors corresponding to the group of boilers from which it normally receives most of its steam.

Seasonal Variation in Vacuum

Since the variation of vacuum with turbine load has a marked effect on the incremental rate, this variation should be taken into account in establishing the turbine input-output curves.

The seasonal change in circulating water temperature causes a change in the vacuum-load characteristics and hence the incremental rates of the individual turbine, but in many instances it will be found that load division between the turbines is not disturbed because all of the units are affected relatively to the same extent. Under these conditions, use of vacuum-load curves corrected to the yearly average circulating water temperature will be sufficiently accurate.

When the seasonal change in circulating water temperature is not the same for all of the stations in a system, or when some turbines are much more sensitive than others to change in circulating water temperature, a series of performance curves may be established for use during different periods of the year.

Heating and Process Steam

When stations supply heating or process steam in large quantities, as well as power, the load division procedure may get too complicated for more than an approximate solution. Where high pressure steam is sold, it is possible that one or more of the boilers of the station will be isolated to supply only the steam for sale. In this case the only effect on the power boilers may be to decrease the number available and hence increase the incremental rate for a given turbine demand.

When the same boilers supply steam both for power and heating, an approximate solution can be made by determining the kilowatt load equivalent to the heating steam. For purposes of system load division, the system demand is considered to include the heating steam equivalent load; the actual load which should be generated by the station supplying the heating steam is the assigned load less the equivalent load of the heating steam. The heating steam can be converted into an equivalent load by dividing the heat in the steam by the average turbine incremental heat rate.

The problem of obtaining the correct load division becomes very complicated when heating or process steam is supplied from the turbine exhaust or by extraction. The solution depends upon the heat balance cycle as well as on operating conditions such as whether the amount of process steam required is variable or constant and whether it is necessary to keep the load on the turbines supplying the steam constant or always above a certain value, in order to maintain the required process steam temperature. Change in the amount of heating steam will change the incremental heat rates as well as the loads at which the admission valves become fully open.

Because each problem depends so closely upon the individual set-up, no solution will be included here. It is felt that the methods discussed for other cases

can be extended to take care of the majority of problems involving the extraction of steam for commercial uses.

Maintenance

The operation of equipment, especially boilers, at or near maximum capacity may result in excessive maintenance costs for the equipment. The loads above which the maintenance costs increase rapidly should be determined and considered as normal operating limits, or else the incremental rates of the equipment in question should be arbitrarily increased for all loads above the one at which the maintenance costs become excessive.

If 2 or more interconnected generating stations have maintenance costs which differ considerably, then it is not correct procedure to divide the common load among them on the basis of their respective incremental heat rates. The respective incremental maintenance costs should be determined and converted into equivalent heat units which, added to the corresponding incremental heat rates, will give the adjusted incremental heat rate curves that should be used to determine the division of load.

Table VII—Computation of Boiler Inputs Using Incremental Rates

Boiler Output Million Btu/Hr	Incremental Output Million Btu/Hr	Average Incremental Rate	Incremental Input Million Btu/Hr	Boiler Input Million Btu/Hr
2,100				2358.0
	100	1.152	115.2	
2,200				2473.2
	100	1.162	116.2	
2,300				2589.4
	100	1.173	117.3	
2,400				2706.7
	100	1.185	118.5	
2,500				2825.2
	100	1.198	119.8	
2,600				2945.0
	100	1.202	120.2	
2,700				3065.2
	100	1.217	121.7	
2,800				3186.9
	100	1.233	123.3	
2,900				3310.2
	100	1.250	125.0	
3,000				3435.2
	100	1.268	126.8	
3,100				3562.0
	100	1.287	128.7	
3,200				3690.7
	100	1.307	130.7	
3,300				3821.4
	100	1.328	132.8	
3,400				3954.2
	100	1.350	135.0	
3,500				4089.2
	100	1.373	137.3	
3,600				4226.5
	100	1.397	139.7	
3,700				4366.2
	100	1.422	142.2	
3,800				4508.4
	100	1.448	144.8	
3,900				4653.2
	100	1.475	147.5	
4,000				4800.7

The adjustment for maintenance must be made empirically because no definite relationship between incremental maintenance costs and instantaneous values of load is known.

Computation of Station Performance

After having selected the specific method of computing the performance of the individual equipment in the station, and having carried through the computations, making any necessary corrections for auxiliary power, feedwater temperature, and steam superheat, the station input-output and incremental rate curves are determined. For any desired turbine and boiler combination, the turbine room input-output curve should be calculated, and then combined with the boiler curves to give the station performance.

Very great care must be taken in drawing the input-output curves, in order to get consistent incremental rate curves. If a great many combinations of turbines and boilers are required, accuracy sometimes can best be secured by using input-output tables instead of curves, interpolating, if necessary, to obtain values that are not tabulated. In constructing the tables, the approximate input-output curve should be drawn; the incremental rate curve should be determined and carefully adjusted so that it is consistent and so that the area included under it, represents the difference between the maximum and minimum inputs. By selecting convenient values of incremental output and multiplying them by their respective average values of the incremental rate, the corresponding incremental inputs are obtained, which, added cumulatively to the minimum input, give successive values of input. A sample computation using this method is shown in Table VII for a group of boilers.

Whether or not the expenditure of the time and labor required for a rigorous calculation of station performance is justified, depends upon the use that is to be made of the computations. If the use is solely for load division purposes, it is doubtful whether a rigorous calculation can be justified, because the variation in the loading of generating stations within reasonable limits, will not appreciably affect the over-all production costs of the system. When considerable work is done in station heat balance computation, however, as is often the case for large modern steam generating stations, a detailed computation arranged so that it can easily be applied under widely divergent conditions of operation, may be a very profitable undertaking.

Approximate Method of Calculating Station Performance

An approximate method for computing station performance curves has been developed which is very simple to apply and which permits the computation of curves for numerous combinations of boilers and turbine-generators in relatively little time. This method should have extensive use in cases where rigorous calculations cannot be justified.

In this method performance curves, similar to those shown in Fig. 30, are established for the turbine room, boiler room, and steam and electric

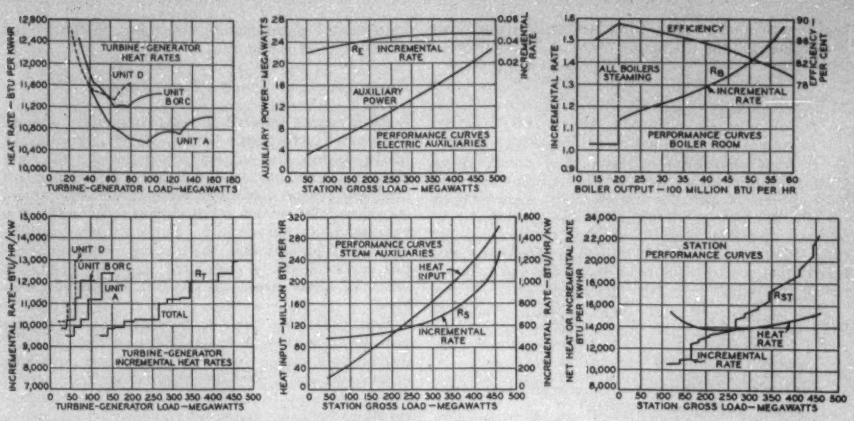


Fig. 30. Performance curves required for the calculation of station incremental heat rates by an approximate method

auxiliaries. The station incremental rates can then be derived from the incremental rates of the above-mentioned equipment by means of the relation:

$$R_{ST} = \frac{R_B(R_T + R_S)}{1 - R_E}$$

Where

R_{ST} = station incremental rate
R_B = boiler room incremental rate
R_T = turbine room incremental rate
R_S = incremental rate of steam auxiliaries
R_E = incremental rate of electric auxiliaries

A sample computation in which this method was applied is shown in Table VIII. The station heat rates can be computed from the net station loads, the total boiler room output (which is the sum of the inputs to the steam auxiliaries and main turbines) and the boiler room efficiency. The latter was derived in the manner illustrated in Table VII.

It should be noted that the boiler room incremental rate curve for the banked boiler region cannot be determined directly from the individual boiler incremental rates, but must be derived from an average input-output curve for the banked range of the boiler combination in question. In many cases sufficient accuracy can be had by computing the input at the minimum required boiler output, and at the point at which the last boiler is taken off bank. The difference in input divided by the corresponding difference in output gives the average incremental rate which should be used in the banked boiler region.

The derivation of the above relation, included in Appendix C, is based upon the assumption that the electric and steam auxiliaries are both functions of the gross station load only. This assumption is not strictly correct but as was indicated in the previous discussion on station auxiliaries, is sufficiently accurate for most purposes.

If the station auxiliaries are essentially steam driven, then the probability is that the electric auxiliary power is practically constant and independent of the station load. The incremental rate of the electric auxiliaries is zero, and the relation becomes

$$R_{ST} = R_B(R_T + R_S)$$

Likewise when the station auxiliaries are essentially electrically driven and the input to the steam auxiliaries is relatively constant, the incremental rate of the steam auxiliaries is zero, and the relation becomes

$$R_{ST} = \frac{R_B R_T}{1 - R_E}$$

Load Division Between Generating Stations

Assuming the performance of each generating station in an interconnected system has been established, taking into account such factors as coal cost, circulating water conditions, and maintenance, the problem then arises of how to load the stations to get the best system economy. Load division between stations is usually limited by such factors as tie-feeder capacity, voltage and power factor regulation, and safety of operation.

The problem of load division, when the transmission line losses are negligible, becomes merely one of operating the stations at equal incremental rates. On the other hand, if the losses are appreciable, the load division procedure must be modified to take them into account. To illustrate the effect of tie line losses, the simplest case to consider is that for 2 interconnected generating stations. In order that it be economical to transfer a given load from one station to another, the following relation must prevail

$$R_s = R_r \times E_{ii}$$

Where

R_s = incremental rate of the sending station
R_r = incremental rate of the receiving station

E_u = incremental efficiency of the transmission line corresponding to the given load transferred

Analysis of the above equation, which is derived in Appendix D, shows that in the case of interconnected generating stations the general rule is corrected to include a factor E_u, the incremental efficiency of the transmission line. The latter is a function of the line losses, being the increment of load at the receiving end divided by the increment of load at the sending end.

When several stations are linked together, it may be impossible to determine the loading which will give maximum over-all efficiency except by trial-and-error computations. Any detailed analysis depends so much upon the physical set-up of the individual system, that none will be included here. The principles to be applied are the same as those which govern load division within the station, namely, to keep individual stations operating as closely as possible at the same incremental rates, taking into account transmission line losses. (A more complete discussion of the effect of transmission line losses is given by the article "Incremental Loading of Generating Stations," by M. J. Steinberg and T. H. Smith, ELEC. ENGG., October 1933, p. 674–7.)

When a system contains several large generating stations with many turbine-generator units, the problem of selecting the correct combination of units for a given system load resolves itself into 2 parts:

1. Determination of the order in which units should be added to the line at each individual station, as the *station* load increases.

2. Determination of the order in which units should be put in service throughout the system, as the *system* load increases.

Since, at a given time, the same group of boilers will be used to supply steam to any combination of units in an individual station, the sequence in which units should be added is in the order of their relative efficiencies. Thus to determine the proper combination at a given station load, it is only necessary to plot the turbine heat rate curves of successive combinations and select the one which gives the lowest turbine input. When several stations are operating in parallel, units put on the line at one station must get their steam from the boilers of that station, hence the total boiler input of the system must be used as the criterion in adding units, not the total turbine input. Calculation of the system input for several combinations will be required before the proper one can be ascertained for the given system load.

Computation of the system inputs for each of the numerous combinations, which requires a great deal of time and labor, can be eliminated by applying the following method:

1. For each individual station, compute the station input-output curves corresponding to the proper sequence of adding units.

2. Plot the curves of (1) and draw an average input-output curve through them.

Table VIII—Sample Calculation of Station Performance Curves

Turbine-Generator Loads Megawatts					Elec. Aux. Power Megawatts	Station Net Load Megawatts	Turbine Inputs, Million Btu/Hr				Steam Aux. Input, Million Btu/Hr	Total Boiler Room Output, Million Btu/Hr						Boiler Room Eff. Per Cent	Station Net Heat Rate Btu/Kwhr
A	B	C	D	Total			A	B	C	D			R_T	R_B	R_E	R_S	R_{ST}		
40	30	30	20	120	6.1	113.9	461	373	373	261	60	1,528		1.028	0.036	500	10,670	86.8	15,450
50	30	30	20	130	6.5	123.5	555	373	373	261	65	1,627	9,510	1.028	0.036	510	10,690	87.2	15,410
60	30	30	20	140	6.9	133.1	651	373	373	261	70	1,728		1.028	0.037	520	10,710	87.8	14,790
60	30	30	20	140	6.9	133.1	651	373	373	261	70	1,728		1.028	0.037	520	11,080	87.8	14,790
60	43	30	20	153	7.4	145.6	651	501	373	261	78	1,864	9,860	1.028	0.038	520	11,090	88.5	14,460
60	43	43	20	166	7.9	158.1	651	501	501	261	85	1,999		1.028	0.038	520	11,090	89.0	14,210
60	43	43	20	166	7.9	158.1	651	501	501	261	85	1,999		1.140	0.038	520	12,490	89.0	14,210
70	43	43	20	176	8.2	167.8	752	501	501	261	90	2,105	9,920	1.148	0.039	530	12,600	89.0	14,090
78	43	43	20	184	8.6	175.4	830	501	501	261	95	2,188		1.156	0.040	540	12,720	88.9	14,030
78	43	43	20	184	8.6	175.4	830	501	501	261	95	2,188		1.156	0.040	540	12,910	88.9	14,030
78	43	43	30	194	9.0	185.0	830	501	501	359	100	2,291	10,180	1.172	0.041	540	13,100	88.8	13,950
78	43	43	44	208	9.6	198.4	830	501	501	505	108	2,445		1.194	0.041	550	13,250	88.5	13,930
78	43	43	44	208	9.6	198.4	830	501	501	505	108	2,445		1.184	0.041	550	13,350	88.5	13,930
85	43	43	44	215	9.9	205.1	902	501	501	505	112	2,521	10,260	1.187	0.042	560	13,410	88.4	13,910
96	43	43	44	226	10.3	215.7	1,014	501	501	505	118	2,639		1.194	0.042	560	13,490	88.2	13,870
96	43	43	44	226	10.3	215.7	1,014	501	501	505	118	2,639		1.194	0.042	560	13,490	88.2	13,870
96	64	43	44	247	11.3	235.7	1,014	717	501	505	131	2,868	10,260	1.210	0.043	580	13,710	87.7	13,870
96	64	64	44	268	12.1	255.9	1,014	717	717	505	142	3,095		1.221	0.044	600	13,870	87.3	13,850
96	64	64	44	268	12.1	255.9	1,014	717	717	505	142	3,095		1.221	0.044	600	14,800	87.3	13,850
96	64	64	55	279	12.5	266.5	1,014	717	717	629	149	3,226	10,990	1.230	0.045	620	14,950	87.1	13,900
96	64	64	64	288	12.9	275.1	1,014	717	717	725	155	3,328		1.236	0.045	630	15,040	86.9	13,920
96	64	64	64	288	12.9	275.1	1,014	717	717	725	155	3,328		1.236	0.045	630	15,300	86.9	13,920
110	64	64	64	302	13.6	288.4	1,182	717	717	725	164	3,505	11,190	1.250	0.045	650	15,500	86.5	14,050
128	64	64	64	320	14.4	305.6	1,372	717	717	725	176	3,707		1.265	0.046	680	15,740	86.1	14,090
128	64	64	64	320	14.4	305.6	1,372	717	717	725	176	3,707		1.265	0.046	680	15,830	86.1	14,090
128	77	64	64	333	14.9	318.1	1,372	863	717	725	185	3,862	11,260	1.280	0.046	700	16,050	85.8	14,150
128	77	77	64	346	15.5	330.5	1,372	863	863	725	195	4,018		1.293	0.046	730	16,250	85.4	14,240
128	77	77	64	346	15.5	330.5	1,372	863	863	725	195	4,018		1.293	0.046	730	17,290	85.4	14,240
128	110	77	64	379	17.2	361.8	1,372	1,260	1,863	725	224	4,444	12,030	1.343	0.047	820	18,110	84.3	14,570
128	110	110	64	412	18.6	393.4	1,372	1,260	1,260	725	249	4,866		1.386	0.047	920	18,830	83.3	14,850
128	110	110	64	412	18.6	393.4	1,372	1,260	1,260	725	249	4,866		1.386	0.047	920	19,330	83.3	14,850
145	110	110	64	429	19.4	409.6	1,596	1,260	1,260	725	265	5,106	12,370	1.422	0.047	1,020	19,980	82.7	15,070
160	110	110	64	444	20.1	423.9	1,768	1,260	1,260	725	281	5,294		1.455	0.047	1,100	20,570	82.1	15,210
160	110	110	64	444	20.1	423.9	1,768	1,260	1,260	725	281	5,294		1.455	0.047	1,100	21,500	82.1	15,210
160	110	110	70	450	20.4	429.6	1,768	1,260	1,260	806	288	5,382	12,980	1.472	0.047	1,150	21,830	81.8	15,320
160	110	110	80	460	20.8	439.2	1,768	1,260	1,260	933	300	5,521		1.500	0.047	1,260	22,410	81.4	15,440

3. Compute and plot the average incremental rate curve corresponding to the average input-output curve of (2). On the incremental rate curve indicate the loads at which it is proper to add additional units.

4. Divide the system load on the basis of the average incremental rate curves of (3). The station loads so determined will indicate the combination of units that should be operated at each station.

5. Redivide the system load using the actual incremental rate curves that correspond to the combinations determined under (4).

Conclusion

In reading this paper one may get the impression that the application of incremental rates to load division is very complicated and difficult. The question arises "Are the savings that can be effected worth the effort?"

It certainly is apparent that in the larger stations of recent design with highly efficient units available, it will be advantageous to study the loading sequence carefully in order to maintain the operating procedure at its highest efficiency. In these stations a small gain in efficiency will result in savings of considerable magnitude, due to their large outputs. In addition to the gains effected by accurate load division, there are benefits to be derived from having available accurate performance data on the individual equipment, permitting the calculation of a reliable "bogey" performance, which, compared with the actual performance, will direct the attention of the operating personnel to any faulty performance.

In the case of stations of the older type, with relatively lower operating efficiencies, the careful analysis of operating procedure for the purpose of establishing the incremental rates, may lead to changes in practice which will result in savings of the same magnitude as those effected by a change in load division.

Application of the principles of incremental rate loading, based upon careful analysis of operating conditions, gives assurance that equipment of the system is being utilized to the best advantage. It also has the valuable effect of keeping the operating personnel on the alert to maintain the most efficient operation.

Appendix A

(See p. 445, March 1934 issue of Electrical Engineering.)

Appendix B

Proof That Independent Loading of Boilers and Turbines Incrementally Will Result in Maximum Station Efficiency

Consider 2 boilers operating with 2 turbines; the characteristics of the boilers and of the turbines are different. Either turbine may be partially or wholly supplied from either boiler. With both boilers and both turbines on the line, let

L = total station load
L_1 = load on turbine No. 1
L_2 = load on turbine No. 2
T_1 = heat input to turbine No. 1
T_2 = heat input to turbine No. 2
O_t = total heat output of boilers
O_1 = heat output of boiler No. 1
H = heat output of boiler No. 1 not used in turbine No. 1
O_2 = heat output of boiler No. 2
I_1 = heat input to boiler No. 1
I_2 = heat input to boiler No. 2
I_t = total heat input to both boilers

T_1 and T_2 include the respective turbine auxiliaries. I_1 and I_2 are the inputs necessary to furnish O_1 and O_2 plus the respective boiler auxiliaries. All auxiliaries are steam driven. Then

$$L = L_1 + L_2$$

$$T_1 + T_2 = O_t = O_1 + O_2$$

$$T_1 + H = O_1; \quad T_2 - H = O_2$$

and

$$I_t = I_1 + I_2$$

Suppose L_1 and O_1 are chosen as the 2 independent variables. The problem is to determine, for any total load L, the values of L_1 and O_1 which will give the minimum station input. Let us assume that the boiler and turbine input-output curves are all continuous and that the respective incremental rates never decrease as the output increases.

The condition for a minimum is expressed mathematically by the equation

$$dI_t = 0 \tag{1}$$

But

$$dI_t = \frac{\partial I_t}{\partial L_1} dL_1 + \frac{\partial I_t}{dO_1} dO_1 \tag{2}$$

Since L_1 and O_1 are independent variables, it is necessary that

$$\frac{\partial I_t}{\partial L_1} = 0 \quad \text{and} \quad \frac{\partial I_t}{\partial O_1} = 0 \tag{3}$$

in order that dI_t shall vanish. But

$$\frac{\partial I_t}{\partial O_1} = \frac{\partial (I_1 + I_2)}{\partial O_1} = \frac{\partial I_1}{\partial O_1} + \frac{\partial I_2}{\partial O_2} \times \frac{\partial O_2}{\partial O_1}$$

Also

$$O_2 = O_t - O_1$$

and

$$\frac{\partial O_2}{\partial O_1} = \frac{\partial O_t}{\partial O_1} - \frac{\partial O_1}{\partial O_1} = -1$$

Since O_t is independent of O_1. Hence

$$\frac{\partial I_t}{\partial O_1} = \frac{\partial I_1}{\partial O_1} - \frac{\partial I_2}{\partial O_2} = 0$$

or

$$\frac{\partial I_1}{\partial O_1} = \frac{\partial I_2}{\partial O_2} \tag{4}$$

This simply means that the boiler incremental rates are equal. Similarly

$$\frac{\partial I_t}{\partial L_1} = \frac{\partial I_1}{\partial L_1} + \frac{\partial I_2}{\partial L_2} \times \frac{\partial L_2}{\partial L_1}$$

$$= \frac{\partial I_1}{\partial O_1} \times \frac{\partial O_1}{\partial L_1} + \frac{\partial I_2}{\partial O_2} \times \frac{\partial O_2}{\partial L_2} \times \frac{\partial L_2}{\partial L_1}$$

Also

$$\frac{\partial L_2}{\partial L_1} = \frac{\partial (L - L_1)}{\partial L_1} = -1$$

Now, since

$$\frac{\partial I_t}{\partial L_1} = 0 \tag{3}$$

$$\frac{\partial I_1}{\partial O_1} \times \frac{\partial O_1}{\partial L_1} = \frac{\partial I_2}{\partial O_2} \times \frac{\partial O_2}{\partial L_2} \tag{5}$$

But

$$\frac{\partial I_1}{\partial O_1} = \frac{\partial I_2}{\partial O_2} \tag{4}$$

Hence eq 5 reduces to

$$\frac{\partial O_1}{\partial L_1} = \frac{\partial O_2}{\partial L_2} \tag{6}$$

Furthermore $O_1 = T_1 + H$, $O_1 = T_2 - H$

$$\frac{\partial O_1}{\partial L_1} = \frac{\partial T_1}{\partial L_1} + \frac{\partial H}{\partial L_1} \tag{7}$$

and

$$\frac{\partial O_2}{\partial L_2} = \frac{\partial T_2}{\partial L_2} - \frac{\partial H}{\partial L_2} = \frac{\partial T_2}{\partial L_2} - \frac{\partial H}{\partial L_1} \times \frac{\partial L_1}{\partial L_2} = \frac{\partial T_2}{\partial L_2} + \frac{\partial H}{\partial L_1} \tag{8}$$

Substituting eq 7 and eq 8 in eq 6

$$\frac{\partial T_1}{\partial L_1} = \frac{\partial T_2}{\partial L_2} \tag{9}$$

But $\frac{\partial T_1}{\partial L_1}$ and $\frac{\partial T_2}{\partial L_2}$ are the incremental heat rates of turbines number 1 and number 2, respectively. Hence, the requirements for a minimum station input, as shown by eqs 4 and 9, are to operate (*a*) the 2 boilers at the same incremental rates, and (*b*) the 2 turbines at the same incremental rates, respectively. It has already been shown that conditions (*a*) and (*b*) are those which result in minimum boiler room and minimum turbine room inputs, respectively.

Effect of Steam Tie Line of Limited Capacity

When there is a tie line of limited capacity between boilers number 1 and number 2, it may no longer be possible to assume that L_1 and O_1 are independent variables. Assume that the maximum heat that can be transferred through the tie line is H_0. As long as the difference between O_1 and T_1 is less than H_0 the turbines and boilers can be loaded independently. When the transfer through the tie reaches H_0 eqs 4 and 6 no longer hold. There is only one independent variable, say L_1. Equation 1 becomes

$$\frac{dI_1}{dL_1} = 0 \tag{10}$$

$$= \frac{dI_1}{dL_1} + \frac{dI_2}{dL_2} \times \frac{dL_2}{dL_1}$$

$$= \frac{dI_1}{dL_1} - \frac{dI_2}{dL_2}$$

or

$$\frac{dI_1}{dL_1} = \frac{dI_2}{dL_2} \tag{11}$$

and

$$\frac{dI_1}{dO_1} \times \frac{dO_1}{dL_1} = \frac{dI_2}{dO_2} \times \frac{dO_2}{dL_2} \tag{12}$$

But since

$O_1 = T_1 + H_0$

and $O_2 = T_2 - H_0$

and H_0 is a constant it follows that

$$\frac{dO_1}{dL_1} = \frac{dT_1}{dL_1}$$

and

$$\frac{dO_2}{dL_2} = \frac{dT_2}{dL_2}$$

Hence

$$\frac{dI_1}{dO_1} \times \frac{dT_1}{dL_1} = \frac{dI_2}{dO_2} \times \frac{dT_2}{dL_2} \tag{13}$$

This simply means that the over-all incremental heat rate of turbine and boiler number 1 which is the product of their respective incremental rates, shall equal the over-all incremental heat rate of turbine and boiler number 2. It will be noted that if one boiler is operated at a higher pressure than the other, the quantity H could not be negative, but would have to lie between zero and H_0.

The extension of the above analysis for more than 2 boilers or turbines will not be included here. The same conclusion will be reached, namely, that all of the boilers and all of the turbines, respectively, should be operated at equal incremental rates. When this is not possible, the combined boiler and turbine incremental rates of the several groups should be kept equal.

Appendix C

Derivation of Equation for Station Incremental Rate in Terms of Incremental Rates of Boilers, Turbine-Generators and Auxiliaries

In Fig. 30 are shown the performance curves of the station equipment for a given combination of boilers and turbines. Assuming that the boilers and turbines independently are loaded incrementally, and that the station performance represents continuous functions whose incremental rates are nondecreasing, let

I_T = total station input
O_T = total boiler output
T = total turbine input
S = heat input to steam auxiliaries
E = power consumption of the electric auxiliaries
L = gross station load (total generator load)
L_N = net station load

Then

$O_T = T + S$

$L_N = L - E$

$$\frac{dI_T}{dL_N} = \frac{dI_T}{dO_T} \times \frac{d(T+S)}{dL} \times \frac{dL}{d(L-E)}$$

$$= \frac{dI_T}{dO_T} \times \left[\frac{dT}{dL} + \frac{dS}{dL}\right] \times \frac{1}{1 - \frac{dE}{dL}}$$

Let

$$\frac{dI_T}{dO_T} = R_B;\ \frac{dS}{dL} = R_S;\ \frac{dT}{dL} = R_T;\ \frac{dE}{dL} = R_E;\ \frac{dI_T}{dL_N} = R_{ST}$$

Hence

$$R_{ST} = \frac{R_B(R_T + R_S)}{1 - R_E}$$

Where

R_{ST} = station net incremental rate
R_B = boiler incremental rate
R_T = turbine incremental rate
R_S = incremental rate of steam auxiliaries
R_E = incremental rate of electric auxiliaries

Appendix D

Derivation of Equation for Load Division Between Stations Joined by a Transmission Line

When 2 generating stations are joined by a transmission line, correct load division must take into account the losses of the line when under load.

Let the subscripts s and r designate the sending and receiving ends of the transmission line, respectively. Then let

L_s and L_r = loads in the areas served by the respective generating stations (constants)
G_s and G_r = loads generated by the stations
I_s and I_r = inputs to the generating stations corresponding respectively to G_s and G_r
I_t = combined input to both generating stations
T_s and T_r = loads on the transmission line at the sending and receiving ends, respectively

R_s and R_r = station incremental rates corresponding respectively to the loads G_s and G_r

E_t = absolute efficiency of the transmission line

E_{it} = incremental efficiency of the transmission line = $\frac{dT_r}{dT_s}$

I_s, I_r, T_s, and T_r are assumed to be continuous functions with never-decreasing incremental rates. Then

$$I_t = I_s + I_r \qquad G_r = L_r - T_r$$

$$G_s = L_s + T_s \qquad T_r = T_s \times E_t$$

Let G_s be the independent variable. The conditions for minimum combined input to the 2 stations will then be

$$\frac{dI_t}{dG_s} = 0 \text{ or } \frac{dI_s}{dG_s} + \frac{dI_r}{dG_s} = \frac{dI_s}{dG_s} + \frac{dI_r}{dG_r} \times \frac{dG_r}{dG_s} = 0$$

But $\frac{dI_s}{dG_s} = R_s$; $\frac{dI_r}{dG_r} = R_r$ and

$$\frac{dG_r}{dG_s} = \frac{d(L_r - T_r)}{d(L_s + T_s)} = -\frac{dT_r}{dT_s} = -E_{it} \text{ since } L_s \text{ and } L_r \text{ are constants.}$$

Hence $R_s - R_r \times E_{it} = 0$ or $R_s = R_r \times E_{it}$

References

Dividing Load Between Units, G. R. Davison. *Elec. World*, v. 80, 1922, p. 1,885–7.

Boiler Plant Economics, N. E. Funk and F. C. Ralston. *A.S.M.E. Trans.*, v. 45, 1923, p. 607–41.

Methods of Obtaining Economical System Operation H. M. Cook. *Mech. Engg.*, v. 49, 1927, p. 313–20.

Operating Problems in Interconnections B. Houghton. *Elec. World*, v. 89, 1927, p. 1,064–7.

Dividing Load Economically Among Power Plants, A. Wilstam. A.I.E.E. Jl., v. 47, 1928, p. 430–2.

How to Prepare a Schedule for Economic Boiler Loading, H. B. Reynolds. *Power*, v. 70, 1929, p. 553–7 and 593–5.

Method of Loading Boilers for Maximum Fuel Economy, B. M. Thornton. *Engg.* (England), v. 128, 1929, p. 796–7.

Economics of Combined Hydro and Steam Power Systems, N. E. Funk. *Trans.*, Second World Power Conference at Berlin, v. 11, 1930, p. 281–300.

Load Division in Interconnections, E. C. M. Stahl. *Elec. World*, v. 95, 1930, p. 434–8.

Economical Load Allocations, H. Estrada. *Elec. World*, v. 96, 1930, p 685–90.

Loading Schedules—Key to Power Plant Efficiency, C. D. Zimmerman. *Power Notes*, Diamond Power Specialty Corp., v. 17, 1931, p. 1–5.

Comparison of Steam Station Performance, C. C. Baltzly. *Power Plant Engg.*, v. 35, 1931, p. 610–13.

Economic Value of Major System Interconnections, N. E. Funk. *Jl. of Franklin Inst.*, v. 212, 1931, p. 171–208.

System Coördination, S. B. Jackson. *Elec. Times* (England), v. 80, 1931, p. 241–3.

Dividing Load Between Industrial Turbines. *Power*, v. 74, 1931, p. 278–9.

Economic Loading of Generating Stations, E. C. M. Stahl. Elec. Engg., v. 50, 1931, p. 722–7.

Determining Tie Line Losses, H. Estrada and H. A. Dryar. *Elec. World*, v. 98, 1931, p. 745–50.

Calculating Savings From Power Interchange, E. C. Brown. *Elec World* v. 99, 1932, p. 367–71.

Dividing Hydro Load to Obtain Maximum Efficiency, A. W Reid. *Power*, v. 75, 1932, p. 770–2

Program of Load Control Improves Steam Economy, A. P. Hayward and R. Decamp. *Power*, v. 76, 1932, p. 238–41.

Scheduling Units for Maximum Overall Economy, C. C. Baltzly. *Elec. World*, v. 101, 1933, p. 284–6.

Incremental Loading of Generating Stations, M. J Steinberg and T. H. Smith. Elec. Engg., v. 52, 1933, p. 674–7.

Flying 60 Tons of Machinery Into the Peruvian Andes

Photo Courtesy, the *Compressed Air Magazine*

FOUR HUNDRED years ago the already-ancient Ccochasayhuas gold mine was discovered by the Spaniards about 60 miles from Cuzco, the ancient capital of the Incas. Today, this mine is producing gold, and under the influence of modern methods, its production is being increased. Since 1930, much modern equipment has been installed, and a hydroelectric plant has been built. No means of getting the equipment over the mountains and rugged country was possible except that of transportation by air, and accordingly, after some experimental work, the 60 tons of freight was carried by plane from Cuzco to the mine. The plane averaged 4 round trips daily, and the entire consignment of 60 tons was transported in 12 days. Some of the heavier pieces, such as the transformer shown in the illustration, weighed as much as 2,000 lb, and were transported without difficulty. On most of the trips the total load carried was about 3,000 lb. The Ccochasayhuas mine is at an altitude of about 15,000 ft, and the hydroelectric plant, a few miles away, is at an elevation of about 13,000 ft. The ultimate capacity of this plant is 2,250 hp, of which 2 750-hp generating units were installed last year.

Discussions

Of A.I.E.E. Papers—as Recommended for Publication by Technical Committees

ON this and the following pages appear those discussions of A.I.E.E. winter convention papers that were received in complete and acceptable form at Institute headquarters between February 5 and March 1, 1934, and subsequently reviewed by the various technical committees, and recommended for publication. Discussions received up to February 5, and recommended for publication by the various technical committees previous to the time of going to press of the March 1934 issue, were published therein, p. 446–95. These 2 groups will no doubt account for the bulk of the total discussion of the winter convention papers as published in the August, November, and December 1933, and January 1934 issues. However, discussions which may be received in the future will be given the same attention as those received previously, and will be judged on the same basis for possible publication.

For the majority of papers, authors' formal closures are included in the present issue. Wherever closures have been submitted, they appear at the end of the discussion for the paper. They embrace all discussions received and accepted by March 1.

THIS new department inaugurated with the March 1934 issue of ELECTRICAL ENGINEERING marks a further step in the evolution of the unified publication plan adopted by the A.I.E.E. board of directors in August 1933, the purpose of which is to carry to every member of the Institute all technical and related material as promptly as it can be released and published. Another wish is to stimulate and facilitate a broader participation on the part of Institute members everywhere in the study and discussion of current technical papers. Therefore, members anywhere are encouraged to submit written discussion of any A.I.E.E. paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions should be: (1) concise; (2) restricted to the subject of the paper or papers under consideration; (3) typewritten and submitted in triplicate to C. S. Rich, secretary, technical program committee, headquarters of the American Institute of Electrical Engineers, 33 West 39th Street, New York, N. Y.

Switching at the Hudson Avenue Station

Discussion of a paper by C. M. Gilt published in the December 1933 issue, p. 868–75, and presented for oral discussion at the electric power switching discussion of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 456–61.

C. M. Gilt: Some of the discussions of the papers on generating station switching have suggested a little disappointment at the lack of evidence of uniformity or standardization in design. To me it was somewhat surprising that the system conditions in Detroit and Brooklyn are near enough alike so that the switching at Conners Creek and at Hudson Avenue are both built around a very similar one line diagram and use a similar principle of segregation, although equipment and materials differ. Standardization of generating station design would involve most of the evils of the process and few of its benefits. In general, standardization is a compromise design endured to secure the advantages of interchangeability or lower cost made possible by using special automatic machines in fabrication and mass production. Certainly no stretch of the imagination could attribute any great advantages to general interchangeability between generating stations, or anticipate mass production of them. One would lose a great deal in trying to fit a common station design or equipment to a station like Hudson Avenue, built within a city, close to its load center, itself forming a distributing point, to a station like Long Beach No. 3 which is one of several stations feeding onto a double 220-kv bus over 250 miles long, and to one like State Line which delivers bulk power over and ties together a number of high capacity lines of three different voltages. There is real justification for differences in design of stations even when feeding load under what superficially appears to be similar conditions, as such things as past experiences, training of personnel and existing commitments may be enough to throw the balance of advantages and disadvantages one way or another. Such being the case, it is doubtful that the suggestion of Mr. Hollister that generating stations be divorced from "subtransmission" switching substations should apply in all cases, but rather the economics of all the local factors should govern.

The development of switchgear and bus insulation without oil or inflammable fluids is highly commendable and should be encouraged. While the oilless Deion breakers have been developed, they were not available for 27,000-volt operation when the last switchgear was purchased for Hudson Avenue. Had it been available, I am confident that at least a trial installation would have been made.

While Mr. Sanderson points out that there have been some troubles with disconnecting type of contacts, such as are used on elevating or draw out type of breakers, it should be pointed out that this type of installation was made with the primary purpose of avoiding the disastrous experiences which have occurred all too frequently when a disconnecting switch that was carrying load is opened manually. There have been no troubles with the disconnecting contacts of the elevating breakers at Hudson Avenue. I have no doubt that this is in part due to the fact that the elevating mechanisms are integral with each breaker and therefore insure proper alignment and travel of the contacts when closing. This is somewhat more difficult to obtain when a common, portable elevating platform is used for all breakers.

The question of generator voltage is largely one of economics. If, as Mr. Hollister suggests, the tendency toward high voltage switching at, and transmission from generating stations increases, the urge for higher voltage generators is somewhat reduced, as these higher voltages are commonly beyond the possibilities of direct generation. Higher voltage generation was flirted with throughout the development of Hudson Avenue. The specifications for the last two units were written to give the manufacturers a free hand in designing the best combination of generator and autotransformer, or generator alone, to give 27,600 volts. Loss evaluations were given, and higher voltage generation was encouraged to the extent that the high voltage test specified was reduced somewhat relative to the generator voltage, as the generator voltage was increased, so as to reduce the corona difficulties during test. The most economical overall combination proved to be 16,500-volt generators with autotrans-

formers stepping up to 27,600 volts.

The size of generator selected for a station must be determined by over-all economics and an arbitrary upper limit within manufacturing limits can hardly be set. The size of machine is affected by rate of load growth as well as size of load. Some studies I made a few years ago indicate that one can frequently secure lower cost firm capacity by using relatively few large units even though this results in some excess in total kw capacity installed as compared with the use of smaller machines, and furthermore, this excess capacity soon becomes usable capacity in a growing system.

I am entirely in sympathy with Mr. Sporn's objective of having Institute papers that give reasons for doing things rather than simply a description of what has been done. In reviewing my own paper I find that the explanations are not as clearly pointed out, and particularly the reasons back of the principles which are indicated as being controlling factors are not as well given as I intended in writing the paper. However, an author is limited by the very practical consideration of space and the reader's patience, and the further difficulty of being able to distinguish between a rationalization of what has been done and the real motivating factors that governed when the design was prepared.

Switching at Richmond Station

Discussion of a paper by Raymond Bailey and F. R. Ford, published in the January 1934 issue, p. 156–61, and presented for oral discussion at the electric power switching discussion of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 456–61.

F. R. Ford: With regard to Mr. Hall's statement that he questions the wisdom of installing very large generating units, it might be stated that the economic necessity for utilizing available sites to the fullest extent to secure the lowest possible unit costs per kw justified the selection of the 165,000-kw generator which is being installed at Richmond Station, as this is the largest unit which can be installed in the space available in the existing building. The desirability of using the Richmond site to the fullest advantage is also emphasized by the high cost of new sites for steam plants in or adjacent to Philadelphia.

The new unit will operate on a high capacity interconnection aggregating approximately 2,000,000 kw in generating capacity. The size of new units is determined largely by conditions on the interconnection rather than local conditions in the individual systems interconnected. Although the new unit represents a substantial portion of the Philadelphia Electric Co. generating capacity of approximately 950,000 kw, the high rating is justified by the magnitude of the interconnection which is operated, as nearly as practicable, as would be done if all the companies participating were under one management.

Analyses which have been made indicate that no difficulty need be anticipated with regard to division of load between the 2 windings of the 165,000-kw unit or control of their respective power factors. The unit will normally feed one end of the reactor sectionalized 13.8-kv bus with the 2 windings directly in parallel. With regard to control of load on the bus, this will be facilitated to a considerable degree by a certain flexibility in the use of the 43,000-kva frequency converter sets in the adjacent substation and by the 60,000-kva 13.8/69-kv bus tie transformer banks, as one of each of these equipments is connected to each end of the bus.

Mr. Sporn believes the papers should give more discussion of the fundamental principles underlying the designs of the various plants described. Reference to the discussion by Mr. Lovell summarizing the reason for the papers and the essential features of each will indicate that it was intended primarily to bring out the trends of the latest designs and the limitations and operating experience realized under actual working conditions. On this basis, only sufficient description was given of the Richmond Station to form a background against which the detailed operating experience could adequately be given. Accordingly, no attempt was made to discuss the underlying features of the design, such as the double bus arrangement and the "H" connection of the 13.8-kv line pairs as it was assumed that the relative advantages and disadvantages of such arrangements as have been common for many years are well known at the present time. It was believed that the major point of interest with regard to Richmond Station, at least, was the experience which has been realized with the existing design rather than to elaborate on the design principles involved in the station, the construction of which was started ten years ago. No doubt some of the principles which were felt to be important at that time would be viewed somewhat differently today in developing a new generating station.

Switching at the Connors Creek Plant

Discussion of a paper by A. P. Fugill published in the January 1934 issue, p. 162–9, and presented for oral discussion at the electric power switching discussion of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 456–61.

A. P. Fugill: Although most of the discussion on the paper on the Essex Station of the Connors Creek Plant requires no further comment on the part of the author, a few of the points mentioned might be discussed briefly.

Since Essex has been in service only a short time, there seems to be some doubt as to whether its present good operating record will continue over a period of years. Time only will answer that question but, as mentioned in the paper, there are four other stations on the Detroit Edison system using the same general arrangement and practically identical equipment, particularly the insulated metal housings and bus fault protection. The oldest of these has been in service for $5^1/_2$ years and the most recent for 3 years, and to date no major trouble has occurred.

In speaking of the possible future trend toward unit operation of generator and step-up transformer with transmission to load centers at some higher voltage, F. H. Hollister mentioned Trenton Channel as one of the earlier examples of this scheme but stated that this station uses low tension switching. Actually the low tension switching consists merely of a series breaker and disconnects between each generator and transformer. They were installed principally to provide trip-free operation in case of closure on a fault and to facilitate synchronizing.

The use of higher voltage generators was mentioned in several discussions. This question was considered very carefully in connection with the rehabilitation of Connors Creek and the design of Essex. In this particular instance, since some reactance in series with the generator was needed to meet fault current limitation requirements, the inherent reactance of the auto-transformer eliminated the use of a series reactor. Considering this factor and the present greater cost of higher voltage generators, it was found that the most economical combination was a 14.4-kv generator with an autotransformer to step up to 24 kv, compared to the 12 kv generator used at other plants on the system.

H. Y. Hall points out that ground connections to insulated housings must be carefully made to prevent hazard to operators. Most assuredly, the voltage between the housing and the point where the operator may be standing must be kept to a safe value during fault conditions. To accomplish this most effectively, the impedance of the connection from the housing to the ground bus must be low and the building steel should be thoroughly connected to the same ground bus. Incidentally the reactance of the ground connection is even more important than the resistance. In designing Essex, the desired result was accomplished by using a grid for the ground bus instead of a single bar, tying the building steel to the grid at frequent intervals, and then making the connection between the metal housing and the ground grid as short as possible. Of course, all the ground bus in the station was solidly connected to a low impedance distributed ground mass outside the building.

Mr. Hall is correct in stating that both system interconnections to Essex are made to the equalizer bus. If this bus has an emergency shutdown, the system ties are lost, but the system operation is such that the station can carry its local load until relief is provided. In addition, readily removable links are provided at 2 points in the bus so that any third of the bus can be cut out in a short time and the rest of the bus put back into service. No bus trouble should cause a loss of both system ties for more than about half an hour.

J. K. Ostrander compares the protective scheme for bus faults such as used at Essex with bus differential protection. The Detroit Edison uses both schemes, the former

on indoor stations where positive housing insulation is easily obtained, and the latter on outdoor stations where the insulation of the equipment structures present a rather difficult problem. There are most certainly applications for both types of bus fault protection, but, in indoor stations at least, our experience indicates that there are fewer complications in a new station in applying this insulated metal housing scheme than the bus differential method. It is doubtful if any differential scheme can be devised which is as simple, reliable and positive as the type of bus fault protection used at Essex.

C. H. Sanderson suggests that the armored control cable should prove cheaper in cost and maintenance or extension than the conventional rigid conduit installation. On the latter points no information is available but the actual cost of the armored control cable installation at Essex was 30 per cent less than comparable rigid conduit installations at other stations on the system.

The Pitt-Westinghouse Graduate Program

Discussion of a paper by H. E. Dyche and R. E. Hellmund published in the January 1934 issue, p. 103–8, and presented for oral discussion at the education session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 44–9.

C. L. Dawes: In his summary of the program of the Engineers' Council for Professional Development, Dean Barker states that one phase of the program is to stimulate self-education and initiative among the young engineering graduates. Also in the paper by Professor Dyche and R. E. Hellmund, it is stated that "no matter how carefully the curriculum may be planned and how thoroughly the college work carried out, it will have to be admitted that it is at best very difficult to give to the student in a purely university atmosphere that training in developing initiative, resourcefulness, action, and responsibility which is required in actual practice."

Both statements emphasize the lack of initiative in our engineering graduates. Also, of the many criticisms of engineering graduates which I hear from time to time, lack of initiative is the most frequent, and, from personal experience, I feel that there is some justification for it.

I believe that this lack of initiative is due in large measure to the fact that the methods of teaching employed as a rule in our engineering schools, and through our general educational system as well, actually suppress and stifle initiative and resourcefulness. In the lower schools the program of study, the hours devoted to different subjects, even the methods of holding a pen or pencil, are all standardized. In the preparatory schools this same procedure is followed. In the preparation for entrance into higher institutions of learning it is required that definite numbers of hours be devoted to English, mathematics, science, language, history, etc. The student is not given the reasons why the prescribed system of studies best adapts him to the higher education of the college. There probably are none.

In the engineering school the same general process is continued. Curricula have been carefully developed and proportioned. Presumably the proportions of mathematics, sciences, languages, economics, and engineering which will best train all individuals to be good engineers have been determined. The student follows the prescribed curriculum without questioning its purpose, and he knows that if he is at all successful in passing the individual courses he will be given a degree. This may explain in part the fact stated by Messrs. Dyche and Hellmund that the most carefully planned curriculum fails to develop initiative, resourcefulness, and responsibility.

The same tendency to discourage initiative exists in the courses of instruction; the student is given definite assignments to be carried out at definite times; he is assigned definite laboratory experiments to be performed at definite times and the procedure in performing the experiment is usually carefully prescribed.

It is little wonder that after graduation he fails to continue his education, and fails to develop initiative. There is no one to tell him what to study, where to study, when to study, and to assign him experimental work with detailed directions for performing it.

At the graduate school of engineering at Harvard we have attempted to adjust our educational methods so that resourcefulness and initiative are at least encouraged. There is no fixed curriculum. The responsibility for arranging his curriculum is placed on the student. It is required merely that the program be substantial and that it show a definite purpose.

In general, the class-room work consists of informal discussions rather than of formal lectures. Courses terminate in a 3-weeks' reading period during which there is no class-room work, and the student completes the course entirely on his own responsibility. The laboratory work consists of a few projects more or less optional, rather than definite laboratory experiments to be performed at a definite time and in a prescribed manner.

These methods of placing responsibility directly on the student and minimizing supervision may not entirely solve the problem, but certainly they do encourage initiative and resourcefulness. The results confirm our belief that this is true.

The statement in the paper, "There is a distinct danger in extending the engineering college course beyond the usual 4-year program, except for those who expect to make research or teaching their life work," I believe is contrary to the facts. Innumerable instances could be cited of outstanding engineers whose technical education in the engineering college has extended into 1 year and more beyond the usual 4-year course. In fact, at the present time a strong sentiment exists among engineering teachers and in industry as well that the 4-year course in an engineering school is entirely inadequate preparation for an engineering career. (An excellent discussion of this subject is given in a paper "The Five-Year Engineering Course," by W. S. Rodman, presented before the engineering section of the convention of the Association of Land-Grant Colleges and Universities in Chicago, Nov. 13, 1933.) It is my opinion that extension of the 4-year engineering course one or more years is not a danger, but will soon become a necessity in the preparation of engineering students to meet the complex conditions of modern civilization.

The coöperative Westinghouse program described in the paper does develop without doubt a high-grade graduate school, particularly when the requirements for the degree are maintained on the high plane stated in the paper. Some of the graduates whose names appear under "completed theses" bear witness to this fact. However, it must be remembered that relatively few engineering schools are so situated that coöperation with a large industry is possible. It is true, nevertheless, that many such schools can and do maintain a high type of graduate work. Nor are facilities for an advanced type of research entirely lacking. It is significant that many large industries and engineering associations send their research problems to the research laboratories of the engineering schools for development and solution. I know from personal experience that the facilities for certain types of research are greater in some of our engineering schools than in some industrial research laboratories. On numerous occasions the Harvard Engineering School has loaned equipment to such industrial laboratories. It is true that graduate work, particularly of the most advanced type, should be limited to the institutions having the greatest resources. The S.P.E.E. board of investigation and coördination also came to this conclusion. The following statement is found in its report (v. 1, 1928–29, p. 117): "It is desirable that resident graduate work should be undertaken only by engineering colleges with notable teachers and exceptional facilities; ..."

The graduate program described in the paper by Messrs. Dyche and Hellmund is well adapted to conditions in which a large industry is located in close proximity to an engineering school and offers stimulation and excellent facilities to young engineers employed in the industry. I believe, however, that schools not so located will continue to develop graduate students with initiative and resourcefulness, particularly if they employ methods of teaching which place a large measure of responsibility on the individual student.

W. M. Young: While teaching at the Texas Technological College at Lubbock, Texas, the problem of supplementing a man's collegiate education, after he had assumed a position in industry and was connected with a company at a relatively large distance from the college, was frequently brought to mind and the subject was given only general consideration. At that time, no advanced degrees were offered in engineering, and the whole attention of the teaching staff was occupied in establishing a sound engineering school. However, it was then realized that ultimately an educational institution must offer means for professional advancement to men distantly located.

The papers presented this morning and the discussion, in the main, have centered about the problem of supplementing a man's education when the industry and college

were located either in the same town or relatively close together. The solution of this problem as presented by the Westinghouse-Pitt agreement and the M.I.T.-General Electric arrangement has been very interesting.

There remains, however, a much larger problem for consideration. At the present time, we, at the Taylor Instrument Companies, are interested in securing men to fill certain vacancies. We have generally chosen the engineer in preference to the physicist, largely because his fund of information was general and his mode of thinking analytical. The men must then be given additional training in the different departments of the plant to fit them for service in our particular fields of endeavor—temperature and pressure indication and control. At various times, members of different departments have expressed a desire to improve their store of knowledge and have done so through the medium of individual reading, but no means are readily available whereby an employee may obtain an advanced degree through the completion of the necessary courses and thesis.

It frequently happens that small industrial organizations have not only the facilities for conducting research problems but also have men capable of directing these problems. In such instances, it is particularly desirable that members of such organizations have means whereby they can secure advanced degrees through the cooperation of a university or college granting such degrees. When these smaller organizations are located at a relatively large distance from a suitable educational institution, the problem assumes real proportions and up to the present time no satisfactory arrangements are known.

It is suggested, therefore, that the education committee of the Institute give very serious consideration to the problem of offering professional advancement and advanced degrees to men in industry, and to the organization of means whereby this can be accomplished when the industrial organization is small and is located at a relatively large distance from the educational institution.

D. C. Jackson, Jr.: The trend among the majority of industries and utilities because of present business conditions seems to be to continue with a week reduced in length to about 5 days. This is a challenge to the engineering schools to make available to the completest degree for their alumni and for the alumni of sister institutions their facilities for graduate study. By adjustment of schedules, it is possible to place on Fridays and Saturdays those purely graduate courses which are of interest to the engineering alumni in the vicinity. In the case of engineering schools located in cities this is not so necessary, but where an engineering school is situated as many state universities are, in a relatively small city some distance from any large industrial center, such graduate instruction can be carried on only when the practicing engineers interested can have a couple of days in succession free from their regular employment.

The University of Pittsburgh and the Westinghouse Electric and Manufacturing Company have accomplished very worth while and laudable results in their program. Other engineering schools located in industrial centers have also been successful in arranging graduate work for practicing engineers in their vicinity. However, it seems desirable to encourage not merely the engineering schools, but also the abler of our more recent engineering alumni to undertake some such coöperative scheme, especially in those parts of the country where the industrial centers may be at some little distance from the nearest engineering school.

R. E. Hellmund: In closing the discussion of our paper, I should like to call attention to the very general agreement among those who discussed the paper on the broad fundamentals expressed in it. It should also be noted that there is a rather surprising accord between the principles set forth in Dean Barker's excellent report on the activities of the Engineers' Council for Professional Development, which deals to a large extent with postgraduate educational matters, and the fundamental ideas covered in our paper.

As a matter of course, the manner in which these ideas are carried out will have to be governed by local conditions and existing opportunities. In the discussion we have heard of the postgraduate plan carried on in coöperation with the Lynn works of the General Electric Company. This plan apparently is somewhat similar to the University of Pittsburgh-Westinghouse program because the existing conditions are somewhat the same. As pointed out in some of the discussions, however, conditions in the South and West are not so favorable as in the large industrial centers. It is very important that attempts be made to create similar opportunities for graduate students in these sections in keeping with the conditions found there and, in fact, in any cases where the industries are located in places remote from educational institutions. But in the meantime every advantage possible should be taken of the more favorable conditions in the East. Incidentally, the University of Pittsburgh-Westinghouse plan is carried on at the Sharon plant, at a distance of 80 miles from the University, by weekly trips of faculty members to Sharon.

I was very much interested in the efforts made in the St. Louis territory to carry on postgraduate programs for the benefit of the engineers of the local industries. It is to be regretted that such worthy attempts failed largely on account of the financial sacrifice necessary on the part of the students. This is a matter which should be given very careful consideration, because even with the relatively low cost of the University of Pittsburgh-Westinghouse program, quite a number of the students failed to complete their work because of the financial burden it entailed. It must be realized that graduates at that age frequently are in the early period of married life and consequently have many demands upon their very limited financial resources. It is therefore most essential that whatever programs are arranged take this into account.

Appendix II may be somewhat misleading to readers in that it seems to indicate a preponderance of engineering subjects in the postgraduate program. Attention might therefore again be called to the fact that the appendix lists only the courses covered by the Westinghouse lecturers, this being done largely for the purpose of indicating the type of material covered by them. As stated in the paper, at least 10 credits must be obtained through courses given by the regular staff of the University, but it would, of course, be impossible to cover in the paper the very extensive list of subjects available for this purpose. The courses given by the University faculty relate as a rule to mathematics, physics, psychology, economics, etc., and these courses together with those given by the Westinghouse lecturers represent a very well balanced postgraduate program for engineers. As stated in the discussion, it is rather difficult to get a clear picture from Appendix I of the actual material covered by the theses. However, with the subjects available in the appendix, it is possible for anybody interested to obtain abstracts of the theses from the University.

Attention may be called to another point, namely, what appears to be an inconsistency between the statement made in the paper to the effect that a reasonably large percentage of graduate students should be able to obtain additional degrees and the fact that the engineers who have taken the Pitt-Westinghouse course represent a highly selective group and that only a small percentage even of those have obtained degrees. In this connection it will have to be admitted that so far the University has proceeded rather cautiously in conferring degrees. Nevertheless, I personally feel that the various postgraduate coöperative programs should eventually be so arranged that about 20 to 30 per cent of the engineering profession can obtain additional degrees.

One criticism offered to the ideas expressed in the paper is that with regard to the statement that there is danger in spending more than 4 consecutive years in college. From my experience with a great many graduate students, I am firmly convinced that this statement in the paper is correct, but this does not mean that courses extending over a period of more than 4 years are necessarily wrong. The success of these longer courses depends entirely upon the extent to which they recognize the fundamentals of engineering education and carry on the work accordingly. When I say recognize the "fundamentals," I do not mean the usual fundamental knowledge to be acquired during the college course, but rather the recognition of the basic fact that the engineering profession is a profession of creating and that it is therefore essential that any engineering education to be effective must develop in the student not only the desire and ability to create, but also the habit of doing so. This fundamental should be given recognition beginning with the freshman year. Although, as often pointed out by the industries, they do not expect from the colleges engineers fully trained in designing or engineering any particular piece of apparatus, they do expect graduates to display evidence that their ability for creative work of some kind has been cultivated and stimulated. I do not think that the fact that college curriculums are already overcrowded is any excuse for neglecting this phase of engineering education. As a matter of fact, some of the discussions indicate that some schools are making definite

efforts along this line, which is very encouraging.

In this connection, actual experience with the Pitt-Westinghouse program should prove very illuminating because it bears out the above statements. Before the institution of the Pitt-Westinghouse program, the Westinghouse company carried on extensive educational courses. As a rule, many of the better students did not appear to be very eager to take up this work as they were anxious to try out in actual practice the knowledge acquired at school, a spirit which is highly commendable. I therefore felt that when the Pitt-Westinghouse program was started, requiring about 10 additional credits to be acquired at the University in such subjects as mathematics, physics, etc., the students' reaction would not be very favorable. However, it developed that in view of the fact that the habit of studying had been well fixed in them, they peacefully knuckled down to this additional study; but when it came to preparing a thesis, which of course required originality and initiative, the large majority of them exhibited a certain helplessness and this work seemed to be the main stumbling block in the course for the master's degree. To me, this was simply an indication that their college work had failed to develop them sufficiently along these lines.

Pantograph Trolleys I—Design Features

Discussion of a paper by W. Schaake published in the January 1934 issue, p. 182–9, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 451.

W. Schaake: In Harry Brown's discussion his reference to the cambered shoe used by New Haven gives good reasons for the use of this type of shoe. The objection which I have to this form of shoe is due to the fact that the point of contact with the contact wire is over 2 in. above the fulcrum point of the shoe. It is always desirable to have this contact point as near as possible to the fulcrum in order that the frictional contact will not cause rotation of the shoe. The moment of the frictional contact about the fulcrum tends to produce increased wear at the edge of the shoe, whereas it is desirable to have the wear uniformly distributed over the surface of the shoe.

The effect of this camber is also to give additional distance of the end horn below the plane of the contact wire and this might be considered equivalent of a longer end horn and in this respect is an advantage.

As regards the use of side guards I find that if a contact wire should be so far from the center of the track that this displacement, together with the side sway of the pantograph, would cause the entire shoe to be clear of the contact wire, there will not be anything to prevent the pantograph from ascending to its maximum height. There would then be a decided lateral pressure as the car or locomotive proceeds due to the displacement being only local. This pressure of the contact wire against the side guards would be sufficient to tear loose the catenary hangers or wreck the entire pantograph. This, however, would be a very unusual occurrence and could result only due to unusual conditions.

The purpose of the side guards is mainly to prevent hooking of the contact wire when approaching a point where the main line and siding contact wires meet or cross. As the pantograph approaches this point there is a certain location where the distance between the wires is just sufficient to permit one wire to be caught under the end horn. Due to this the contact wire must have sufficient slack so that it will raise above the normal height, due to the pantograph pressure, far enough so that the end horn will pass over the adjacent wire. Either the end horn is broken, the pantograph is wrecked, or the overhead construction is damaged. With a tension in the system well maintained, there is probably not much use for side guards. On a main line operating at high speeds it is essential that the tension be maintained. It is also essential in a line of this character to have the movable pantograph parts as light as possible. Side guards necessarily add to the weight of the movable parts. There are, however, installations where maximum speeds are rather low and where the pantograph operating range is limited so that frequent tension adjustments are not essential provided there is no danger of catching the end horns. In this case side guards become very useful as no matter how slack a siding wire may be the side guards possibly prevent hooking over of the end horns.

The same result is obtained with pantographs of the so-called hornless type. In these the upper frame is so shaped that the side member becomes a guard and only a very short horn is required. The construction is not so good as the frame becomes more complicated. The guard is apt to be damaged and where these are attached to the standard upper frame, damaged guards may be easily removed but when the guard becomes a part of the upper frame the entire pantograph may be put out of commission due to a guard failure.

Investigation of Rail Impedances

Discussion of a paper by Howard M. Trueblood and George Weschack published in the December 1933 issue, p. 898–907, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 450–1.

H. M. Trueblood: Mr. Harry Brown suggests that the impedances of circuits involving 2 rails would be of interest. Although there was not space in the paper to take up such matters, the impedances of circuits made up of rails or tracks (including parallel paths in the earth), trolleys, feeders, etc., can be computed by using the data in the paper to obtain ground-return self-impedances, along with the ground-return mutual impedances of the various conductors involved, following the methods given, for example, in the paper by Carson (reference 2 in the paper). Such methods have, in fact, been used for a number of years in work on inductive coördination with electrified railways. The impedance of a track circuit to signal current can be calculated similarly, although here it would probably not be necessary to take account of the earth.

These comments by Mr. Brown and also the closing remark in Messrs. Maurer and Sunde's discussion raise the question whether the impedance characteristics of a rail are appreciably modified by the proximity of another current-carrying rail at gauge distance, or perhaps at usual third-rail separations. In the tests, in connecting the rail to the secondaries of the power supply transformers, what was done, in effect, was to impress upon each longitudinal filament of the rail sample an a-c voltage which was the same, at least between potential measuring taps, for all such filaments. If by means of current in a parallel conductor an additional voltage, V', likewise the same for all filaments, were also impressed, and the effects would be (1) to change the components of current density at each point of the rail cross-section—and hence the components of total rail current—by the same percentage of their previously existing values, and (2) to change the voltage drop at every point of the rail periphery and in each exploring wire by this same percentage. The effect of adding the voltage V' upon the surface impedances would therefore be nil, and the shape of the magnetic field in the vicinity of the rail would not be changed. Hence, effects of currents in parallel conductors upon the internal impedance and upon the position and size of the circle for calculating external reactance can only arise from a lack of uniformity over the rail cross-section of the longitudinal electric field due to the parallel current. With one ampere in a parallel conductor at standard gauge distance, the maximum variation in this field over the cross-section of a 130-lb rail is from 2 to 4 per cent of the internal reactance (25 cycles). In the case of a third rail at a separation of two ft this percentage is from 5 to 9. It seems obvious from these figures that the effects of the proximity of current in adjacent conductors at ordinary separations can be neglected in engineering work. As a matter of fact, it was found in the tests that results for the surface impedances were the same when the upper side of the current supply rectangle (Fig. 1 of the paper) was 9 ft from the rail and when it was 5 ft from the rail. Also, in the measurements by Benda referred to in the paper, the corresponding conductor was only a little over 3 ft from the rail, while his results for the shape of the field, etc., were much the same as ours.

Concerning the effect of earth-currents upon the test results, measurements were made on the same rail sample, first in the ordinary position and then inverted (flange upward). The results for the surface impedances were the same for these 2 positions within the precision of the measurements, showing the effect in question to be negligible. It was also found that placing an isolated rail at gauge distance had no effect on surface impedances.

Stabilized Feed-Back Amplifiers

Discussion of a paper by H. S. Black published in the January 1934 issue, p. 114–20, and presented for oral discussion at the communication session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 461–2.

F. A. Cowan: H. S. Black's paper describes certain principles by which it has been possible to achieve amplification of extraordinary constancy and freedom from nonlinearity. One application of a similar principle to reduce rather than amplify the magnitude of electric currents may therefore be of some interest.

The long lines department of the American Telephone and Telegraph Company employs a large number of telephone repeaters in connection with the operation of long distance telephone and telegraph service. The vacuum tubes in these repeaters are almost universally supplied with filament power from 24-volt storage batteries. It is the usual practice to operate these batteries on a so-called full float basis. When this method of operation is used it is customary to insert electrical filters between the batteries and the filament circuits of the telephone repeaters so that ripples in the battery voltages, caused by the charging machines, may not cause noise to be introduced into the telephone circuits. These filters have been found to be very effective but at certain offices employing batteries with a very large capacity, it has been found that the currents flowing between the charging machine and the batteries set up electromagnetic fields, the fluctuating components of which act upon the transformers in the telephone repeaters and introduce noise. This noise is, of course, greater for those repeaters so located as to be nearest the closed loop formed by the charging and battery bus bars. The relocation of the filter so that it will be between the charging generator and the battery would not be practicable because the battery is used for other purposes which in themselves would introduce some noise and a filter in the present location would still be required. Various methods have been considered for reducing the noise from this source, some of which are:

1. Place electromagnetic shielding around the transformers and repeaters.
2. So rearrange the battery bus bars as to reduce the effective size of the closed loop in which the noise currents circulate.
3. Introduce a filter in the charging circuit leads.
4. Provide some low impedance shunt for the noise currents near the charging generators.

As may be noted in Mr. Black's paper the feedback circuits of the type described have the effect of reducing noise by the factor $\frac{1}{1-\mu\beta}$. If both the input and output of a suitable amplifier are connected across a circuit the voltages which existed in the circuit prior to connecting the amplifier will be reduced by about the amount of the foregoing factor. This has been tried out in the field by connecting a single special amplifier across the charging generator of a power plant. It was found possible in this case to make reductions in the noise produced by the ripples in the battery charging current corresponding to a power ratio of about 100 to 1. The limiting factor appears to be the power carrying capacity of the amplifier and for power plants of considerable size relatively powerful tubes are required in the output stage or several tubes in parallel may be needed. However, under certain conditions, the cost of this arrangement may prove to be less than the other plans considered.

Although this method of reducing noise was suggested by consideration of feedback such as was discussed by Mr. Black, a review of certain technical literature has shown that Mr. Crisson in his paper "Negative Impedances and the Twin 21-Type Repeater" (see *The Bell System Tech. Jl.*, July, 1931) considered, the action of circuits of the type employed in the foregoing application. A study of Mr. Crisson's paper would be helpful to one desiring a more complete understanding of the principles involved.

Cast Iron and Its Production

Discussion of a paper by M. V. Healey published in the January 1934 issue, p. 120–3, and presented for oral discussion at the electric furnace session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 452–3, 455.

W. E. Moore: Mr. Healey has well set forth the outstanding advantages of electric iron in comparison with cupola iron and has been quite fair to the argument throughout.

The concise explanations which he makes as to the physical reasons for more homogeneous and generally better quality of electric over cupola iron have been given with an unusual degree of clearness.

He is quite correct that for ordinary mechanical purposes electric furnace iron is far superior in physical properties and in uniformity, and that no alloying is ordinarily required.

Electric iron by superheating in a direct polyphase arc furnace develops superior physical properties merely by the complete solution of the carbon or graphite nuclei in the iron held molten at high temperature in a way that is utterly impossible in the cupola, and furthermore is refined by proper slagging action.

While the so-called air furnace or open hearth furnace is capable of developing a higher temperature in the iron than the cupola, the temperature is still not sufficiently high to dissolve entirely all of the carbon-graphite particles necessary to produce the improvement so marked in physical properties characteristic of electric iron. Nevertheless the so-called air furnace iron has long been known as a superior quality iron and in former times was known as "gun iron" because cupola iron was too unreliable and too irregular for casting cannon.

The ability of the electric furnace to make cast iron of low carbon content is also of marked advantage as compared to the cupola, particularly when molding thick castings, such as rolls and heavy machinery, where there is with cupola iron a marked difference between the grain structure of the iron at the surface and on the interior of the casting.

Electric furnace iron containing a high percentage of steel scrap for such wearing parts as tube mill liners and grinding balls used in the ore milling industry are now produced not only cheaper than by the cupola process, but with a life 200 to 300 per cent greater.

The electric furnace used in Mr. Healey's experiments shows a production in a 3 ton furnace of 5 tons in 3 hr or $1^1/_2$ tons per hour, which indicates that it is of an older slow-type furnace. With the modern arc furnace of the same rating 3 tons or more of cast iron per hour can readily be produced when "cold melting" and it may also be operated to advantage on a continuous melting cycle where so desired.

Since electric furnaces can be run all day and produce a steady flow of hot metal ready for tapping, it is thus quite practicable to operate the molding floor continuously, which requires far less flask equipment and floor area than that required with the cupola process where the heat is concentrated into 2 or 3 hours of melting in the afternoon.

The greater strength and toughness of electric furnace iron should be a sufficient advantage to cause users of machinery to specify, where obtainable, that the equipment they purchase will be made from electric iron.

Electric furnaces may be used for duplexing to splendid advantage, the metal being melted in a cupola, brought in a ladle (or spouted) to the electric furnace, and the electric furnace operated on a "continuous cycle" delivering small ladles of superheated metal at frequent intervals, and at corresponding intervals receiving molten but not superheated metal from the cupola. The metal thus refined in the electric furnace has the same superior properties of iron that has been cold melted in the electric furnace and the furnace, of course, has greatly increased capacity. In a case where a half ton per hour modern type direct arc furnace is operated in this manner, a molten bath of $1^1/_2$ tons is maintained in the furnace, a flow of over 3 tons per hour of metal is refined in the electric furnace. This metal is used for continuous pouring in machine conveyor molds with highly economical results. In this case the power consumption is averaging less than 50 kwhr per ton; the electrode consumption 2 lb of graphite per ton, and the refractory cost is $0.16 per ton.

Another larger installation of electric malleable iron duplexing furnaces averages 20 tons per furnace per hour; 2.5 lb of graphite electrodes per ton, and under 50 kwhr per ton power consumption, and under $0.05 per ton refractory maintenance.

In one plant some 4,000 electric-iron automobile brake drums are cast per day, along with 1,000 camshafts, with most satisfactory results.

In another plant 2,000 automobile crankshafts are now cast per day of electric-iron, giving a highly superior product, having an elastic modulus of more than 30,000,000 lb.

The electric furnace in the cast iron foundry has produced a revolutionary prod-

uct, a new engineering material, opening up new economies and with possibilities previously unknown. Electric iron will have a widespread and growing use and add new life to the iron foundry upon which the steel foundry and welding shops have made severe inroads.

Rocking Indirect Arc Electric Furnaces

Discussion of a paper by E. L. Crosby published in the January 1934 issue, p. 132–8, and presented for oral discussion at the electric furnace session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 452–3, 454–5.

W. E. Moore: The development of the Electro-Metallurgical furnaces has been quite remarkable since the beginning of the Twentieth Century, although hampered initially by high costs and lack of suitable power supply. With the ample Central Station Power Supply and reasonable rates now obtainable the further advance of the Electro-Metallurgical furnace will be rapid indeed, particularly in connection with the rapid development of stainless steels, alloy steels, and electric cast iron.

The indirect arc or Rocking type electric furnace was one of the early Electro-Metallurgical developments, as was evidenced by the Stassano furnace and others. The use of an indirect arc struck between horizontal or approximately horizontal electrodes is also old, but those furnaces have generally had more or less delayed development due to the greater surface of electrodes exposed to oxidation and to their horizontal position which has caused increased breakage so that the horizontal electrode furnace has always had against it a high electrode cost.

With a horizontal arc the flow of heated gases between electrodes is deflected upward by air currents; in fact, it was due to this effect that Sir Humphry Davy named it the electric arc. When the arc is diverted by heated air currents, the arc stream being no longer coaxial with the electrodes, is subjected to magnetic repulsion or "blowing" which further accentuates the divergence in an upward direction. This upward divergence is unfavorable to refractory roof life.

In distinction the direct arc type of furnace with single vertical electrode and current return through the charge and bottom was the first form of commercial Electro-Metallurgical furnace, as with that design instead of exposing two electrodes, as with the horizontal indirect arc furnace, there was only one electrode exposed to oxidation. A number of these furnaces are still in commercial use, but owing to the demand for larger furnaces and after the power supply became universally three phase, the trend became notably toward larger electric furnaces of the vertical electrode polyphase direct arc type.

The improved screw jointed continuous electrode was a great improvement over the old single piece electrode in which a large portion or "butt" had to be discarded after use. The screw jointed electrode made the trend toward the vertical electrode furnace still more accentuated.

As the furnaces grew larger in size the disadvantages and complications of carrying the current direct through the furnace metal structure either vertically or horizontally became more apparent, as the iron structure of the furnace shell introduced large reactive drop and iron losses with a heavy secondary current flow directly through the surrounding iron work, consisting of shells, heads, etc. With the polyphase electric furnace the currents all being carried in through the nonmagnetic refractory roof with the electrodes closely paralleled and the cables spaced near together, the power factor conditions were much improved.

With the vertical electrode furnace it also became practicable to have a convenient operating door or doors through which the charge might be placed in the furnace, or the slag or heat worked in the desired manner. The wearing areas of banks or refractory surfaces wetted by the slag were also at a minimum, and the refractory lining most remote from the heat of the arcs so that the wear and maintenance on the refractories was at a minimum.

With the vertical electrode furnace the electrodes arc directly to the metal—the heavy current passes through the metal of the bath when superheating, using the slag in part as a resistor medium, the arc craters closely facing and radiating directly toward the bath. This effect is to superheat the metal in the center of the bath causing a thermo-syphon-circulation upward through the center of the bath, then radially outward toward the sidewalls, down along the bottom, and back up the center—a quiet non-turbulent circulation that exposes all parts of the metal to the purifying effects of the slags, to the superheating effects of the arcs, and allows all non-metallic inclusions ample opportunity to coalesce with the slag blanket covering the metal.

With the direct arc furnace it is practicable to run a reducing or an oxidizing atmosphere merely by the door adjustment on the furnace, the arcs may be of any advantageous length, as for instance made longer in the manufacture of low carbon alloys. Through the ample workroom sidedoor it is easy to take samples to check the adjustment of the mixture as to carbon, sulphur, phosphorus, or other alloys in a manner not possible in the small door drum type furnace. If the sulphur be too high that can be reduced by a lime slag and the same applies to the phosphorus content; if the carbon be too high that can be adjusted as by the addition of ore. One does not therefore have to melt carefully weighed and cleaned scrap of known and uniform composition like in crucible melting, and depend upon a watthour meter to tell when the temperature is right as with the closed drum type furnace.

The vertical electrode furnace is ideal for refractory maintenance, since the sidewalls being vertical do not tend to cave in and the bottom may be of either shaped refractories or cheaply rammed in granular material, and may be readily fettled or repaired by shovelling in additional granulated material between heats when desired. The roof being of arched spherical form gives freedom for expansion and supports itself in an ideal manner. As might be expected, the refractory maintenance on the vertical electrode direct arc furnace is very low. In the rapid melting type acid furnace refractory maintenance rarely goes above $0.25 per ton on batch cold melt practice and as low as $0.15 or better per ton, for material and labor. Likewise the electrodes being held in the most favorable position show minimum breakages and, being of short length, show minimum consumption by oxidation, so that it is rarely the case that the electrode consumption on the vertical electrode direct arc rapid type furnace exceeds one-half to two-thirds that required by the larger size horizontal electrode single phase indirect arc furnace.

The direct arc electric furnace is particularly well adapted for cast iron melting and it is quite easy to get any degree of superheat to completely dissolve, without difficulty, the graphite nuclei. The graphite having once all been put into solution, which is not possible in the cupola, does not contain focal points, as in cupola iron, around which the segregating graphite may grow and produce flaky-weak structures or cleavage planes in the metal.

The refining and metal manipulation under a slag is one of the most valuable features of electric furnace work for without a slag blanket there is no appreciable refining.

With an all-scrap charge readily machinable castings may be produced without difficulty in a direct arc electrical furnace using an all-scrap charge—a thing not practicable with cupola melting. In like manner the electric furnace is just as adaptable for white or chilled iron making, such as chilled iron rolls, wearing plates for crushers, ore mill grinding balls for tube mills, or for making white iron castings to be malleablized which must be practically free from graphite segregation in order to make proper strength malleables.

With the arc electric furnace, since the graphite is completely dissolved in the superheated metal and there being no focal points or nuclei around which the graphite may segregate when freezing, a metal higher in silicon may be cast without graphite segregation, which means a metal more readily and more rapidly annealed. In this manner small malleables have been made in the direct arc electric furnace and annealed within a period of four hours.

High strength gray iron is a growing product, made in the arc furnace, and with proper refining even poor grade scrap may be put into the highest grades of high strength electric iron, either alloyed or plain low carbon mixtures.

The rapid type direct arc furnaces are today used in large numbers for high quality gray iron. While electric furnace gray iron has been made commercially for more than 15 years, the demand for it has largely developed within the last 8 years.

There is today in use in this country approximately 125,000 kw capacity of electric melting furnaces on various irons. In this field approximately 80% of the capacity is of the polyphase direct arc melting and refining type. The total electric melting furnace load in the U.S. today amounts to approximately 600,000 kw capacity. This load may be expected to total over 1,000,000 kw within the next ten years.

High Frequency Induction Furnaces

Discussion of a paper by C. A. Adams, J. C. Hodge, and M. H. MacKusick, published in the January 1934 issue, p. 194–205, and presented for oral discussion at the electric furnace session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 452–3; 455–6.

H. Poritsky: This paper gives a good review of furnace design. We should like to present in greater detail the theory of inductive heating. First we shall review the circuit equations of a transformer. These apply essentially to the iron core low frequency furnace.

The circuit equations of the transformer, in complex vector notation, are:

$$\left.\begin{aligned} Z_1 I_1 + Z_{12} I_2 &= E \\ Z_{12} I_1 + Z_2 I_2 &= 0 \end{aligned}\right\} \tag{1}$$

where

$$\left.\begin{aligned} Z_1 &= R_1 + j\,(L_{1\sigma}\omega) \\ Z_{12} &= jM\omega \\ Z_2 &= R_2 + jL_{2\sigma\omega} \end{aligned}\right\} \tag{2}$$

Eliminating I_2 we obtain

$$\left(Z_1 - \frac{(Z_{12})^2}{Z_2}\right) I_1 = E$$

Thus the effect of the secondary is the same as if an impedance

$$\left.\begin{aligned} Z' &= R' + jX' = -\frac{(Z_{12})^2}{Z_2} \\ &= \frac{(M\omega)^2}{R_2 + jL_{2\sigma\omega}} = \frac{M^2\omega^2(R_2 - jL_{2\sigma\omega})}{R_2^2 + L_{2\sigma}^2\omega^2} \end{aligned}\right\} \tag{3}$$

were introduced in series with the primary.

The power delivered to the secondary is

$$P_2 = \frac{1}{2}\left|I_1\right|^2 R' = \frac{1}{2}\left|I_1\right|^2 R_2 \frac{M^2\omega^2}{R_2^2 + L_{2\sigma}^2\omega^2}, \tag{4}$$

where $|I_1|$ is the peak value of the current. The power delivered to the primary is

$$P_1 = \frac{1}{2}\left|I_1\right|^2 R_1 \tag{5}$$

Hence the efficiency

$$\eta = \frac{P_2}{P_1 + P_2} \tag{6}$$

can be found. Note also that if in (4) we replace I_1 by E/Z we obtain

$$P_2 = \frac{1}{2}\frac{|E|^2}{|Z|^2} R' = \frac{|E|^2}{2}\frac{|Z_2|^2 R'}{|Z_1 Z_2 - Z_{12}|^2}$$

$$= \frac{|E|^2}{2}\frac{R_2 M^2\omega^2}{[R_1R_2 + (M^2 - L_1L_2)\omega^2]^2 + \omega^2\,(R_1L_2 + R_2L_1)^2} \tag{7}$$

Suppose now that R_1, R_2, L_1, L_2, M are constants (independent of ω) then it follows from the above that the efficiency η increases with ω, varying as ω^2 for low ω and approaching

$$\frac{1}{1 + \frac{R_1}{R_2}\left(\frac{L_2}{M}\right)^2} \tag{8}$$

for large ω.

While for the same furnace $P_2/|I_1|^2$ continually increases with ω approaching the value $M^2\omega^2/2R_2$ for large ω, the ratio $P_2/|E|^2$ behaves differently. Indeed, from eq 7 we see that $P_2/|E|^2$ increases as ω^2 for small ω and decreases as $1/\omega^2$ for large ω; it must therefore exhibit a maximum. This is taken on at

$$\omega^2 = \frac{R_1R_2}{L_1L_2 - M^2} \tag{9}$$

Roughly speaking, the above equations show why removal of the iron core requires an increase in frequency. Indeed, from eqs 4 and 5 follows

$$\frac{P_2}{P_1} = \frac{R_2}{R_1}\frac{M^2\omega^2}{R_2^2 + L_2^2\omega^2} \tag{10}$$

Now if M, L_2 have both been reduced in a certain ratio through the removal of the core, it is necessary to increase ω in the same ratio in order to obtain the same P_2/P_1 and hence the same efficiency.

If one attempts to apply the above equations to coreless furnaces and high frequencies, caution must be observed to replace $R_1, R_2, \ldots$ by proper equivalent values that can be calculated only when the current distribution is known. This, as will be shown later, can be done both for low and high frequencies. Before considering this let us see what results may be obtained by means of dimensional analysis.

Dimensional analysis can be used to advantage in investigating the effect of size, frequency, resistivity. According to its principles any relation between physical quantities must reduce to a relation between dimensionless combinations of these quantities. Thus if it is granted that the efficiency η depends on the size as characterized by some length l, on the resistivity ρ, the permeability μ, and the frequency f, then it follows that the relation sought

$$\eta = f\,(l, \rho, \mu, \omega)$$

must reduce to an equation

$$\eta = f\left(\frac{\mu\omega l^2}{\zeta}\right) \tag{11}$$

since, with 4 fundamental units, say of mass, length, time, and permeability, $\mu f l^2/\rho$ is essentially the only dimensionless combination of the 4 quantities l, ρ, μ, f. This shows, for instance, that if in a test with a model, a certain efficiency has been reached at a proper frequency, that a larger size will allow the frequency to be decreased as the square of the size increases and the same efficiency will be obtained. (Strictly speaking, this conclusion follows from dimensional analysis only if the primary coil, too, be geometrically magnified.) Again, if the *tonnage* of a furnace be increased say r-fold by proceeding to a larger furnace of similar design, the dimensions will be magnified as $r^{1/3}$, while a decrease of frequency in the ratio $r^{2/3}$ will lead to the same efficiency.

As already pointed out in connection with eq 10, a change in μ can be compensated for by a reciprocal change in ω. However, this change in μ means now that the permeabilities of *all* points (air included) be changed in the same ratio. Hence the result is only of qualitative value.

For P_2 we obtain similarly by dimensional analysis

$$\frac{P_2\rho}{l|E|^2} = f\left(\frac{\mu\omega l^2}{\rho}\right) \tag{12}$$

From this we may conclude that the value of ω that renders $P_2/|E|^2$ a maximum varies inversely as the square of the furnace size.

A more detailed analysis of the coreless furnace shows that:

1. η, $P_2/|I_1|^2$, $P_2/|E|^2$ all vary as ω^2 for small ω.
2. $P_2/|I_1|^2$ continually increases with ω, varying as $\sqrt{\omega}$ for large ω.
3. The efficiency η increases with ω and approaches a limiting value (<1).
4. $P_2/|E|^2$ takes on a maximum value for a proper ω, and eventually decreases as $\omega^{1/2}$.

Consider first frequencies so low that the induced currents are small compared to the primary current, so that the magnetic field is essentially the same at each instant as the d-c field corresponding to the instantaneous value of primary current. The magnitude of the induced electromotive force as well as of the induced currents will vary as the *rate of change* of the field, hence as ω. The power P_2 will thus vary as

$$P_2 = (\text{const.})\ |I_1|^2\omega^2\rho \tag{13}$$

The constant can be determined from a flux plot Similar formulas are easily proved for η and $P_2/|E|^2$. The induced currents are 90 deg out of phase with I_1.

Suppose next that the frequencies are high so that the field due to the induced currents becomes of the same order of magnitude as the field of the primary current. For these high frequencies the effect of the field of the induced currents in itself inducing currents is so large, that the induced current, so to speak, trip over themselves. This constitutes the phenomenon of "skin effect" according to which both the field and the currents penetrate but a small distance into the conducting solids.

The simplest case for investigating this phenomenon is offered by a uniform tangential field that is applied at the boundary of a semi-infinite solid of resistivity ρ and permeability μ.

In this case the solution of Maxwell's equation shows that the electric and magnetic vectors are at right angles to each other, that their amplitudes decrease exponentially with the depth of penetration, decreasing to $1/e$ of their boundary values in the depth

$$T = \frac{1}{2\pi}\sqrt{\frac{\zeta 10^{-9}}{\mu f}} \tag{14}$$

where practical cgs units are used.

The quantity T can be used as a general index of how pronounced the skin effect is for any shape solid: if the dimensions involved are larger than T the effect will be pronounced, if less they will not. Indeed, in other cases in which the complete field distribution have been obtained theoretically, for instance, in the case of an infinitely long charge in a uniform solenoid,

it is found that at high frequencies the distribution of flux and eddy currents conforms to the above type. On physical grounds this may be predicted from the fact that if the depth of penetration T is considerably less than the radii of curvature of the boundary, the latter may be effectively considered plane.

In applying the above to a coreless furnace of dimensions greatly exceeding T, it is commonly assumed that magnetomotive force of the primary coil is consumed on its inside. This determines the applied field in terms of ni, the primary, ampere turns per unit height. The induced electric field at the boundary comes out to be

$$H = Z_0 (ni)$$

where

$$Z_0 = (1 + j)\, 2\pi \sqrt{\rho_H f\, 10^{-9}} \qquad (15)$$

Neglecting and effects due to the finite size of the coil and charge, the effect of the secondary may now be shown to be equivalent to an impedance

$$Z_2 = N^2 A Z_0, \qquad (16)$$

where A is the area of the charge covered by the primary, N the total number of turns.

From eq 16 it will be seen that Z_2 varies as $\sqrt{f}$ or $\sqrt{\omega}$. Thus, for a given I_1 the power P_2 will increase continually as $\sqrt{f}$. It is also concluded that R_2 and X_2 ($= L_2\omega$) tend to become numerically equal for high ω.

At first glance it would appear that since P_2 rises indefinitely with f, that the efficiency could be made close to unity by choosing a high enough frequency. This, however, is not the case, as soon the skin effect appears in the primary winding, too. For a rectangular closely wound coil, the limit P_2/P_1 approaches $\sqrt{\rho_2/\rho_1}$, where ρ_2, ρ_1 refer to the secondary and primary, respectively (assuming permeabilities = 1) and η approaches

$$\frac{\sqrt{\rho_2}}{\sqrt{\rho_1} + \sqrt{\rho_2}} \qquad (17)$$

Actually this limiting efficiency is further decreased due to the larger radius of the primary and to the space between the windings. Such a corrected value was obtained by Burch and Davis by means of a complex analysis.

While Z_2 as given by eq 16 takes care of the voltage due to the secondary, it does not take account of the voltage due to the flux in the gap between the primary and secondary. Now Z_2 varies as $\sqrt{\omega}$ but the latter voltage varies as ω and thus the reluctance of the air space will be the limiting factor for the current I_1 at high frequencies, and will cause the power factor angle of the furnace to increase from the 45 deg angle displayed by the skin effect formulas toward 90 deg at high frequencies. Hence, for large ω

I_1 varies as E/ω

P_2 varies as $(E^2/\omega^2) \cdot \sqrt{\omega} = \dfrac{E^2}{\omega^{3/2}}$. Thus for the coreless furnace, too, $P_2/|E^2|$ first increases as ω^2 then decreases (as $\omega^{-3/2}$ and will possess a maximum.

The above elementary treatment can be improved and some of the neglected factors included. It is also possible to cover the commercially important intermediate frequencies at which the fields due to the induced currents cannot be neglected, and yet the skin effect is not so pronounced as to concentrate the eddy currents at the surface. This has been accomplished by a combination of powerful analytical and graphical methods relying on successive approximations.

The 3-Phase Electric Arc Furnace

Discussion of a paper by Samuel Arnold, 3rd, published in the December 1933 issue, p. 839–43, and presented for oral discussion at the electric furnace session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 452–4.

W. E. Moore: The writer has specialized for some years on the development of the fast making polyphase direct arc furnace. This principle of operation has been developed to the extent that arc furnaces, instead of making 3 to 4 heats per 24-hr day, as formerly, now frequently run 6 to 18 heats per day of 24 hr, with correspondingly increased output, greatly improved electrical efficiency, reduced consumption of electrodes and refractories and with decreased labor costs.

With this type of direct arc furnace the efficiency is high because the time of heat loss during the heat is short and because the heat is applied directly to and in the metal. The refractories also are favored in that they are normally maintained under a soaking heat for but a comparatively short time, namely, during the superheating portion of the furnace cycle and thus are cooled when a repetition of the melting cycle again permits them to release heat to the next metal charge.

This type furnace has been so designed for electrical stability as to permit the use of arcs of much higher voltage than was the prior custom so that electrode diameter and cross section of load carrying parts has been correspondingly reduced. With these longer arcs the possible stability of the furnace is also improved by reason of any irregularities in the scrap charge forming a smaller portion of the total arc length.

With rapid work the furnace efficiency has been so improved that on acid steel and iron melting and refining, when operating under favorable conditions, the power consumption can be assumed to be 500 kwh per ton and sometimes goes as low as 450 kwh per ton melted and superheated. However, on smaller furnaces and furnaces on slow discontinuous operation the unit power consumption is not so good. By the same token the electrode consumption has been reduced to as low as 8 lb per ton with carbon electrodes and with graphite electrodes as low as 4 lb per ton; in fact, one user reports 2.82 lb of graphite electrodes per ton charged yearly average; although this electrode consumption would necessarily not be so good on furnaces of the smaller sizes or when operating under slow part-time conditions.

With the direct arc furnace it is quite practicable to make low carbon products without carbon pick up, quite in contrast to the older style slow arc furnaces in which it was considered practically impossible to make low carbon heats such as ingot iron, permalloy, or remelting stainless iron without undesirable carbon "pick-up."

To the 3 classifications of furnaces mentioned in the paper should be added 2 others; namely, class (4) continuous melting, and class (5) continuous refining, in which the furnace is kept continuously supplied with a bath throughout the operating period—whether that be by the day or by the week—the metal being tapped off at frequent intervals in comparatively small ladles in quantities ranging usually from 10 to 25 per cent of the holding capacity—and corresponding charges added at frequent intervals. With this type of furnace insulated refractories are especially desirable. In fact, furnaces fitted with insulated refractory linings have been in use for the past half dozen years or more showing reduced heat losses—both for batch melting and continuous melting. An insulated refractory lining is, however, more costly in installation and maintenance so that operators ordinarily prefer to use a rapid type furnace to obtain high efficiency with the standard-shaped-refractory-linings.

Now that ample central power supply is available it is entirely practicable to construct direct arc polyphase electric furnaces of 25,000 kva capacity and greater.

Large furnaces may be fitted with side doors of sufficient size to permit the ordinary open-hearth-type-horizontal-charging machine to be used for mechanically charging the furnace. While this is an improvement over hand charging, it is still not a rapid means of charging and permits a marked "cool-down" of the furnace between heats, also a large loss of time during which power demand must necessarily continue to be charged and it is rough on the furnace structure and refractories; it does not permit of filling the furnace with a full charge up to the electrodes, as is necessary with bulky scrap to avoid recharging.

This difficulty has now been successfully overcome by the top-charge furnace. The top-charge furnace roof is lifted slightly and swung to one side by means of a hydraulic cylinder, uncovering the entire opening in the furnace crucible, and the charge contained in a cylindrical bucket with orange peel bottom opening is lowered into the furnace and deposited at one time without delay and to the full capacity of the crucible and without injury to the refractories or electrodes. This process frequently requires only a period of 4 min from "tap" to power on again—in contradistinction to the period often ranging from one-half hour to one hour or more for charging the old side door furnace. This correspondingly improves the output of the furnace without increasing the demand charge, and with an economy in the unit power consumption due to shorter time for heat losses during the furnace cycle. It also reduces the time in which the white hot electrodes are exposed to oxidation in the outside atmosphere—as well as reducing the lost time of the attendants. Top-charging also allows the use of large scrap. This improvement has in certain cases reduced the melting cost from \$1.50 to \$2.00 per ton—although the furnace plant is somewhat more expensive

in first cost. More than a dozen top-charge furnaces have been installed.

The electrodes and refractories of the roof, not being tilted are not strained, weakened, nor broken while charging and the marked advantages of quicker time are thus gained without resulting in disadvantageous conditions.

With the modern direct arc furnace it is standard to use a transformer having 4 or more voltage connections, and the usual voltages for such operating requirements as are standard for any given operation are made available at the switchboard. Provision is also made for stabilizing the power to the furnace at whatever arc voltage may be in use.

With the modern direct arc electric furnace the cost of the furnace installation for a given daily production is now less than that obtainable for modern open hearth furnace installations, and is in active competition with the open hearth furnace. Approximately 80 per cent of the tonnage of electric iron is at present furnaced in direct arc furnaces.

The connected capacity of direct arc furnaces in the United States now totals some 600,000 kw, and with a return of activity in steel and other metallurgical enterprises it is estimated that within the next ten years an increase of 400,000 kw in electric furnace load may be confidently expected.

The following table shows an estimated cost per net ton for a modern rapid-melting type direct arc top-charge polyphase electric furnace when in steady, continuous operation, under favorable conditions:

500 kwhr @ 0.6¢	$ 3.00
10 tons steel melting scrap @ $12 per ton	6.00
10 tons steel turnings @ $8 per ton	4.00
Plus melting loss—3 per cent	.30
8 lb carbon electrodes @ 7¢	.56
Ferro-alloys and slag additions	1.20
Refractories maintenance	.20
Furnace attendants	.24
Cost per ton of steel at spout (not including ladle, mold nor overhead costs)	$15.50

Samuel Arnold, 3rd: The discussion by W. E. Moore is very interesting and brings out a number of points worth considering. I agree entirely with Mr. Moore that there is quite a difference between modern furnaces and furnaces of the older type. Modern furnaces are usually equipped with high power transformers, higher voltages and multiple voltage control so that the operator may choose at will the voltage most adaptable to the furnace conditions. The rate of melt is, of course, directly proportional to the rate of power input and as I mentioned in my paper, efficiencies have been increased materially by decreasing the time of radiation. Today all direct arc furnaces in common use are of the Heroult type and there is very little difference in the general dimensions of the shell. The most important differentiation being in the method of tilting and the method of operating the electrode arms. The effective voltages used for a given power input are also practically the same. It is my opinion, however, that the melting voltage to be used is largely dependent upon the amount of power to be introduced. This is especially true in the larger units and I might add that on a 50 ton Heroult furnace, melt down voltages are available as high as 290 volts across phases which I believe are the highest voltages that have ever been used on production work.

I wish to point out, however, that in my paper I gave due recognition to the use of higher power inputs but mentioned that some thought should be given to increasing the efficiency of the furnace along other lines. This for the reason that high demand charges often penalize the furnace operator and with a comparatively low load factor the high cost of power frequently more than offsets the gain obtained by decreasing the kilowatt hours per ton.

With regard to insulation as a means of increasing furnace efficiency, I know that this has been tried from time to time but from all the data I have been able to gather, has not been tried with any real degree of engineering application. At the time of giving the paper, some experiments were being conducted with a small arc furnace, utilizing insulating brick in the side walls and to date these experiments have indicated that further efforts along this line would be warranted. The first lining life of this small unit of approximately one ton nominal capacity was 207 heats with acid operation and the power costs were reduced about 50 kwhr per ton with a demand charge of approximately 80 per cent of that necessary without the insulation, based on the same tonnage being produced. The question of the added cost of this insulating material as opposed to the savings obtained and just how far the insulation can be carried are, of course, open at the present, but there is every reason to believe that advantages accrue from insulating electric furnaces, and I again wish to emphasize the desirability of further experiments.

Mr. Moore mentions that continuous melting and refining furnaces should be added to the classification. This is simply a question of nomenclature and I prefer to use the term semi-continuous melting and refining for the reason that the metal is tapped and charged at intervals.

Mr. Moore further mentions that it is entirely practical to construct direct arc polyphase furnaces of 25,000-kva capacity and greater. He does not say but I believe he means that in these larger capacities, multiple electrodes are necessary. In my paper I mentioned a 6-electrode 20,000-kva furnace and from data so far obtained on the operation of this unit, it is questionable if higher kilowatt capacities can be used per electrode and that any increase in capacity would mean additional electrodes.

As to the open or removable roof type of charging, this method has been successfully used on furnaces from 3 to 10 tons in capacity, but I question very much the efficiencies claimed by Mr. Moore for this type of furnace. Heroult furnaces have been built and are in use utilizing this method of charging which, of course, shows economies over hand charging primarily on account of the time saved, but when it is considered that a furnace is opened up and that there are two large radiating bodies at a temperature of 3,000 deg F or above, you can easily visualize the tremendous loss of energy even in a very short period of time. This was brought out in the moving pictures shown where it was noted how rapidly the brick lose their temperature and become blackened. With furnaces from 1 to 3 tons, I believe the chute method of mechanical charging is the best. With furnaces from 3 to 10 tons in capacity it is an open question as to the efficiency of the removable roof type, and on furnaces from 15 tons capacity up, the open hearth charging machine is unquestionably the best method of charging that so far has been developed.

Mr. Moore's data on melting costs are very interesting. I wish that I could agree that average costs would be somewhat in line with what he has given. In the first place, if steel turnings were used by all electric furnace users as indicated by Mr. Moore, the steel turning market would soon be dried up. In the second place, the labor costs he gives are very much lower than the average. Assuming 48 cents an hour for furnace labor, which is exceedingly low, this would mean that two tons of metal will be produced per man hour. In addition to this, there are a number of other items of costs such as crane charges, scrap handling, water, miscellaneous power, furnace maintenance and other items which he has not included and which should properly be charged to metal production costs. There may be one or two isolated conditions with methods of accounting that would indicate metal costs in line with that which Mr. Moore has given, and if production costs in general could be obtained as low as indicated, open hearths would soon disappear.

I wish also briefly to comment on the discussion of Mr. Frank W. Brooks and Mr. C. C. Levy. I believe that Mr. Brooks is sincere in his statements regarding insulation, but I am not at all convinced that the field should not be explored more definitely. As to ratings of furnaces, standardization is, of course, a fine thing, but today furnace users know something about furnaces and usually it is very difficult to give them something in the line of standard equipment. Nearly always and I believe rightly they wish to incorporate some of their own ideas. As to Mr. Levy's question, I believe I answered this in my paper where I stated that the diameter of the shell, the nominal holding capacity, and the tons per hour for production for a specified product should be given.

Steady State Stability of Composite Systems

Discussion of a paper by S. B. Crary published in the November 1933 issue, p. 787–92, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Another discussion of this paper was published in the March 1934 issue, p. 477.

S. B. Crary: H. L. Hazen brings up the interesting question of how to determine the distribution of loads among the generators of a system when making a stability study. All of the four assumptions discussed by Hazen, may be used in any one stability study. Assumption 1, that the relative rotor position of a group of machines

remains unchanged with respect to each other, is in effect equivalent to considering that group as one equivalent synchronous machine. This is a necessary and practical assumption in many cases. Hazen suggests, by assumption 2, that the inherent speed regulation of the prime mover may be used to determine the load division. This is undoubtedly a worth while consideration in some cases, although in general, the inherent regulation of a prime mover with constant gate or throttle opening is large compared with the regulation of the machines which are governor controlled. Therefore, if the period immediately after the governors of the governor controlled machines have acted is under consideration, the machines with constant gate or throttle openings can be considered as fixed power machines. This assumes that a reasonable ratio exists between the relative capacities of machines under governor control with those that are not.

However, it may be advisable in some cases to make assumption 2, as Hazen suggests. For example, it may be found that using the inherent speed regulation of the prime movers results in lower limits than if governor regulation had been used. The limit of safe operation should accordingly be determined by this more pessimistic result. Each study usually presents problems which makes necessary an examination and evaluation of the assumptions to be used for each case.

Attenuation and Distortion of Waves

Discussion of a paper by L. V. Bewley published in the December 1933 issue, p. 876–84, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 471–3.

Otto Ackermann: Nobody realizes the importance and the significance of L. V. Bewley's paper better than those who, in their regular work, have studied lightning surges and experimented with traveling waves. They often were confronted with and puzzled by wave phenomena which could not satisfactorily be explained on the basis of the conventional theory. The first ones, I believe, were C. L. Fortescue and his staff who obtained klydonograph records with positive and negative characteristics in the same figure from conductors which obviously had carried only induced surges. In his paper presented at the Worlds Power Conference at Paris in 1932, Mr. Fortescue attributes this phenomenon to a peculiar coupling effect involving waves of different speeds whereas formerly it had been erroneously interpreted as indicating an oscillatory lightning discharge.

In Switzerland, K. Berger recorded lightning surges by means of 2 cathode ray oscillographs on parallel phases as early as 1930 and was surprised by finding induced waves starting with a potential opposite to that of the main surge. In the S.E.V. Bulletin, 1931 Nr. 17 one finds his attempt to explain this phenomenon. In 1931, the writer visited Mr. Berger and the discussion brought forth marked coincidence between Mr. Berger's observations and measurements made by the Westinghouse company in coöperation with the Public Service Company of New Jersey. In Fig. 1 is the copy of a lightning surge recorded by Mr. Berger 66 miles from the point of origin (published in the S.E.V. Bulletin, 1932 Nr. 12, p. 295). In Fig. 2 is shown the record of an artificial wave and the induced voltage 5 miles from the origin taken on a line of the Public Service Company of New Jersey. It is only one sample of a great number of similar records showing opposite polarity on the induced surge. Encouraged by the apparent similarity in the behavior of natural and artificial surges Mr. Berger advanced our explanation of the phenomenon in his abovementioned paper in 1932. It may be said now that all these attempts to explain this perplexing phenomenon were lacking considerably in one way or another and Mr. Bewley must be credited with having advanced the complete understanding of a question which has occupied many a student of traveling waves in the last few years.

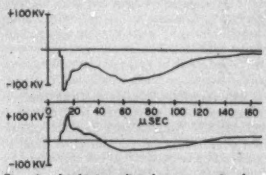


Fig. 1. Lightning disturbance on 2 phase wires, recorded 66 miles from the origin

Retraced from the S.E.V. Bulletin, 1932, p. 295, Fig. 8

However clear the mathematical derivation, the mental picture of this interesting process is somewhat hard to form, since it demands us to imagine a surge creating another one of exactly the same magnitude but of opposite polarity on an isolated parallel conductor. Yet, the final result is exactly the same as if a surge were applied between 2 parallel conductors by means of an impulse generator. In this case, the 2 wires carry equal surges of opposite polarity.

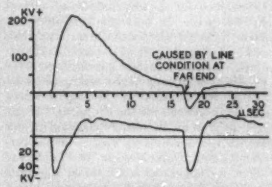


Fig. 2. Artificial surge and induced wave recorded 5 miles from the origin

A surge between line and ground has the inherent tendency to travel at the speed of light. If it is impeded by ground currents or corona, at least such components as can form pure electromagnetic fields of the classical description propagate at full speed. This possibility is given if a second parallel wire in air is present. It carries the opposite charge just as if a surge was applied directly between the 2 conductors. The balance of the charges follows at slower speeds. From this fundamental conception it follows that there always must be a wave component propagating at the speed of light as long as the establishment of a pure undistorted electromagnetic wave between conductors is at all possible. From this standpoint, the faster speed component must always be equal to one. If calculations as in Mr. Bewley's paper, p. 880, columns 4, 5, and 6 show even the higher speed to be less than that of light, it must be postulated that either the constants are not chosen so as to represent natural conditions or that from this faster wave another one separates traveling faster yet, namely, at the speed of light.

As to the fallacies in the way of choosing constants, it may be pointed out that, contrary to the assumption on p. 879 of Mr. Bewley's paper, an isolated wire in the field of another one does not necessarily form corona corresponding to its potential in this electrostatic field. It should be remembered that, however high its potential, this wire is in a field of lower intensity than the critical corona gradient as long as this wire is outside of the corona envelope of the first one. A cylinder of any diameter in a homogeneous field simply raises the maximum field strength at its surface to twice that of the original field. This alone determines whether or not there is initially any corona on the secondary wire.

At any rate, Bewley's analysis gives the key to the full understanding of most traveling wave phenomena laid down in oscillographic records. Especially, the sensible evaluation of attenuation data is now possible since almost all records of waves accompanied by parallel conductors clearly indicate the separation in 2 principal components each of which can be analyzed separately sufficiently well by means of an exponential attenuation law. In this connection it may be suggested that we work toward the adoption of a system of attenuation constants which is both logical and convenient for practical use. The fundamental terms could be of the form

$$e = E_n \times \epsilon^{\frac{-x \cdot 0.69}{K_n}}$$

or somewhat similar where x is the distance travelled and K_n the distance in which the wave component E_n drops off to half voltage due to its particular attenuation characteristics. In adding the different components one must remember that they travel at different speed which now explains to the greatest part why these constants have varied so widely when derived from actual observations without this important new consideration. They ranged about as follows:

Due to Corona.
1 to 6 miles for attenuation to half value.

Due to Resistance.
10 to 25 miles for attenuation to half value.

C. L. Fortescue: L. V. Bewley has presented the A.I.E.E. with a very interesting and stimulating paper. Largely on account of its stimulating character, I think this paper is the best one that Mr. Bewley has contributed to the Institute.

There is no question in my mind as to the superiority of Mr. Bewley's method over the previous approximate methods where in both cases true attenuation is ignored. Mr. Bewley's paper will, therefore, be of great value to electrical engineers. In the past few years I have given much thought to obtaining approximate solutions of wave problems satisfactory for practical purposes. Such solutions are naturally partly empirical as is the case with many of our engineering solutions. Mr. Bewley's theory will eliminate a large part of this empiricism.

Dr. Slepian has shown in his discussion of Mr. Bewley's paper why Mr. Bewley's equations and the solutions he derives are really incompatible. This is easily visualized by considering a charge on an infinite wire having a perpendicular field constrained in some manner to move with a velocity v less than the velocity of light. The motion of this charge will be at once to create a magnetic field in space and the changes set up will be propagated with the velocity of light. The potential of the line ahead of the moving charge at the start of the motion will be zero, but with the motion a change will take place at the conductor surface and parallel component of electric force will appear so that the electric force will be no longer perpendicular. In other words, energy will be transferred from the slowly moving charge to the portion of line in front of it creating a wave which will move with the velocity of light. In short, a wave on a wire in air in the presence of a perfectly conducting earth plane will move with the velocity of light whether corona be present or not. The distortion of the wave, however, should be capable of representation by considering the wave to be made up of several waves moving at velocities less than that of light and one wave having the velocity of light. This could be done by considering a component of current to exist in the corona envelope parallel to the line due to the fact that at the front of the wave the direction of ionization is not radial to the line when corona is present but at an angle thereto.

It is certainly true that the electrons moving in the direction of the radial field will be subjected to a force parallel to the conductor in the direction of motion of the wave on the wire. Whether the component of current due to this force will be of sufficient magnitude to noticeably affect the velocity of propagation of the wave is open to question.

Let us now consider the penetration in the earth. At the surface of the conductor there exist 2 types of current, namely, conduction current in a direction parallel to the conductor and displacement current usually taken as being at right angles to the surface of the conductor. When the earth is represented by an infinite perfectly conducting plane, a similar charge distribution of opposite sign will exist on the surface of the earth provided the wave on the wire is traveling with the velocity of light and this charge distribution and corresponding conduction and displacement can be properly represented by the image of the wire with its wave considering the surface of the earth as a perfectly plane mirror.

In the case where the earth is represented by a semi-infinite dielectric having dielectric constant K and where q is the charge per unit length of the conductor, accepting Mr. Bewley's perpendicular field, this field in the air may be obtained by assuming a charge q' less than q at the optical image of the conductor in the dividing plane between the air and the dielectric. The field in the dielectric will be given by q'' an imaginary charge distribution on the conductor. The values of q' and q'' are given by

$$q' = \frac{K-1}{K+1}\,q$$

$$q'' = \frac{2K}{K+1}\,q$$

It will, therefore, be plain that the displacement currents do penetrate the earth to a considerable distance and that the capacities obtained by considering q' as equal to q are much too large. q' can be equal to q only when K becomes infinite, *e. g.*, the earth is a perfect conductor as K diminishes, the field in the air approaches that due to an isolated conductor in space. It will also be quite evident that the surface of the earth considered as a dielectric will not have a potential of zero.

When the conductivity of the earth is low, it is probable that its dielectric constant K will have a preponderating influence in determining the current and field distribution. Both displacement currents and conductive currents will be present in the earth. The distribution and depth of penetration will probably be somewhere between that determined for a perfect conducting earth and that determined by considering K alone. I think that any penetration into the earth of conduction or displacement currents will have the effect of slowing up the waves of the wires by energy and actual attenuation. Moreover, it is possible that the velocity of propagation is not uniform but decreases with time and distance traveled.

What I wish particularly to emphasize in the above discussion is that the current is a solenoidal vector and that the electromagnetic and the electric fields are inextricably tied together by this fact so that the so-called zero potential plane or planes are determined by the distribution of current in the earth. In only one case does this plane lie at the surface of the earth and this is when the resistivity of the earth is zero.

Mr. Bewley's theory indicates that the presence of ground wires will greatly increase the attenuation of waves above corona traveling over the line wires. If this is true it is an important addition to our knowledge of traveling surges, and it furnishes another advantage in favor of ground wires, for apparatus has little to fear from traveling waves below the corona point. If a ground wire system has a high enough protective level so that flashover due to a lightning stroke cannot occur, the traveling wave that appears on the line wires will be very small as the positive and negative traveling waves induced by the corona on the ground wires do not have time to separate appreciably and the portions that are in phase tend to cancel each other, the net result is a wave of low magnitude having both negative and positive parts. This is indicated by cathode ray oscillograph waves that were obtained at the Roseland substation during lightning storms in the summer of 1930.

If I am not mistaken Mr. Bewley's theory provides the missing factors which have been baffling us during the past few years and furnishes the answer to the apparent high coupling factors that result when corona is present as a result of a lightning stroke to line or tower. The coupling factors are actually less but this is more than compensated for by the energy transfer from the ground wire to the line which after a fraction of a micro-second begins to decrease the amplitude of the wave on the ground wires and increase the amplitude of the potential on the line wires. At the crest of the wave a considerable reduction has been affected in the difference of potential between line and ground wires. Apparently this difference of potential will increase more abruptly but the crest and tail of the difference of potential wave will be considerably reduced.

To summarize, I think that a factor is missing in Mr. Bewley's equation which should bring in a wave of small magnitude traveling with the velocity of light. Tests have been made by us on velocities of waves below the corona point and the velocity of the front agrees with that of light within the probable errors of measurement. Corona does not take place at the front of the wave and in fact a corona time lag is probable so that a considerable portion of the front has passed a given point before corona begins to form at this point. There appears to be no valid theoretical reason for assuming that the discontinuity at the front of a wave having corona does not travel with the velocity of light.

In conclusion, I wish to congratulate Mr. Bewley on this paper which presents a theory which is a big step in advance of the past generally accepted theories of wave propagation under corona conditions. The defects which appear to me to be present in his physical interpretations are not pointed out in the spirit of criticism but in the hope that further analytical research may show the way to remove these defects and arrive at a still better interpretation of the problem of wave propagation over wires.

Appendix to Discussion

I prefer to express Mr. Bewley's equations in a little different form from those he uses. For simplicity consider the 2-conductor problem. The first 2 equations are the same as his, the next 2 are the reciprocal equations to his. The system of equations then becomes

$$\left.\begin{aligned}
-\frac{de_1}{dx} &= L_{11}\frac{di_1}{dt} + L_{12}\frac{di_2}{dt}\\
-\frac{de_2}{dx} &= L_{21}\frac{di_1}{dt} + L_{22}\frac{di_2}{dt}\\
-\frac{1}{C^2}\frac{de_1}{dt} &= L_{11}'\frac{di_1}{dx} + L_{12}'\frac{di_2}{dx}\\
-\frac{1}{C^2}\frac{de_2}{dt} &= L_{21}'\frac{di_1}{dx} + L_{22}'\frac{di_2}{dx}
\end{aligned}\right\} \qquad (1)$$

where C is the velocity of light and the inductances may be expressed in practical or absolute units. By differentiating the first 2 equations with respect to x and the second 2 with respect to t, we obtain 4 equations re-

lating $\frac{d^2e_1}{dx^2}$ and $\frac{d^2e_2}{dt^2}$ to $\frac{d^2i_1}{dx\,dt}$ and $\frac{d^2i_2}{dx\,dt}$ eliminating $\frac{d^2i_1}{dx\,dt}$ and $\frac{d^2i_2}{dx\,dt}$. From these 4 equations we obtain 2 linear equations relating $\frac{d^2e_1}{dx^2}$ and $\frac{d^2e_2}{dx^2}$ to $\frac{d^2e_1}{dt^2}$ are $\frac{d^2e_1}{dt^2}$. Obviously the rest of the solution will proceed along the same lines as Mr. Bewley's solution. If $L_{11}' = L_{11}$ and $L_{12}' = L_{12}$, eq 1 shows that

$$\frac{1}{C^2}\frac{d^2e_1}{dt^2} = \frac{d^2e_1}{dx^2}$$

and

$$\frac{1}{C^2}\frac{d^2e_2}{dt^2} = \frac{d^2e_2}{dx^2}$$

the ordinary equations of propagation of waves along wires with the velocity of light.

L. V. Bewley: Prof. A. R. Miller gives a somewhat different method of analysis for the 2-conductor system, and calls attention to the pair of waves moving in the other direction. In Appendix I of the paper I was interested merely in the forward waves, and therefore, did not explicitly specify the backward waves. But in the general solution given in Appendix II for any number of conductors the complete system of forward and backward waves is explicitly derived. Professor Miller also points out that resistance and leakance are neglected. I gave the differential equations for this case in a previous paper ("Traveling Waves on Transmission Lines," A.I.E.E. TRANS., v. 50, 1931) and repeated it in chap. 6 of my book ("Traveling Waves on Transmission Lines," John Wiley & Sons). However, I confess that I have never carried through a complete solution of these differential equations except in the case of a 2-conductor system. The solutions with losses included are no longer simple traveling waves. I very much doubt the value of calculations based on fixed constants for resistance and leakance; especially since most of the loss is due to corona (a function of the voltage) and the ground resistance (a transient skin-effect problem).

Dr. Slepian admits the existence of multivelocity waves and agrees that they result from the finite ground resistivity and corona. But he questions the validity of the differential equations from which I arrived at my conclusions. I do not state, as he implies, that the zero-potential plane lies below the ground surface except in the case of a resistive earth. Nor do I claim that "the component systems propagate with only small attenuation and distortion, and at definite velocities which are independent of the wave shape of the component waves." Under *Conclusions* I named and briefly discussed three principal causes of attenuation and distortion, only one of which was the subject of my paper. As far as the velocity depending upon the wave shape is concerned, it is easy to see that for short waves the average depth of current penetration is less than for long waves, and consequently the velocity must be higher. I pointed out this fact on page 74 of the Feb. issue of the *Gen. Elec. Rev.* in an article on "The Counterpoise." Dr. Slepian's theorem concerning multivelocity components agrees perfectly with the conceptions given in my paper, and is, in fact, a description of my Fig. 7. Regarding Mr. Slepian's contention that the differential equations are not valid for waves moving at less than the velocity of light, I can only say that it has long been recognized that they are approximate, and partly for the reasons given by him (which idea was first developed by Sir J. J. Thompson). The question is: how good an approximation are they? The ideal way to answer this question would be to make a complete analysis based on Maxwell's equations. Mathematically this is beyond me. However, I have gone far enough to see that the solution is not a wave solution and the final formulas would be quite complicated. Therefore, from an engineering point of view such an elaboration is not very practical except as a means for establishing the range of validity for the approximate differential equations. The other way out of the difficulty is to do as I did; consider the great lengths of the wave relative to the height of the line and thus infer intuitively that throughout the greater part of the wave length the longitudinal components of the compressed field of each moving electron are mutually cancelled; so that a pure radial field may be assumed except at the front of the wave or where an abrupt jump occurs (end effects). This means that my differential equations are not open to Dr. Slepian's objections except in the neighborhood of an abrupt jump, and for a distance not much greater than a low multiple of the height of the line. For example, if a wave is 30 μsec long and has an abrupt front, and the line height is 50 ft above earth, then for 0.1 μsec or so at the wave front my differential equations are probably poor approximations, but for the other 29.9 μsec of the wave (away from the "end effect") they are probably very good approximations. In any event, they yield a simple solution which agrees with the experimental evidence and suffice to explain the observed phenomena.

Mr. R. D. Evans offers some figures on the effective depth of return for a conductor located 100 ft above the ground surface and for a frequency of 1,000,000 cycles, and finds that the effective depth is different for magnetic than for electric effects. I take it that the figures he gives are distances below the overhead conductor, rather than depths below the ground surface. If this is so, then his figures verify my contention that the ground surface is essentially a zero potential surface with respect to the electrostatic field from overhead conductors. I agree with Mr. Evans that the depth of current penetration in the ground is not so great at the wave front as on the tail. But if this variation is taken into account the analysis becomes unmanageable. If any average depth for the current images is used, then only simple traveling wave components result. I suppose that an analysis of this type, if it is to have much engineering use, must remain simple. Nevertheless, an appreciation of the variable depth of penetration allows us to visualize certain aspects of traveling wave phenomena; for example, the elongation on the tail of short chopped waves. Consider, for instance, a short rectangular wave, which we may think of as the superposition of two displaced infinite rectangular waves of opposite polarity. Let Fig. 8 of my paper indicate the current distribution in the earth of each infinite rectangular component. Superimposing two such patterns of opposite polarity and displaced by distance equal to the length of the chopped wave, clearly shows how the tail of the wave will be built up, the front rounded off, and the crest reduced. A sketch made in this fashion shows a striking similarity to the distortion experienced by chopped waves.

Mr. Otto Ackermann suggests that the calculations given in Table I of the paper which show the fast velocity less than that of light, are either based on incompatible assumed constants or else there is a third wave present moving at the velocity of light. I believe the latter to be right, as I will try to show in answering Dr. Fortescue's discussion. Mr. Ackermann points out that an isolated wire in the field of another wire does not necessarily form corona corresponding to its pontential in this field. He is quite right, and one should compute the gradient taking cognizance of the fact that a cylindrical wire immersed in a uniform field doubles the intensity. Regarding a workable attenuation formula, exponential terms certainly have the advantage of easy manipulation in mathematical formulas, as well as being simple and compact. For estimating purposes I have found the Foust and Menger empirical formula of great help, particularly concerning questions of station outages.

Dr. C. L. Fortescue, as well as Dr. Slepian and Mr. Ackermann, argues for a wave component traveling at the velocity of light. There is no doubt in my mind that there is such a component present, but I believe that it is small compared with the components which I calculated. This velocity-of-light component is due to the electromagnetic field sweeping ahead of the main surge. Sir J. J. Thompson, O. Heaviside, and many others have shown by means of Maxwell's equations that an isolated electron (or spherical charge) suddenly set in motion at a velocity less than that of light will give birth to a spherical wave propagating at the velocity of light. Now, if this single charge happens to be guided by an isolated wire, then the associated electromagnetic field will induce in that wire a potential traveling at the velocity of light. If there is an adjacent wire the field will induce in it a potential *of the same polarity*. This is contrary to the observed polarity at the front of the induced wave, unless this induced component happens to be so small that it is lost on the oscillograms in comparison with the major wave components. But why should it be so insignificant? I hazard the guess that the proximity of a resistive earth carrying the approximate image of the advancing charge on the overhead conductors also has a velocity-of-light electromagnetic field which being essentially equal and of opposite sign to that of the charge on the line, practically nullifies the field ahead of the advancing surge at a distance equal to a few times the height of the line. Therefore, the amplitude of the velocity-of-light component on the overhead conductors decreases rapidly and at short distances ahead of the advancing main surge ceases to be apparent. Regarding a permittivity constant K for the earth, I am a bit dubious. I believe that the conductivity of the earth is always sufficient so that displacement currents in the earth may be ignored a hundred feet or so behind a wave discontinuity. But I

hope to know more about this point later on.

The wholesome and constructive criticism on my paper is most gratifying to me. I appreciate fully that the theory which I presented is merely a stepping stone toward, I hope, a better understanding of traveling wave phenomena.

Counterpoises for Transmission Lines

Discussion of a paper by Charles L. G. Fortescue published in the December 1933 issue, p. 908–17, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 467–80.

J. P. McKearin: The 115-kv and 66-kv system of the Turners Falls Power and Electric Company, one of the constituent companies of the Western Massachusetts Companies, extends throughout the western part of Massachusetts connecting Turners Falls, Pittsfield, Springfield, and Hartford, with taps to most of the intervening towns and cities. This system is connected at 115 kv with the New England Power Company's system and at 66 kv with the system of the Hartford Electric Light Company at Hartford.

Three years ago a program of improvement in protection against lightning was started and Table I shows the indicated results up to the present time, as well as the detailed changes made. (See also Figs. 1, 2, and 3.)

The most outstanding example of improved protection against lightning on this system is the 33.1-mile 66-kv interconnecting line between Agawam and Hartford. Comparing the 6-year record before, with the 3-year record after improving its protection against lightning, flashovers due to lightning have been reduced 95 per cent.

There have been 3 lightning flashovers since it was reinsulated in the spring of 1931. Of these 3, one was on a river crossing tower so high that it could not be protected. There is a short tap line, $3^2/_3$ miles long, of the old unprotected type of construction, connected to the Hartford line, and one of the other 2 lightning flashovers may have occurred on this tap line.

The record on the 36.7-mile 115-kv line from Cabot to Pittsfield shows a good improvement against lightning flashovers, but the improvement is not as great as that on the Hartford line. The reduction in light-

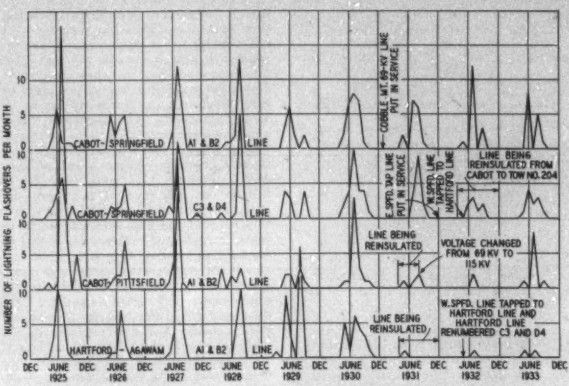


Fig. 1. Lightning flashovers per month on Turners Falls Power and Electric Company's 66-kv and 115-kv transmission lines

All tap lines are included. Entire Hartford-Agawam line is included. West Springfield and Margaret Street lines are included as part of Cabot-Springfield C3 and D4 lines until tapped to the Hartford line. The E5 line is not included

In Figs. 1, 2, and 3, a flashover is taken as one flashover regardless of whether or not it flashes over one or both circuits of a double circuit line

Table I—Lightning Protection of Western Massachusetts Companies Transmission Lines

	Agawam to Hartford C3 and D4		Cabot to Pittsfield A1 and B2		Cabot to Agawam C3 and D4		Cabot to Agawam A1 and B2
	Before Reinsulation	After Reinsulation	Before Reinsulation	After Reinsulation	Before Reinsulation	After Reinsulation	
Line kv	66	66	66	115	66	66	66
Miles of line (exclusive of taps)	33.1	33.1	36.7	36.7	39.8	39.8	48.7
Miles reinsulated		33.1		36.7		18.8	None
Lightning F.O. per yr (6 to 9 yr avg)	22.3		20.2		16.4		16.4
Lightning F.O. per yr (3 yr avg)		1.0		5.3*			
Lightning F.O. per yr (2 yr avg)						9.5	
Size of insulators in inches	5 × 10	5 × 10	$5^3/_8$ × 10	$5^3/_8$ × 10	$5^3/_8$ × 10	$5^3/_8$ × 10	$5^3/_8$ × 10
No. of insulators in string	5 and 6	9 and 10	6 and 8	9 and 10	4 and 5	8 and 9	4 and 5
Type of gap	None	Ring	Horn	Horn	Horn	Ring	Horn
Gap length in inches		39 and 44	$24^1/_4$ and $32^3/_8$	$36^1/_4$ and $43^3/_8$	$15^3/_8$ and $20^3/_4$	40 and $45^3/_4$	$15^3/_8$ and $20^3/_4$
% of line having counterpoise	None	60%	None	87%	None	33%	27%
Type of counterpoise		$^3/_8$" steel		1/0 Cu.		1/0 Cu.	1/0 Cu.
No. of overhead ground wires	1	2	1	1	1	1	1
Type of overhead ground wires	$^3/_8$" steel	$^3/_8$" steel and ACSR	$^3/_8$" steel	$^3/_8$" steel	$^3/_8$" steel	$^3/_8$" steel	$^3/_8$" steel
Phase conductors	4/0 ACSR	4/0 ACSR	2/0 Cu.	2/0 Cu.	1/0 and 2/0 Cu.	1/0 and 2/0 Cu.	1/0 Cu.
Phase spacing in ft (vertical)	10	10	10	10	9 and 10	9 and 10	8, 9, and 10
Average length of span in ft	564	564	584	584	512	512	533
Approx. height bottom conductor in ft	45	45	45	45	45	45	45
% of footing resist. over 20 ohms before counterpoise was installed	45%						

*There have been 16 lightning flashovers on this line during the 3 years since it was reinsulated. Seven of these flashovers occurred within a period of 23 min. July 21, 1933, during one of the most severe lightning, wind, and rain storms experienced in this territory.

ning flashovers is 74 per cent. However, the Pittsfield line does not have as much protection as the Hartford line. It has only one overhead ground wire, carries a little less insulation, and has an exposed route over the Berkshire Mountains. The route of the Hartford line is down the valley of the Connecticut River.

The 39.8-mile 66-kv line from Cabot to Agawam has been reinsulated for about $^1/_3$ its length and its lightning flashovers have been reduced 42 per cent.

The 48.7-mile 66-kv line from Cabot to Agawam, has not been reinsulated and there has been no significant change in its number of lightning flashovers per year. This would indicate that the reduction in lightning flashovers obtained on the other lines has been due principally to the increased protection against lightning rather than to a reduction in the severity of the lightning storms to which they have been exposed.

C. L. Fortescue: In reply to the general discussion of my paper, I wish first of all to disclaim any intention on my part to present a complete analytical theory of counterpoise action. In the first place, a thorough analysis of this complicated problem presents extreme difficulties and would not be justified on account of our meagre knowledge at present of so many of the factors that enter into the problem. In the second place, it is my opinion that only a fair approximation to the solution of the problem is necessary and that closer approximation, even if our knowledge of lightning phenomena made it possible, would not be justified if it entailed the very great complications that the complexity of the problem seems to indicate. Therefore, it seemed to me that an approximate semi-empirical method based on the actions in a homogeneous medium which could be adapted to the requirements of the increased statistical knowledge of these actions in the course of time would prove satisfactory. I suppose no one is more fully aware of the shortcomings of his paper than the author himself, but in the present paper I feel that I have quite frankly told my readers that the method outlined while it explains the operations of counterpoises approximately on the basis of our present statistical knowledge may need revision from time to time as our knowledge increases.

Considering Mr. Bewley's discussion in more detail, I cannot subscribe to Mr. Bewley's assumption that the ground plane for the electric field is at or near the earth's surface when the resistivity of the soil is high. I have discussed this matter in connection with Mr. Bewley's paper presented at this present session and will refer those interested to my discussion. This will account to a great extent for the difference between Mr. Bewley's numerical results and my own.

Regarding Mr. Bewley's views as to the proper value to ascribe to the surge impedance of the lightning stroke, I wish to point out that the value of 200 ohms which I have used has been applied to the analysis of a great number of existing lines on which there is reliable statistical data and seems to accord very well with this data. It also appears to be consistent with value of surge current in towers that have been recorded during the past few years and the maximum values of surge potential that have been measured on well insulated lines. However, it should be pointed out that this surge impedance cannot be considered constant over the whole length of the lightning channel and it seems reasonable to suppose that where the ground plane is a great distance below the surface of the earth there may be an increase in the value of the surge impedance of the lightning channel where it strikes a transmission line.

With regard to the high coupling factors obtained in my numerical calculations, this can be remedied in 2 ways, (1) by changing the value of S used in the numerical calculations, and (2) by decreasing the depth of the ground plane. By using a larger value of K (which may be justified) and a smaller value of S, the same protection level will be obtained numerically. The numerical results seem to accord well with the results obtained by the single counterpoise over High Knob. Whether these results should be obtained numerically by decreasing the depth of the ground plane using higher values of K and changing the values of S or by any other combination permitted by the method and the physical characteristics of the location is a matter of judgment. I am personally convinced that Mr. Bewley's value of 0.44 is much too low and applies more nearly to a case where the resistivity of the soil is fairly low and the ground plane is at a depth of 50 ft. Referring to Mr. Bewley's remarks that the numerical work was carried out in too much detail, I may say that this was intentional and was done to show that the actual wave of impressed voltage diminished very rapidly to about one-half value in 3 μsec. I have developed a shortcut method which has not been published by which the solution can be obtained approximately in about $^1/_4$ the time required for the detailed calculation given in the paper. This method checks with the longer method within 5 per cent.

With regard to the supposed geometric mean radius used in my calculations, the term geometric mean radius used is a misnomer. The method actually used is

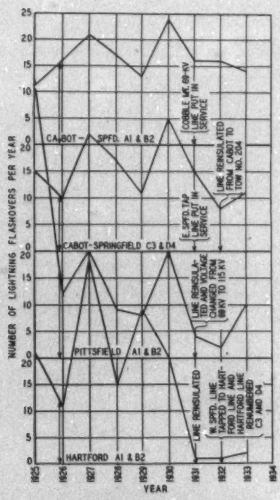


Fig. 2. Lightning flashovers per year on Turners Falls Power and Electric Company's 66-kv and 115-kv transmission lines

All tap lines are included. The Hartford line is included. The E5 line is not included. The West Springfield and Margaret Street lines are included with the Cabot-Springfield C3 and D4 line until tapped to the Hartford line

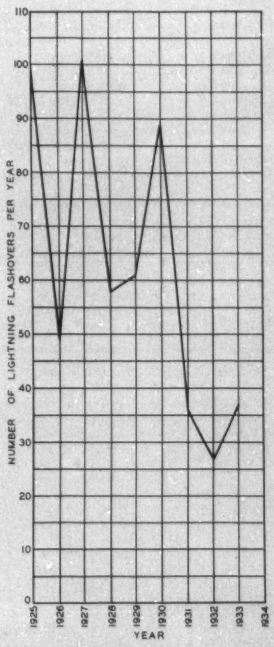


Fig. 3. Lightning flashovers per year on the Turners Falls Power and Electric Company's 66-kv and 115-kv transmission system

The entire Hartford-Agawam line is included. The E5 line is not included. Otherwise all the company's lines and taps are included

the same as that given by Mr. Bewley, the detailed calculations were omitted as being of no particular interest. An inadvertent omission was made in the calculations which Mr. Bewley points out in (5) of his discussion, but which does not materially change the final results.

Mr. G. P. McKearin's discussion is extremely interesting and furnishes important data regarding the performance of counterpoises. I have no data regarding the resistivity of the soil in the territory over which the lines he refers to pass or to put it another way, the average normal tower footing encountered along the right-of-way of the line, but I believe that in New England these values will generally be high. From this standpoint the greater part of the reduction in outages of the Agawan to Hartford line may be credited to the counterpoise. In the case of the Cabot to Pittsfield section of the line the larger share of the outages of the finally insulated line may be directly credited to imperfect shielding against which there is no effective measures for protection. It seems reasonable to ascribe 3 to 4 of the outages per year of this line to imperfect shielding. While the effectiveness of the counterpoise would have been more positively shown had the Cabot to Agawan A_1 and B_2 been insulated with 9 and 10 insulators, I think that Mr. McKearin's paper furnishes invaluable data in connection with the studies of the protective effect of counterpoises. It is to be hoped that he will follow this up with further records in future years and that others will be encouraged to install counterpoises on lines which are showing poor performance against lightning, so that more statistical data will be available.

Referring to the discussion of Mr. Cozzens, he has apparently misinterpreted my general comments on counterpoises. In my paper the idea of crowfoot or radial versus parallel counterpoises was discarded entirely and I pointed out that all counterpoises may be considered as composed of parallel and cross counterpoises, the former being parallel to the transmission line and the latter at right angles. Under the same conditions the parallel counterpoise and the cross counterpoise have the same surge impedance but the parallel counterpoise will not be so effective in lowering the potential of the transmission system due to its surge impedance on account of its mutual surge impedance with the overhead ground wires. It follows naturally that if this mutual surge impedance is zero or negligible there is no particular merit for the parallel counterpoise over the cross counterpoise except its continuity eliminates the possible ill effects of end reflections. In considering the surge impedance of wires leaving the tower footing in opposite direction, I have used the simple expedient of considering them as being in multiple without mutual surge impedance. I believe this approximation is all that is justified from a practical standpoint. There are some differences from my viewpoint in the fundamental conception of the problem in Mr. Cozzens' discussion which I am not prepared to discuss at the present time and which perhaps will be clarified with increased statistical knowledge of the problem.

Referring to Mr. Hertz's discussion, I wish to supplement it by remarking that when two or more ground wires or counterpoise wires are used a variation in the diameter of these wires over rather wide limits has little effect on the electrical characteristics. From an electrical standpoint, it apparently makes little difference what material is used for the overhead wires. The main requirements are that they shall have ample mechanical strength and shall be capable of withstanding the weather conditions without corrosion and be capable of withstanding the most severe direct stroke of lightning without being sensibly weakened by pitting. Since the breaking of a ground wire would probably cause as much disturbance to service continuity as the breakage of a line wire, a large factor of safety should be used in the ground wire construction.

Herman P. Miller, Jr., has kindly given the viewpoints of a radio engineer in his discussion of which I wish to express my appreciation. Some of the ideas he expresses have been already incorporated in our ground wire theory, particularly in connection with the effect of the tower on the potential of the system after being struck by lightning. The calculations are usually carried out by the method of reflections which, of course, is another way of saying that the natural period of the various elements is taken into account. The ideas expressed by Mr. Miller are worthy of careful consideration.

Replying to the discussion by P. B. Stewart and F. E. Sanford, I wish to say, although I have not read the article by N. Bogoiavlensky that I am rather skeptical as regards radio activity having any substantial effect on the frequency of thunderstorms. The effect of pointed profiles may be just as easily explained by the simple phenomenon of the wind currents being deflected upwards. Of course, we know that in many localities the isoceraunic level is much higher than the average as represented in the Government's isoceraunic map of the country. The topography of those localities will generally explain the reason but the frequency of thunderstorms has nothing to do with the design of a transmission line for a particular protective level. This is purely a matter of electrophysics. The problem of outages on the transmission line is a matter of protective level and probability based on the isoceraunic level of the territory through which the line passes. Naturally if a certain line performance is desired (outages per 100 miles per yr) where the isoceraunic level is high the line must be designed for a higher protection level whether it happens to be a 115 kv line or a 230 kv line. I have yet to find a case where the principles of ground wire protection properly carried out have not produced expected results. One of the principal troubles I have encountered in teaching the theory of ground wire protection is to get engineers to see the importance of adequate shielding. To be adequate, shielding must be practically 100 per cent. Another is the tendency of engineers to apply a voltage classification to transmission lines. Thus a 132 kv line is supposed to require 9 or 10 suspension insulators in a string. This is frequently stuck to whether the isoceraunic level is exceedingly high or not. There is no reason why if the 132 kv line is important enough it should not be insulated with 12 insulators or 14 if found necessary.

Corona Losses From Conductors of 1.4-In. Diameter

Discussion of a paper by Joseph S. Carroll, Bradley Cozzens, and Theo. M. Blakeslee, published in the December 1933 issue, p. 854–60, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 470–1.

T. F. Peterson: I hesitate to offer a discussion on this paper without first commenting on the stupendous nature of the work undertaken at the Stanford University laboratories. There are very few places where loss measurements could be made on conductors designed for such high voltage operation, and erected with normal line spacing and insulation. There is small wonder, then, that all conceivable variables have not been introduced into the work. The length of time available for the testing would certainly have militated against this, even if all types of conditions could have been created.

Personally, I feel that the authors have done a very valuable piece of work (even if only for academic reasons) in so clearly presenting the influence of grease coatings on the total corona loss. This may be viewed as due to dielectric loss in the dielectric (grease) interposed in the electric circuit. I think it should be of interest to note that similar phenomena have been observed at Massachusetts Institute of Technology where power factor increase of nominally "zero" loss condensers has been attributed to oxidation of surfaces.

It seems obvious that losses due to grease films will diminish with time and weathering. The authors point out that corona loss may be modified by bird deposits. Certainly normal weathering will cause some changes. In view of this, is it economical to clean conductors? Since we are concerned with the capitalization of losses over a long period, is it justifiable to put too much weight on loss measurements made under ideal conditions? In reality the losses are almost the same for all conductors for voltages considerably in excess of the operating value. Real differences are brought out only at very high voltages. In this range the curves are easily shifted by change in surface conditions and, for similar surface treatment or time of weathering, the percentage shifts may vary considerably depending on designs. Is it not quite possible, therefore, that mechanical features are far more important than any differences brought out in the paper?

For the benefit of one of the previous discussors, who raised the question of rain loss, may I point out that work in which I took part about 10 years ago (see "Power Measurements at High Voltages and Low Power Factors," by J. S. Carroll, T. F. Peterson, and G. R. Stray, A.I.E.E. Trans., v. 43, 1924, p. 1130–8) indicated that, although relatively smooth surfaced, locked wire conductors showed lower clear weather losses than stranded conductors of like size; the former developed a much greater percentage increase in loss during rain. I don't know whether this could be attributed to the fact

that each drop of water on a smooth surface caused a greater loss than on stranded surface, or whether the frequency of appearance of drops along the conductors was such as to produce results. As a matter of passing interest it might be pointed out that design *F* had a radius of curvature of each segment less than the radius of the conductor in order to "submerge" the edges and also to create a scalloped effect designed to approach "ordinary strand" rain characteristics.

T. J. Little and L. F. Hickernell: The data presented in the paper are very interesting from an academic point of view and represent a valuable contribution in the study of corona loss. It is believed, however, that certain of the conclusions warrant some discussion.

Conclusion 1 states that "The importance of the die grease as affecting corona loss was further emphasized by the 1933 tests."

It is assumed that the *degree* of importance assigned to this condition applies principally to the accuracy of the results obtained in the laboratory.

Conclusion 2 states that "Complete grease removal either by thoroughly washing, or by washing in connection with a period of aging, is necessary to obtain consistent corona loss data."

It is again assumed that this applies directly to laboratory test results since the authors have shown in their previous paper (A.I.E.E. TRANS., v. 52, 1933, p. 58, Fig. 5) that cable which had aged 7 months showed lower corona losses than at its initial washed condition.

Conclusion 3 states that "Both gasoline and soap and water washings are necessary to accomplish complete cleaning of the cables."

Presumably this applies to the conditioning of samples for laboratory tests. Cases have been brought to our attention where radio interference (a measure of corona loss), noticeable upon erection of the line, has practically vanished after the first few months of operation as a result of the aging of the conductor.

Conclusion 4 states that "Rain greatly increases the corona loss from conductors, but there appears to be little correlation between loss and rainfall rate."

Of more importance than the correlation between loss and rate of rainfall would be a comparison of the loss during stormy weather among the several types of cable constructions. It is to be regretted that the investigation was not extended to include comparable data during stormy weather on *all* of the samples submitted.

Conclusion 5 states that "While the differences in the corona loss for separate types of 1.4-in. stranded conductors are slight, the tests indicate that the size of the outside strands and the neatness of the stranding are factors affecting corona."

It is quite generally accepted that the smaller the size of strand, the lower the loss and neatness of stranding naturally tends toward a more uniform surface.

Conclusion 6 states that "Smooth, properly formed segment conductors have a lower corona loss than stranded conductors of the same diameter."

Reference to Fig. 13 shows very slight difference in losses in the operating voltage range and these losses would undoubtedly be reduced after aging to a value of small or no economic importance.

Reference to Fig. 13 also shows that Type *F* (a segmental conductor) has higher losses than Type *B* (a stranded conductor) which emphasizes *Conclusion 7* stating that "The smoothness of the segments is of prime importance in eliminating loss from a segment type of conductor."

Power Limits of 220-Kv Transmission Lines

Discussion of a paper by Alex A. Kroneberg and Mabel Macferran published in the November 1933 issue, p. 758–66, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 473–5.

R. C. Bergvall: The effectiveness of series stabilizing resistance in preventing pull-out during the transient condition was checked on a 100-kva system but space limitations did not enable me to present the detailed test data in my January 1931 paper. The tests checked calculations very closely and on the particular system tested, over 50 per cent additional power could be delivered by its use without loss of synchronism during severe faults, which increase is of the order of magnitude calculated by the authors.

The former transient power limitations have been removed to such an extent by the various methods proposed that in the future consideration will have to be given toward obtaining a proper balance between the machine and system characteristics that control the transient and steady state limits.

Present methods of calculation have been checked by experience to a sufficient extent that system performance with the series stabilizing resistance can be determined with assurance, and if desired a further check could be made on properly portioned miniature systems now available.

A. A. Kroneberg: No final decision has been made in regard to the design of the Boulder Dam transmission system for the Southern California Edison Company, Ltd.

We are fortunate in Southern California in that lightning is responsible for a very small percentage of short circuits and faults. Therefore a lightning proof line is not a solution of the transient stability problem.

The problem presented by S. M. Zubair can be solved with integraph curves if the following modifications are performed. Equation 8 of appendix IV when expanded becomes

$$R \sin \delta + S \cos \delta - E = - J$$

where

$$R = \frac{E_1 E_2}{Z_{12}} \cos \alpha_{12}$$

$$S = \frac{M_1 - M_2}{M_1 + M_2} \frac{E_1 E_2}{Z_{12}} \sin \alpha_{12}$$

$$E = \frac{M_2(P_1 - P_{11}) + M_1(P_{20} - P_2)}{M_1 + M_2}$$

$$J = \frac{M_1 M_2}{2\pi f(M_1 + M_2)}$$

This equation is further modified

$$B \sin (\delta + \beta_1) - E = - J \frac{d^2\delta}{dt^2}$$

where

$$B = \sqrt{R^2 + S^2}$$

$$\beta_1 = \tan^{-1} \frac{S}{R}$$

Then (introducing new variables)

$$\psi = \delta + \beta_1;$$

$$\tau = t \sqrt{\frac{B}{J}};$$

$$\frac{d^2\psi}{d\tau^2} + \sin \psi = \frac{E}{B}$$

which can be solved with integraph curves. It will be necessary, however, to correct the equations of appendix II.

$$A' = \int_{\delta_0}^{\delta_1} E d\delta - \int_{\delta}^{\delta_1} B \sin (\delta + \beta_1) d\delta$$

$$A'' = \int_{\delta_1}^{\delta_2} C \sin (\delta + \beta_2) d\delta - \int_{\delta_1}^{\delta_2} F d\delta$$

also

$$\psi_0 = \delta_0 + \beta_1$$

$$\psi_1 = \delta_1 + \beta_1$$

The constructive criticism and suggestions appearing in the discussions are accepted by the authors with thanks.

Power Limits of Synchronous Machines

Discussion of a paper by Edith Clarke and R. G. Lorraine published in the December 1933 issue, p. 780–7, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 475–7.

Edith Clarke and R. G. Lorraine: We agree with H. L. Hazen that steady-state stability is fundamentally a dynamic problem. Nevertheless, it differs from transient stability in that the disturbance (whether an increment of load or a change in angle) is slowly rather than suddenly applied. Consequently, when an increment of load is applied, there is a slow change in the angular positions of the machines of the system until they reach new positions of stability or lose synchronism. During these slow changes the electrical torque is determined by the synchronous reactances of the machines.

In accordance with the usual assumption of constant field currents during a test for steady state stability, the action of voltage regulators is neglected. We have assumed for the multimachine system that one generator only supplies the additional in-

crement of power required. Although it is not so stated in the paper, this is equivalent to the assumption that this generator is equipped with automatic frequency control, while all other machines whether generators, motors, or condensers, have fixed mechanical loads. Under this assumption, if the system is to remain in equilibrium under steady conditions and normal frequency, these "other machines" must take up angular positions such that their electrical power is equal to their mechanical power, and since their mechanical load is constant they will of necessity be fixed power machines.

Professor Dahl has discussed the advisability of assuming all other machines fixed in phase with respect to each other when an increment of load is added to one machine of the system. For the general case this can be true only in the first instant after an increment of load is suddenly applied.

In the case of a generator supplying power over a long transmission line to a load center, the assumption of constant phase angles between the machines in the load area will, as Professors Dahl and Hazen both point out, give a fair approximation to the truth. The assumption that the machines in a group remain fixed in phase with each other is equivalent to replacing the group by a single equivalent synchronous machine (see Appendix III). The given system is, in effect, reduced to a two-machine system. The error in treating the system as a two-machine problem will be small when the combined impedance of the generator, transformers, and line (or lines) is large relative to the equivalent load impedance; but when this is not the case, the error may be large.

We are heartily in sympathy with Professor Dahl's statement that agreement in these matters is important. The tests he contemplates making should be of considerable value in evaluating the various factors involved.

The idea of fixed power machines follows directly from the assumption of automatic frequency control on the generator which is being tested. This assumption will, we believe, give a lower stability limit than would be obtained if the required increment of load were supplied by more than one machine. In developing a criterion and in making simplifying assumptions we have endeavored to obtain stability limits which will never be higher than those which will be obtained in actual practice by gradually increasing the system load until synchronism is lost.

For systems in which maximum power occurs on the motor before it does on the generator as the angle between generator and motor increases with the addition of load in the test for stability, our criterion will give satisfactory results. For systems in which maximum power occurs on the generator before it does on the motor, stability limits obtained by our method may be too low.

Mr. Crary in his discussion has explained why this is so for two machine systems. For the 2-machine problem with a shunt impedance load he gives the criterion for stability that

$$-\frac{dP_2}{d\delta_{12}}\frac{1}{H_2} \text{ must be greater than } -\frac{dP_1}{d\delta_{12}}\frac{1}{H_1}.$$

We agree with this criterion and advocate its use for 2-machine systems in which maximum power occurs on the generator before it does on the motor. A system of this type would be a generator supplying power to a shunt impedance load over a transmission line with a condenser at the receiving end.

We would point out that Mr. Crary in his discussion and in the subtitles under his figures gives conditions which are not necessarily sufficient. For example, in Fig. 4(a) the system is unstable because

$$-\frac{dP_2}{d\delta_{12}}\frac{1}{H_2} \text{ is less than } -\frac{dP_1}{d\delta_{12}}\frac{1}{H_1}.$$

It will not necessarily be unstable when $H_2 > H_1$ unless at the same time

$$-\frac{dP_2}{d\delta_{12}} \text{ is less than or equal to } -\frac{dP_1}{d\delta_{12}}.$$

Power Limit of a Transmission System

Discussion of a paper by W. S. Petersen published in the August 1933 issue, p. 569–72, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 477–8.

W. S. Peterson: Due to the fact that the publication of the paper "Power Limit of a Transmission System," by W. S. Petersen, was made without inclusion of the mathematical development, it is well to point out that the calculation of the permissable duration of short circuit as given in the third portion of Table II has some limitations that come from simplifying assumptions. These limitations are not such as to interfere with the great majority of calculations and make themselves evident in items 156 and 157, by producing values greater than unity so that items 158 and 159 cannot be determined.

The items 143 to 161 are to calculate the duration of short circuit after having determined δ_1. It involves a solution of the following integral.

$$t = \frac{1}{\sqrt{4\pi f}}\int_{\delta_0}^{\delta_1}\frac{d\delta}{\sqrt{115\delta + 95\sin(\delta + \theta_{Fb}) - 97\sin(\delta - \theta_{Fb}) + 119}}$$

where the underlined (or italic) numbers are items in the tabulation. This was solved by assuming

$$\theta_{Fb} = \pi/2$$

and a further approximation that

$$\cos\delta = 1 - \frac{\delta^2}{2.3}.$$

For some unusual cases this did not give absolutely perfect results. Where there is doubt about the accuracy, the integral given above can be solved by obtaining the area under a plotted curve between the limits of δ_0 and δ_1.

An Experimental Ignitron Rectifier

Discussion of a paper by L. R. Ludwig, F. A. Maxfield, and A. H. Toepfer published in the January 1934 issue, p. 75–8, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 488–9.

J. J. Linebaugh: The experimental rectifier described by L. R. Ludwig and associates is an interesting and serious attempt to broaden the field of the mercury arc rectifier by raising the efficiency and to improve operation by simplification and reduction of number of arcbacks.

The most radical departure from accepted design seems to be placing the anode and cathode so close together without any mechanical protection from mercury splash and with a direct straight path from cathode to anode. This departure gives a very low arc drop and if feasible from an arcback standpoint, will make the rectifier a direct competitor with the synchronous converter at 220 to 300 volts direct current.

It would be interesting to know if the ignitron rectifiers described were loaded much beyond the amperes mentioned or to destruction, with a brief statement covering their behavior and what parts were affected or destroyed.

I trust this work will be continued, increasing the capacity of the tank and voltage range and report made to the Institute through a paper at some later date.

L. R. Ludwig: The authors were much interested in obtaining the comparative data offered by C. C. Herskind. The comparison which he has made serves very nicely to illustrate the advantages of the ignitron as a rectifier. For approximately the same rating as he has stated, the volume and the arc drop are both considerably less in the case of the ignitron. In answer to his question, we see no reason why the ignitron rectifier cannot be built for higher voltages and higher current ratings than those given in the paper. As a matter of fact, of the particular units mentioned, satisfactory tests have been made up to 600 volts and 600 amperes since the paper was written. The cooling coil in the cathode has given some advantage in reducing the arc drop. Some variations and results have been obtained but a reduction of from one to three volts is customary.

In reply to the question of Mr. Haar, no observation has been made directly as to vibration of the anode stems. It has been found however, that as originally built, they were somewhat light, and at the present time, several detailed improvements in the design have been made, of which this is one.

The authors agree with Mr. Linebaugh in feeling that the ignitron will considerably broaden the field of the mercury arc rectifier. The 6 anode unit described in the paper was tested to destruction. The cathode structure seems quite adequate for currents very much larger than the figures given. Difficulty was obtained with the

anode structures however, principally due to the leads burning at their junction of the shank. Some changes in design have been made to improve these conditions and so far, tests seem quite satisfactory with no destruction under conditions of operation such as the ignitron will be required to fill.

Equivalent Reactance of Synchronous Machines

Discussion of a paper by S. B. Crary, L. A. March, and L. P. Shildneck, published in the January 1934 issue, p. 124–32, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 484–8.

Charles Kingsley, Jr.: In analyzing engineering problems it is frequently helpful to set up an "equivalent" model of the actual circuit or piece of apparatus which we are attempting to analyze. This is the method of attack used in the paper under discussion. The authors set up an "equivalent" unsaturated synchronous machine to serve as a model for the solution of the more complicated saturated machine whose operating characteristics are desired. The particular operating characteristic with which the paper is chiefly concerned is the calculation of the synchronizing power coefficient, $dP/d\delta$.

Whenever we use an "equivalent" model to replace an actual piece of apparatus, we must be sure that the 2 are actually equivalent in all respects which will affect the applicability to the actual piece of apparatus of the results obtained from the analysis of the model. Hence let us compare the actual, saturated synchronous machine with its "equivalent" unsaturated model in order to determine in what respects the 2 are equivalent and where they differ. This may be done more readily for the relatively simple cylindrical rotor machine than for the more complicated salient-pole machine. I shall therefore confine my discussion to the cylindrical rotor case.

On the basis of the assumptions stated in the paper, the vector diagram of Fig. 1 of the paper (p. 125 of ELECTRICAL ENGINEERING for January 1934) may be drawn for a cylindrical rotor machine. Within the accuracy of these assumptions the angle δ is the true phase position of the rotor of the actual saturated machine with respect to the system voltage e_s. The difficulty in analyzing the actual machine arises due to the occurrence of the saturation factor k in equations developed for the actual machine. The saturation factor k is a variable and must be treated as such in any calculations requiring differentiation.

In the paper under discussion this situation is simplified by replacing the actual machine by an "equivalent" unsaturated machine which may be considered to have a constant excitation e_{eq} and a constant reactance x_{eq} for differentially small changes away from any given operating point. The 2 machines have the same resistance, leakage reactance, and air gap voltage, and at any given operating point they are indistinguishable as far as terminal operating conditions are concerned. However, they are not alike if we cross the air gap and consider rotor phase positions; i. e., the rotor phase position angle δ_{eq} of the unsaturated machine with respect to the system voltage e_s is not the same as the angle δ of the actual machine, as is clearly shown in Fig. 1 of the paper. Hence the synchronizing power coefficient $dP/d\delta_{eq}$ of the unsaturated machine is not the same as the synchronizing power coefficient $dP/d\delta$ of the actual machine unless the difference between the angles, i. e., $\delta - \delta_{eq}$, remains constant for a differential change in load. Concerning this apparently important point the paper is silent. In the paper, in eq 14 and the sentence following it, it is apparently assumed that $dP/d\delta = dP/d\delta_{eq}$. If this is true, the burden of proof rests upon the authors of the paper under discussion. If it is not true, an approximation is introduced, the importance of which should be discussed.

That the synchronizing power coefficient $dP/d\delta_{eq}$ of the "equivalent" machine is not always equal to the synchronizing power coefficient of the actual machine may readily be seen by considering the following simple example. Consider a cylindrical rotor synchronous machine with negligible resistance directly connected to an infinite bus of constant voltage e_t and with constant excitation e_d. The power-angle equation for this machine is:

$$P = \frac{e_d e_t}{x_d - x_l + kx_l} \sin\delta \qquad (1)$$

This equation is exactly like eq 12 in the paper with $x_e = 0$ and therefore $e_s = e_t$. Differentiating with respect to δ, and remembering that k is a variable:

$$\frac{dP}{d\delta} = \frac{e_d e_t}{x_d - x_l + kx_l} \cos\delta - \frac{e_d e_t x_l}{[x_d - x_l + kx_l]^2} \sin\delta \frac{dk}{d\delta} \qquad (2)$$

This is the correct expression for the synchronizing power coefficient of the actual machine. The difficulty arises in evaluating the term $dk/d\delta$, as the paper points out. But suppose the machine were operating as a synchronous condenser. Then $\delta = 0$, $\cos\delta = 1$, and $\sin\delta = 0$, and the term involving $dk/d\delta$ drops out. Hence we obtain for the synchronzing power coefficient of an actual saturated synchronous condenser with constant field current and directly connected to an infinite bus:

$$\frac{dP}{d\delta} = \frac{e_d e_t}{x_d - x_l + kx_l} \qquad (3)$$

Consider the machine used as an example on p. 127 of the paper. Let us operate the machine as a synchronous condenser at rated kilovolt-amperes and normal terminal voltage. Then

$e_t = 1.00 \quad i = 1.00 \quad \phi = \theta = 90$ deg

$x_d = 1.11 \quad x_l = 0.11 \quad x_d - x_l = 1.00$

$e_i = e_t + ix_l = 1.11$

$e_d = 2.4$ (assumed)

$k = 1.27$ (from Fig. 6)

$e_d = ke_i + i(x_d - x_l) = 2.41$

$1 + a/b = 2.68$ (from Fig. 7)

$kx_l = 0.14 \quad x_d - x_l + kx_l = 1.14$

Therefore

$$\frac{dP}{d\delta} = \frac{2.41 \times 1.00}{1.14} = 2.11$$

This is the synchronizing power coefficient of the actual synchronous condenser to within the accuracy of our fundamental assumptions.

(I have used this same method to calculate the no-load synchronizing power of a 44-kva cylindrical rotor machine with the following constants and load conditions:

$e_t = 1.20 \quad i = 1.00 \quad \delta = 0$

$x_d = 0.97 \quad x_l = 0.11 \quad r = 0.02$ (neglected)

$k = 1.30 \quad a/b = 1.77$

For this machine the calculated value of synchronizing power is 4 per cent less than that obtained by measuring the slope of the experimentally determined power-angle characteristic. Hence, this calculation can be relied upon to within engineering accuracy.)

According to eq 14 of the paper:

$$\frac{dP}{d\delta_{eq}} = \frac{e_{eq} e_t}{x_{eq}} \cos\delta_{eq}$$

when $x_e = 0$. And according to eq 5 of the paper:

$$x_{eq} = x_l + \frac{x_d - x_l}{k\left[1 + \frac{a}{b}\right]}$$

for a synchronous condenser. Hence, for the machine used as an illustration in the paper:

$$x_{eq} = 0.11 + \frac{1.00}{1.27 \times 2.68} = 0.40$$

$e_{eq} = e_t + ix_{eq} = 1.40$

$\delta_{eq} = 0, \cos\delta_{eq} = 1.00$

Therefore

$$\frac{dP}{d\delta_{eq}} = \frac{1.40 \times 1.00}{0.40} = 3.50$$

But

$$\frac{dP}{d\delta} = 2.11, \text{ as previously shown.}$$

Hence, for this case, the discrepancy between the synchronizing power coefficient $dP/d\delta$ and the synchronizing power coefficient $dP/d\delta_{eq}$, as calculated by eqs 5 and 14 of the paper, is 66 per cent of $dP/d\delta$.

Results obtained by the application of the methods of the paper, as in eq 14 and Fig. 9 of the paper, give the synchronizing power coefficient $dP/d\delta_{eq}$ of the "equivalent" machine, which in itself does not appear to have any particular significance if it may differ so widely from the synchronizing power coefficient $dP/d\delta$ of the actual machine.

It may be argued that the above case is not one of practical importance, and perhaps it is a case in which the difference between $dP/d\delta$ and $dP/d\delta_{eq}$ is unusually large. However, if a discrepancy of this magnitude occurs for any case, it is sufficiently significant to warrant my request that the authors of the paper justify their apparent assumption that the results obtained for the synchronizing power of the "equivalent" machine are directly applicable to the actual machine.

R. H. Park: Messrs. Crary, Shildneck, and March have presented an interesting extension of synchronous machine theory which is directly applicable to the problem of steady state stability, and which should be of considerable practical utility. As an example of its usefulness it would appear that "equivalent reactance" would be preferable to short-circuit ratio as a means of specifying degree of inherent steady state stability. The usefulness of the paper in this or other ways, however, would be increased if a further analysis were presented in which certain of the assumptions employed were carefully examined, and the method of computing curves of the type shown in Fig. 5 of the paper explained.

While well suited to the purpose for which it was intended the method of analysis presented nevertheless suggests the desirability of a more general analysis which is not limited to steady state conditions and which does not require any assumption in regard to the effects of the system to which a machine may be connected.

Now it may be noted that actually saturation does not interfere with the linear relations obtaining between small changes in the flux linkages and currents in the various circuits of a machine, but may rather be regarded as merely modifying the constant coefficients which obtain when saturation is absent. Saturation will, however, introduce an element of assymetry under other than no-load conditions and consequently requires the introduction of coefficients which are absent or which may be thought of as having zero value when saturation is absent. Thus for a machine with no rotor circuits other than the field but with both direct and quadrature axis field windings the equations for armature and rotor flux linkages may be written in the form,

$$\psi_d = m_{fmd}i_{fd} + m_{fmq}i_{fq} + m_{mdmd}i_d + m_{mqmq}i_q$$
$$\psi_q = m_{fdmq}i_{fd} + m_{fmq}i_{fq} + m_{mdmq}i_d + m_{mqmq}i_q$$
$$\psi_{fd} = m_{fd}i_{fd} + m_{fd}i_{fq} + m_{mfd}i_d + m_{mfd}i_q$$
$$\psi_{fq} = m_{fd}i_{fd} + m_{fd}i_{fq} + m_{mfq}i_d + m_{mfq}i_q$$

and imply the existence of per unit vector operators of the form, $x = \begin{pmatrix} x_d & x_{dq} \\ x_{qd} & x_q \end{pmatrix}$

It would appear that in some cases the use of the assymetric equations given above, which are independent of the system to which the machine is connected, and which include transient as well as steady state conditions would possess advantages. Also, there is a use for this type of theory even when saturation is absent. Thus, although the capacitor motor, for example, may be analyzed by applying alternating current to the fields of a synchronous machine with the armature short circuited, the same thing cannot be done for a shaded pole motor unless the conception of an assymetrical magnetic structure is introduced.

In connection with the flux linkage equations given it may be helpful to note that if absolute direct and quadrature quantities be defined in accordance with the relations,

$$Q_d = \sqrt{\tfrac{2}{3}}\left\{ Q_a \cos\theta + Q_b \cos(\theta - 120^\circ) + Q_c \cos(\theta + 120^\circ) \right\}$$

$$Q_q = -\sqrt{\tfrac{2}{3}}\left\{ Q_a \sin\theta + Q_b \sin(\theta - 120^\circ) + Q_c \sin(\theta + 120^\circ) \right\}$$

rather than in the usual way all of the reciprocal mutal coefficients are equal, i. e., not only are $m_{mqmd} = m_{mdmq}$, $m_{fdfq} = m_{fqfd}$ and $x_{dq} = x_{qd}$, but also $m_{fdmd} = m_{mdfd}$, $m_{fqmd} = m_{mdfq}$, $m_{fdmq} = m_{mqfd}$, and $m_{fqmq} = m_{mqfq}$. The usefulness of this change in form, it may be added, is not restricted to cases in which assymetry is present.

In connection with the analysis of shaded pole or similar assymetric machines it should be noted that obliquity in the axes *fd* and *fq* does not require obliquity in the axes *d* and *q*. To avoid confusion however, replacement of the notation *fd* and *fq* by *f1* and *f2* would seem desirable. Evidently extension to a multiplicity of assymetric field windings is possible.

G. C. Dahl: This paper represents the first attempt at a rational analysis of the effect of saturation on the synchronous reactance of salient pole and nonsalient pole machines. The results are valuable and the methods presented give the equivalent saturated reactances to be used under specified conditions of load. Excepting the performance charts which correctly include the effect of saturation, previous schemes of selecting the proper saturated reactance have, as the authors point out, been largely empirical. Nevertheless it is believed that some of these may be sufficiently accurate and give calculated results to engineering accuracy.

In this connection I should like to call attention to an extremely simple *empirical method* which I have occasionally used for more than a dozen years with quite satisfactory results. The method is particularly applicable to nonsalient pole machines but also may serve as an approximation for salient pole machines. In either case it involves the representing of the machines by a single synchronous reactance and the use of a voltage (excitation voltage) behind this reactance selected from the open circuit magnetization curve at the field current at which the machine is operating.

The air gap voltage under the particular operating conditions considered is used as the criterion of the degree of saturation in the machine. From an open circuit and a zero power factor curve synchronous reactance for various values of terminal voltage (and corresponding excitation voltage) may be determined and the air gap voltage for each of these values computed. A curve of synchronous reactance versus air gap voltage may then be plotted, as indicated in Fig. 1 of this discussion, which also shows the characteristics of the machine considered. Data for the synchronous-reactance curve are given in Table I of this discussion.

In solving a steady state synchronous machine problem by the use of the saturated synchronous reactance, the air gap voltage of the machine is first calculated for the desired operating condition by adding the leakage reactance drop vectorially to the terminal voltage. The curve of synchronous reactance versus air gap voltage (Fig. 1) is entered and the proper reactance selected. This then is used in the further solution of the problem using, as already mentioned, an excitation voltage directly obtained from the open circuit magnetization curve at the field current at which the machine operates.

The method disregards any effect of power factor in that the synchronous reactance is obtained under zero power factor conditions. This approximation, however, does not seem to be serious. The effect of current magnitude is more important. Fig. 2 of this discussion shows a family of synchronous-reactance curves for the same machine for various values of current. It will be noted that although there is some

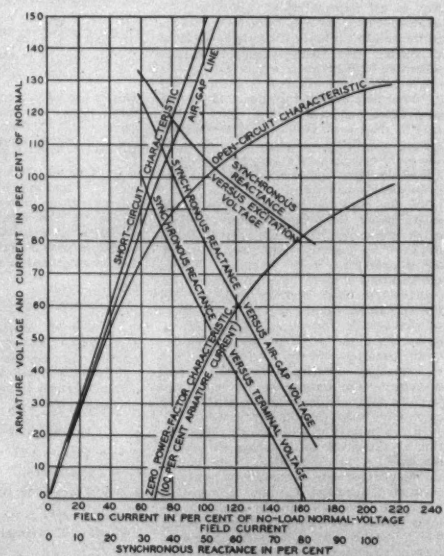


Fig. 1. Synchronous reactance vs air gap voltage

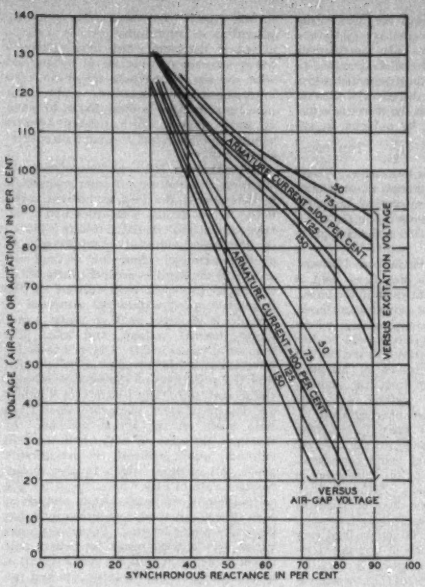


Fig. 2. A family of synchronous reactance curves

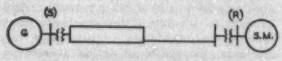


Fig. 3. Diagram of 2-machine system

difference in the values of synchronous reactance, its variation with current is not excessive. It is believed that in many problems, therefore, especially such where the general data otherwise may be uncertain, it is sufficiently accurate to use synchronous reactances obtained on the basis of 100 per cent current under all conditions.

The method, which admittedly is empirical, has been checked by a number of field current calculations for machines of various types. Over the whole range of loads as well as power factors the check between field currents so calculated and those obtained by more correct analysis (for instance, by the general method or by charts) has been very satisfactory. Certain test values have also agreed well with the calculated results.

The method has further been checked by applying it to the calculation of the power limits of 2-machine systems. Results from the system shown in Fig. 3 of this discussion, consisting of a synchronous generator supplying power to a synchronous motor over a transmission circuit involving a long line with step up and step down transformers, may be referred to as representative. Using synchronous reactances selected as above, and the general method presented by Edith Clarke in her paper "Steady-State Stability of Transmission Systems" (A.I.E.E. Trans., v. 45, 1926, p. 22) the maximum power which could be transmitted to the motor under conditions of normal (100 per cent) bus voltages was obtained by a series of trial-and-error computations. The power of the machines had to be assumed initially in order that the synchronous reactances and the field currents and excitation voltages could be determined. A value of maximum power was calculated next, and it was checked whether this value was consistent with the initial assumption. If not, adjustments were made involving new and improved values of synchronous reactances and excitation voltages and the maximum power recalculated. In this manner a correct result was ultimately obtained.

The same system next was analyzed by graphical methods in which the machines as well as the transmission circuits were represented by appropriate performance charts. The machine charts included the effect of saturation. Assuming a value of load at normal bus voltages, a system characteristic in terms of power versus voltage at the motor terminals (stability curve) was obtained by proper manipulation and superposition of the various charts. Repeatedly using other "initial" power values, several such curves (as a rule 3 or 4 are sufficient) were determined. By extrapolation of the maxima of these separate power voltage characteristics the maximum power at normal bus voltages was obtained. The graphical solution gave essentially the same value as that calculated analytically by the synchronous-reactance method described.

Table I—Calculation of Data for Synchronous Reactance Curves
(Normal armature current at zero power factor lagging)
(All quantities in per cent)

Field Current	Excitation Voltage	Terminal Voltage	Leakage Reactance Drop	Air Gap Voltage	Synchronous Reactance
0	0	−70.2	23.2	−47.0	70.2
14.5	30.0	−61.3	23.2	−42.1	81.3
46.0	60.0	−31.8	23.2	− 9.6	91.8
68.5	81.2	0.0	23.2	23.2	81.2
100.0	100.0	41.6	23.2	64.8	58.4
123.0	108.8	61.6	23.2	84.8	47.2
140.5	114.2	72.0	23.2	95.2	42.2
161.0	119.9	81.2	23.2	104.4	38.7
193.0	126.4	92.0	23.2	115.2	34.4
228.0	130.8	100.0	23.2	123.2	30.8

DATA ON MACHINE

1. 37.5-kva (30 kw at 0.8 power factor), 240-volt, 3-phase (Y-connected), 60-cycle, 1,200-rpm, salient-pole alternator (G. E. Serial No. 305,977).
2. Short circuit ratio = 1.46
3. Armature resistance per phase = 0.053 ohm (3.44 per cent)
4. Armature leakage reactance (by Potier method) = 23.2 per cent
5. Ratio of pole arc to pole pitch = 0.67
6. Field current to give normal voltage on open circuit = 3.73 amp.

S. B. Crary, L. A. March, L. P. Shildneck: We consider the method of testing for equivalent reactance which Mr. Butler has presented in his discussion a valuable contribution to the technique of testing for equivalent reactance of salient-pole machines. It provides a simple method for testing for the relative values of equivalent reactance of different machines under conditions closely approximating their actual load conditions—full load field current and full load fundamental air gap density. Some correction is necessary, especially in the case of unity power factor machines, to allow for the difference in the direct axis flux, ε_{ia}, and the total flux, ε_i. However, even in the case of unity power factor machines the method suggested by Butler will indicate very well the relative steady-state stability characteristics of the machines. We agree with Mr. Butler that the A.I.E.E. should consider standardizing the definition of leakage reactance.

We agree with Mr. Dwight that, "a very satisfying test for the over-all accuracy for the method of calculation is to show maximum power in kilowatts, by test and by calculation." Unfortunately, the tests of pull-out power which we have available are not very satisfactory. The test data that we have were made under conditions such that the machines pulled out of synchronism with very little or no saturation, and no measurement was made of their power-angle displacements before they reached the pull-out angle. The data we have could all be checked very well neglecting saturation entirely or including only a slight correction for it. We expect to have available in the near future tests in which appreciable saturation exists at pull-out and thus check the method under the conditions suggested by Mr. Dwight. All of our checks with tests have been made by comparing test and calculated excitations and volt-ampere characteristics. These comparisons have been very satisfactory.

Mr. Dwight's results in determining the natural frequency of oscillation of a synchronous machine should prove interesting.

However, unless the frequency of oscillation is very small, the transient reactance and circuit time constants will also play an important part in determining the natural frequency, so that an "adjusted" value of synchronous reactance cannot be used directly in its determination.

It should be emphasized that the equations Mr. E. H. Freighburghouse develops are for the particular case of constant power factor and should not be confused with the general equations for x_{sq}. However, there are numerous constant power factor cases such as condensers, marine synchronous motors, and generators, etc., so that these equations are very valuable. They are also very interesting from the test possibility standpoint. The condition of constant power factor can be very easily realized in test and x_{sq}, therefore, readily obtained under these conditions. Mr. Butler's discussion is an example of the use of a zero power factor volt-ampere characteristic to approximately determine the equivalent reactance of a salient pole machine.

Mr. Beckwith points out the importance of properly analyzing for the effect of saturation. Mr. Beckwith states, "the relative unimportance of transient stability will allow normal operation to be much closer to the steady-state stability limit than in most other comparable systems." This statement, we believe, will be applicable to more and more systems in the future. With the types of breakers and relays now available, the transient limitations are approaching more closely those of steady-state. This will make highly desirable in the future a more accurate determination of the steady-state limits.

We cannot agree with Mr. Beckwith that the saturation curve to be used in determining the equivalent reactance differs from the no load saturation curve only by an amount due to the change in field form with change in load, for two reasons. First, if appreciable saturation exists in both the stator and the rotor it is necessary to consider the fluxes in the rotor and stator separately because of the difference between, e_{1d}, the direct axis flux, and e_t the total air gap flux. Second, in the case of salient pole machines, the amount of saturation in the rotor depends considerably upon the field leakage flux. The total field flux may change as much as 30 or 40 per cent depending upon the load.

By neglecting these important factors, Mr. Beckwith obtains the relatively simple equation given in his discussion for the equivalent reactance. This equation is similar to equation (11) of the paper and is identical with that suggested by C. A. Nickle and referred to in reference 2 of the paper, except that Mr. Beckwith uses e_{1d} rather than e_t, on the no load saturation curve to obtain the ratio of the slope of the saturation curve to the slope of the air-gap line. Beckwith's Fig. 5 shows very clearly and ingeniously the wide range that x_{sq} may be expected to take with change in the operating condition. His Fig. 6 is further confirmation that x_q or $x_{q(sq)}$ has very little influence on the actual pull-out power. However, this should not be interpreted to indicate that the effect of quadrature axis flux in influencing the value of direct axis flux is unimportant. However, the error involved in making this latter approximation can be easily evaluated by means of equations (C-9) and (C-14) in the paper. The approximate equation which includes all factors (C-14), differs from the approximate equation which would be obtained if the effect of quadrature axis saturation on the direct axis flux were neglected (C-9), by a factor in the denominator equal to $k_1 \frac{a_1}{2b_1}$. This factor depends only on stator saturation. Therefore, if the stator saturation is small compared with the rotor saturation, the effect of quadrature axis saturation on the direct axis flux can be neglected without appreciable error.

Mr. Evans compares the use of an empirical method which has been used in stability work with that given in the paper. This method, as most empirical methods, cannot be expected to give correct results over the whole range of operation or does not provide a satisfactory method of predicting the performance of machines whose designs depart from the conventional. Mr. Evans' method will tend to give too low values of equivalent reactance, especially if there is less than normal saturation existing in the machine at the operating point being considered. This is also borne out by the table given in Mr. Kilgore's discussion. Although Figs. 8 to 11 do not show the effect of change in field current on the equivalent reactance, Figs. 5, 6, 7, 10, and 11 can be used very readily to obtain values of equivalent reactance with field current as a variable.

We agree with Mr. Evans that the equivalent reactance will not supplant the use of short circuit ratio as an index for measuring the sizes of machines and transient reactance for determining their transient stability characteristics. It was not intended for such purposes. However, we do believe that projects similar to the one mentioned by Mr. Beckwith and systems similar to those now in operation which will not depend upon exciter performance to hold them in synchronism will continue to be built and that the equivalent reactance or some similar characteristic of the machine will be used to determine the increasingly more important steady-state stability limits.

Mr. Kilgore, as does Mr. Evans, apparently favors the use of empirical formulas for taking into account the effect of saturation. We believe that a rational method for the calculation of equivalent reactance when the necessary data is available leaves little justification for the use of empirical methods. The use of empirical methods, which do not show properly the effect of saturation, tends to retard improvement in design and understanding of the phenomena. The routine use of saturation factors in rational design methods would seem to justify their use in the calculation of equivalent reactance. Tests can be made to test the accuracy of such design factors and indirectly the values of equivalent reactance.

By assuming the stator saturation to be a function of the voltage back of leakage reactance, the effect of the harmonic fluxes produced by the quadrature axis mmf. is neglected. These parasite fluxes congest the iron paths of the fundamental fluxes and affect the final result only to the extent that they change the required fundamental mmf. By neglecting pole tip saturation no appreciable error is involved except in machines which have relatively heavy amortisseur windings in comparison with the size of the pole tip or have an unusual pole tip construction. Appreciable pole tip saturation is more likely to occur in small motors which usually operate against an infinite bus and have no saturation at pull out.

Table II of Mr. Kilgore's discussion shows the error to be of second order magnitude in determining the field excitations, even if the burden of the total discrepancy between tested and calculated results is placed on the aforementioned assumptions. As another example, when the method described in the paper is used, the ratio of the calculated to tested field current of the large slow speed waterwheel generator of Fig. 10 is 99.2 per cent at unity power factor, normal voltage, and kva. The first set of values in Mr. Kilgore's table for the calculated field currents can be obtained from design data before the machine is built, the second, third, and fourth sets of values are dependent upon values obtained from tests made on the actual machine. In this light, the accuracy with which the field currents were predicted is remarkably good. All methods which involve Potier reactance are of little value except for the calculation of excitation from test data, even then the method is empirical for other than zero power factors. Potier reactance varies over a wide range for salient-pole machines depending on the load saturation and may become two or three hundred per cent of the leakage reactance (Mr. Kilgore's shows a ratio of 225 per cent). Any attempt to calculate Potier reactance must involve the calculation of saturation coefficients, the major objection voiced by Mr. Kilgore. We believe that a method involving reactances, which are independent of saturation, and saturation coefficients which are dependent on the load and power factor has much to recommend it over the present widely used methods of calculating excitation and equivalent reactance.

The question of the relation between the actual and the equivalent synchronizing power coefficients which Mr. Kingsley's discussion raises applies only to the cylindrical rotor case, as the salient pole machine has the same load angle, δ, as the actual machine and the equivalent reactances, $x_{d(sq)}$ and $x_{q(sq)}$, were determined so that the equivalent machine would have the same de_{1d}/di_d, de_{1q}/di_d, di_q/di_d and $d\delta/di_d$ as the actual machines.

Equation (14) of the paper has a typographical error. It should read

$$\frac{dP}{d\delta_{(sq)}} = \frac{e_{sq}e_s}{x_{sq} + x_s} \cos \delta_{sq} \tag{14}$$

as it was obtained directly from equation (13). The statements following the equation in the paper could be revised to more accurately state, "therefore, the synchronizing power coefficient of an equivalent machine which indicates the stability of the actual machine can easily be written in terms of the equivalent reactance, excitation and angle." That is, $dP/d\delta_{sq}$ does not necessarily equal $dP/d\delta$. However, $dP/d\delta_{sq}$ indicates the stability of the actual machine. This is illustrated by Fig. 4 of this discussion, which presents a comparison between the actual and the equivalent

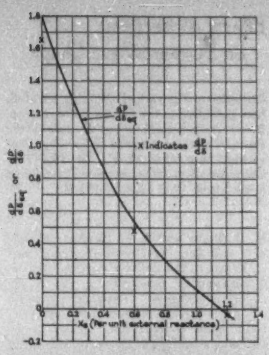


Fig. 4. Actual and equivalent synchronizing power coefficients of a cyclindrical rotor synchronous generator connected to a system through external reactance, normal voltage, normal kilovoltamperes, 0.8 power factor lagging

synchronizing power coefficient for the case of $r_a/x_a = 0$ of Fig. 9 of the paper. It should be noted that $dP/d\delta$ and $dP/d\delta_{eq}$ equals zero for the same value of external reactance. This would be expected since the equivalent machine has the same response as the actual machine for any changes as its terminals, and the angle between e_d and e_1 of the actual machine and between $e_{d(eq)}$ and el can be expected to increase with increase in δ_{eq} and δ for the usual ratios of external resistance to reactance. Some error may be involved for unusual conditions but this is not expected to be appreciable at pull out. In any case the actual synchronizing power coefficients can be calculated, if necessary.

The derivation for the formula used in Fig. 4 of this discussion for the actual synchronizing power coefficient in the case of zero external resistance follows

From equation (12)

$$P = \frac{e_d e_a}{x_d - x_1 + k(x_1 + x_a)} \sin \delta$$

Differentiating,

$$\frac{dP}{d\delta} = \frac{e_d e_a}{x_d - x_1 + k(x_1 + x_a)} \cos \delta - \frac{e_d e_a (x_1 + x_a)}{[x_d - x_1 + k(x_1 + x_a)]^2} \sin \delta \frac{ak}{be_1} \frac{de_1}{d\delta} \qquad (1)$$

The only unknown is $de_1/d\delta$. This can be obtained from the following relation.

$$e_1^2 = \left[e_a + \left(\frac{e_d}{k} \cos \delta - e_a\right) \frac{k(x_1 + x_a)}{x_d - x_1 + k(x_1 + x_a)}\right]^2 + \left[\frac{e_d}{k} \sin \delta \frac{k(x_1 + x_a)}{x_d - x_1 + k(x_1 + x_a)}\right]^2 \qquad (2)$$

Differentiating and simplifying,

$$\frac{de_1}{d\delta} = \frac{\dfrac{e_d (x_1 + x_a)}{x_d - x_1 + k(x_1 + x_a)} [\sin \alpha \cos \delta - \cos \alpha \sin \delta]}{1 + \dfrac{(x_1 + x_a) e_a \cos \alpha}{[x_d - x_1 + k(x_1 + x_a)]} \dfrac{ak}{be_1} + \dfrac{(x_1 + x_a)^2}{x_d - x_1 + k(x_1 + x_a)]^2} \dfrac{ak}{be_1} \left[\begin{array}{l} e_d(\cos \alpha \cos \delta \\ \quad + \sin \alpha \sin \delta) \\ \quad - k_a \cos \alpha \end{array}\right]} \qquad (3)$$

where α is the angle between e_a and e_1.

The numerical comparison that Mr. Kingsley has made between the synchronizing power coefficient of the actual and the equivalent machine is incorrect as he used equation (5) to determine the equivalent reactance. Equation (5), as stated in the paper, is based on the restrictions that $\phi = 90°$ and $d\phi = 0°$. These are the conditions for the operation of a synchronous condenser, but they are not the conditions for the operation of a machine whose load angle changes with respect to its terminal voltage. That is, for Kingsley's case $\phi = 90°$ but $d\phi$ must be determined. This can be done by solving equation (3) and (B-4) simultaneously to determine de_1/di and $\cos \phi \frac{d\phi}{di}$ for the conditions of the problem. It is interesting to note that for this case, although $\phi = 90°$ and $\cos \phi = 0$, $\cos \phi \frac{d\phi}{di}$ has a definite value and is not necessarily equal to zero. Solving correctly for the equivalent synchronizing power coefficient a value of 2.45 is obtained instead of 3.50, the value obtained by Kingsley. The actual synchronizing power coefficient is 2.11.

We quite agree with Mr. Park that a more general method of analysis would be desirable and believe that such a method will be forthcoming in the near future. Although the equations for equivalent reactance that we have developed depend upon the connected system, equation (3) for the cylindrical rotor machine, equation (C-2) for the direct axis of the salient-pole machine and a similar equation for the quadrature axis which can be obtained from equation (B-2) are not. These equations can be solved directly for any set of conditions at the terminals involving small changes. However, these equations, as Mr. Park points out, are limited in their application because they neglect the effect of additional circuits and were derived for steady-state conditions only.

Simultaneous Control of Voltage and Power Factor

Discussion of a paper by L. F. Blume and F. L. Woods published in the December 1933 issue, p. 884–9, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 483.

R. N. Slinger: Messrs. Blume and Woods have called our attention to a scheme by which 2 well-known devices may be combined and made to operate as a single unit. The consideration of a practical application brings up several interesting questions, one of the first being: What are the operating advantages of such a device?

The authors have mentioned some of the advantages but there are a number they have omitted. The merits of the step voltage regulator alone are already known as are also the merits of capacitors used for power factor correction. The important point is that there appears to be no basic reason why all of the respective operating advantages of each of these 2 devices should not be retained when they are combined, as the authors have suggested.

In addition, there are further advantages of an economic nature that accrue from such a combination of regulating transformer and capacitor. The former seems inherently well suited to serve as an automatic control device for the capacitor, at the same time that it is performing its normal function as a voltage regulating device. Thus, more efficient operation of the regulated circuit than could be obtained with the insertion of a fixed block of corrective kilovoltamperes is possible without incurring any extra expense for oil circuit breakers or other control equipment. Furthermore, because such a regulator would be inherently automatic in operation it could be located at a point on a system where the services of an operator are not available.

It may also be pointed out that the variable corrective kilovoltamperes provided by this new regulator would reduce the wattless requirements of the regulated circuit and would result in improved voltage conditions for all loads tapped off at intermediate points.

The next question is: What is the proper application for such a device? It is essentially a new and improved form of step voltage regulator. Hence, it is only logical to conclude that wherever an ordinary step voltage regulator could be applied to advantage, there is a possibility that operating economies and improved operation may be obtained with this new scheme.

In the low capacity field, the step voltage regulator usually can be shown to have definite economic advantages over its chief competitor, the induction regulator, for all voltages above 4,800 volts. In some instances, depending upon local conditions, the step regulator also has the advantage in the moderate capacity range over synchronous condensers, whose cost per kilovoltampere is relatively high in the small ratings. Therefore, it seems only reasonable to expect that the most favorable field of application for the new type of regulator probably will be on small and medium capacity stub feeders where the load power factor is low and the line voltage is above 4,000 volts.

Another question of interest is: How much corrective kilovoltamperes in the form of capacitors should be included with this new regulator? Theoretically there should be no limit to the amount that could be added, although there are certain practical limitations. In all cases a point would finally be reached beyond which it would be less expensive to obtain the required amount of corrective kilovoltamperes by means of synchronous condensers. In addition there would also be practical limitations imposed by the current carrying capacity of the ratio adjusters and the various windings of the regulating transformer.

The amount of capacitor kilovoltamperes that ought to be included is strictly an economic problem with a right amount for each individual case which is dependent upon such things as magnitude of the peak load, load factor, power factor, cost of energy, etc. In arriving at this economic balance the cost of capacitors in various ratings should be balanced against the capitalized value of the corresponding improvement in power factor conditions. Later on as the load builds up it may be economically advantageous to add additional capacitor kilovoltamperes to compensate for load growth. By following such a program, an appreciable part of the investment which is represented by the capacitors may be deferred until such time as there is economic justification for it.

E. K. Shelton: In the novel method proposed by the authors for control of voltage and power factor on transmission systems, a combination of 2 types of electrical apparatus is used—the load ratio control transformer and the capacitors. The first is a quite familiar type of equipment to transmission engineers, and well established in service. The use of capacitors in this field, however, represents a novel application. To many transmission engineers, the question of reliability and service performance of the capacitors will present itself. I desire to emphasize briefly the present status of capacitor development which has placed this useful and widely applicable tool on a plane of service performance fully equal to that of the more commonly used and better known forms of electrical apparatus.

The first real impetus was given to this development when the problem of low power factor became of major importance in the power distribution field. This brought the capacitor actively into the industrial field and from then on, the advance in this development has been steadily accelerated. Within the last 3 years, the waxes and mineral oils have been replaced, to a large extent, by an entirely new synthetic treating material of vastly improved stability, both from an electrical and chemical standpoint. To this new class of liquid insulations, has been applied the name "pyranol" in recognition of the noninflammability of the material, and the nonexplosive nature of the vapors or products of decomposition when mixed with air. The high dielectric strength combined with a relatively high dielectric constant are obviously favorable factors in improving the economy of capacitor design.

High working stresses are a necessity from an economic standpoint, but these have been attained with a high factor of safety to breakdown voltage through the careful control of materials, more efficient treating processes and improved designs. Stresses of 400 volts alternating current (rms) per mil of dielectric, have been used for several years in capacitors for industrial application. Stability of electrical and chemical characteristics have been proved by the decrease in power factor with service on voltage and by the absence of any indications of chemical deterioration. The impulse strength of the dielectric is high, while the losses will not exceed $^1/_2$ of one per cent.

The service record of many thousand kilovoltamperes of capacitors in industrial applications up to 6,600 volts over a considerable period of years, including several series capacitors in transmission line service, gives clear and conclusive evidence that the capacitor offers definite reliability for the proposed application. It is to be hoped that the theory may be proved by actual service trial in the near future.

Protecting Machines From Line Surges

Discussion of a paper by J. F. Calvert published in the January 1934 issue, p. 139–46, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions on this paper were published in the March 1934 issue, p. 488.

J. F. Calvert: First, I wish to thank Messrs. Beck and Montieth for their helpful discussions.

Along the lines of their discussions, it seems desirable to consider the protective scheme outlined in Fig. 16 of the paper. It will be assumed that the inductance and capacitance each can be treated as lumped constants. (The error in assuming the inductance as a lumped value is minimized by the use of relatively large capacitances.) It can be demonstrated mathematically that the surge impedance of the machine may be assumed infinite without appreciable effect on the results within the normal range of values encountered. It will be assumed that the voltage at the line end of the inductance is suddenly raised and maintained at a constant value.

Then let

E_{LL} = line to line voltage of the machine
Kva = full load machine rating
η = (full load current) reactance voltage of the inductance coil expressed as a decimal fraction of E_{LL}
f = normal machine frequency
L and C are the constants shown in figure 16 in henries and farads, respectively
e_2 = transient voltage across the condenser and machine due to the surge
t = time in seconds

Then,

$$e_2 = E_a\left(1 - \cos\frac{t}{\sqrt{LC}}\right) \tag{1}$$

$$L = \frac{\eta(E_{LL})^2}{2\pi f \times 1.73\ (\text{Kva}) \times 10^3} \tag{2}$$

$$\frac{de_2}{dt}\Big/\text{max.} = \frac{E_a}{\sqrt{LC}} = E_a G_m \tag{3}$$

$$C = \frac{1}{LG_m^2} = \frac{t_a^2}{L} \tag{4}$$

where t_a = time in seconds for the voltage e_2 to rise to crest at the constant rate G_m.

From equation (25) of the paper and with a suitable factor of safety for the turn insulation, t_a can be computed. Then from equations (2) and (4) of this discussion, L and C can be determined for the protection of the turn insulation.

Effects of Rectifiers on System Wave Shape

Discussion of a paper by P. W. Blye and H. E. Kent published in the January 1934 issue, p. 54–63, and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 483–4.

R. D. Evans and E. L. Harder: Messrs. Blye and Kent have made important contributions to the theory concerning the determination of harmonics in the supply circuits of rectifiers. Heretofore the methods which have been published have been based upon conventional rectifier theory assuming a supply circuit represented by an inductance whose reactance varies linearly with frequency. By means of the empirical formulas given in the first part of the paper, the authors have been able to take into account the effects of the actual impedances of supply circuits, particularly the amplification or reductions due to resonance or antiresonance of the supply system at a particular frequency. This is an important contribution.

In examining our 6-phase rectifier data good checks are obtained with the empirical formulas. However, we wish to offer the following:

$$I_n = \frac{V_{\phi-N}}{3n\sqrt{R_0^2 + Z_{e^n}^2}}$$

for the 6-phase rectifiers and

$$I_n = \frac{K(V_{\phi-N})}{3n\sqrt{R_0^2 + \frac{(Z_{cn})^2}{2}}}$$

for the 12-phase rectifiers using the notation of the paper except that $Z_{cn} = Z_{tcn} + Z_{en}$ (vectorially). The term Z_{tcn} is the commutating reactance of the rectifier transformer at harmonic frequency, and may or may not coincide with the nameplate reactance Z_{tn} used in the paper.

This modification of the empirical formula, eq 8 of the paper, is indicated by rectifie theory, and it is proposed to discuss the basis for it at a later date. The formulas just given are believed to give better results for high reactance supply circuits.

The authors have listed a number of remedial measures as follows:

1. Advance planning of method of supplying rectifier from the standpoint of minimizing wave-shape distortion.
2. Frequency selective devices.
3. Coördinated power circuit transpositions.
4. Reduction of power circuit unbalances, such as those caused by single-phase branches.
5. Coördinated telephone circuit transpositions.
6. Reduction of telephone circuit unbalances, such as those caused by the connection of ringer windings from one side of line to ground for selective ringing.
7. Shielding of telephone cable circuits by grounding the cable sheath.

Of these but 2 have been discussed in de-

tail, namely, system planning and frequency selective devices. The fact that detail discussion has been limited to these 2 items, tends to give them undue prominence. It seems pertinent, therefore, to point out that these are not necessarily the most effective methods of coördination. Advance planning and frequency selective devices are applicable to communication systems as well as to power supply systems. Also, in any particular case it may happen that the "best engineering solution" may not involve either of the 2 items discussed in detail in the paper. It is suggested that not only should these 2 methods receive attention in a particular case but that care should be taken not to overlook the other possibilities. All methods should be considered; whether applicable to the power supply system, the communication system, or the coupling between the systems. The choice of the measures to be used should, of course, be such as to provide the "best engineering solution," which has been stated in the "Principles and Practices" of the National Electric Light Association and Bell System.

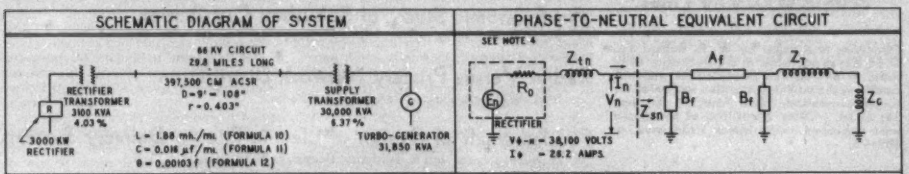
P. W. Blye and H. E. Kent: Dr. Smith has asked as to the accuracy of the empirical formulas when estimated values of system impedance are used. As pointed out in the text the results given in Figs. 3 and 4 of the paper are based on cases in which measurements of the system impedance were available. Our experience indicates, however, that when estimated system impedances are used, while the calculated values of the individual harmonic currents may be somewhat less reliable, the over-all result as indicated by the product of the rms. current and its telephone interference factor (I.T.) is not appreciably affected. The accuracy of calculated individual harmonic voltages is a direct function of the accuracy with which the system impedance is known. However, in this case also errors in the individual harmonic voltages partially cancel one another and the reliability of the calculated voltage T.I.F. to which they contribute is much greater than that of the individual harmonic components. As an example of the accuracy attainable with the empirical formulas in cases in which the system impedance must be estimated, we should like to quote from a case which recently has been investigated. In this instance in which the system impedance was a very complicated function of frequency the estimated voltage T.I.F. was about 125. The measured T.I.F. was subsequently found to be 111, the error in the estimate being only slightly over 10 per cent.

In reply to the question regarding Fig. 3 of the paper the lower values in this figure include both light load conditions on large rectifiers and full load conditions on small rectifiers. In general, the empirical method has been found to work equally well for both cases.

As suggested, a diagram (Fig. 1) has been prepared and is presented herewith indicating: (1) A single line diagram of a power system supplying a rectifier, (2) its equivalent circuit set up in accordance with the methods outlined in the paper, and (3) a table showing the magnitudes of the various impedances involved in the equivalent circuit over a range of frequencies as computed by the formulas given in the paper.

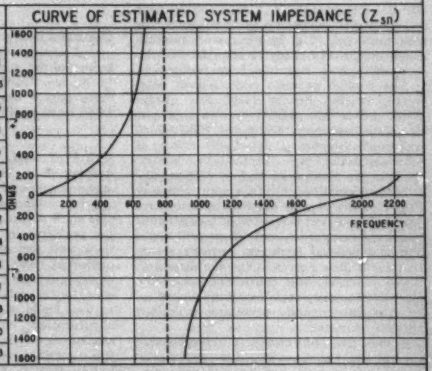
The authors agree with the point made by Dr. Smith to the effect that a large power system may not necessarily be a low impedance power system. In general, a large system does offer a low impedance to harmonic currents but in cases in which the impedance of a portion of the system is increased by the use of current limiting reactors, this relation no longer holds.

The authors are much interested in the modifications of the empirical formulas suggested by Messrs. Evans and Harder. We have not been able to check them against our tests results, however, as we have not had available the commutating reactances of the transformers involved. The fact that these reactances are not



CALCULATED VALUES FOR EQUIVALENT CIRCUIT

QUANTITY		E_n	R_0	Z_{tn}	A_f	B_f	Z_T	Z_c	Z_{sn}	Z_n	I_n	V_n
FORMULA		(4)	(3)	(18)	(13)	(14)	(18)	(34)	NOTE 1	NOTE 2	(6)	(7)
FREQUENCY	n	VOLTS	OHMS	OHMS	OHMS	OHMS	OHMS	OHMS	OHMS	OHMS	AMPS.	VOLTS
300	5	2540	485	+j283	+j103	−j2210	+j 46	+j 75	+j258	+j541	3.51	905
420	7	1815	485	+j397	+j144	−j1540	+j 65	+j105	+j428	+j825	1.9	813
660	11	1152	485	+j623	+j216	−j 970	+j102	+j165	+j1475	+j2098	0.54	796
780	13	977	485	+j737	+j245	−j 810	+j120	+j195	+j2356	+j3090	0.075	940
1020	17	747	485	+j983	+j298	−j 590	+j157	+j255	−j 913	+j 50	1.53	1400
1140	19	668	485	+j1076	+j313	−j 517	+j176	+j285	−j584	+j492	0.97	567
1380	23	552	485	+j1300	+j340	−j 400	+j213	+j345	−j292	+j1008	0.49	144
1500	25	508	485	+j1415	+j343	−j 353	+j231	+j375	−j207	+j1208	0.39	81
1740	29	437	485	+j1640	+j337	−j 274	+j268	+j435	−j 79	+j1561	0.27	21
1860	31	409	485	+j1755	+j314	−j 241	+j287	+j465	−j 34	+j1721	0.23	8
2100	35	362	485	+j1980	+j281	−j 185	+j324	+j525	+j 80	+j2048	0.17	10
2220	37	343	485	+j2100	+j258	−j 151	+j342	+j555	+j153	+j2250	0.15	23



NOTE 1. Z_{sn} CALCULATED AS INDICATED IN PHASE-TO-NEUTRAL EQUIVALENT CIRCUIT

NOTE 2. $Z_n = Z_{sn} + Z_{tn}$

NOTE 3. ESTIMATE INDICATES THAT Z_{sn} IS NEARLY IN PARALLEL RESONANCE AT 780 CYCLES, AND IT IS NOT POSSIBLE TO DETERMINE THE VALUE OF Z_{sn} ACCURATELY. HOWEVER, THIS IS NOT NECESSARY, SINCE FOR ALL LARGE VALUES OF Z_{sn}, V_n APPROACHES THE THEORETICAL VOLTAGE E_n. FOR EXAMPLE, FOR VALUES OF Z_{sn} BETWEEN 2000 OHMS RESISTANCE AND INFINITY, V_n CHANGES ONLY FROM 0.8 E_n TO E_n. ESTIMATE ALSO INDICATES AN APPROACH TO SERIES RESONANCE BETWEEN Z_{sn} AND Z_{tn} NEAR 1020-CYCLES. IN THIS CASE ALSO, AN EXACT KNOWLEDGE OF THE SERIES RESISTANCE IS NOT REQUIRED SINCE FOR ALL SMALL VALUES OF Z_n, THE CURRENT I_n TENDS TO APPROACH A CONSTANT VALUE E_n/R_0. IF ACTUAL VALUE OF Z_n WERE 200 OHMS RESISTANCE, I_n WOULD BE 1.09 AMPERES AND V_n WOULD BE 995 VOLTS.

NOTE 4. ALL IMPEDANCES, VOLTAGES AND CURRENTS ARE REFERRED TO 66 KV.

Fig. 1. An example of the calculation of system impedance and wave shape of supply to rectifier

generally available in the field would appear to make these modified formulas of more value to the manufacturers than to the field people who usually have at hand only the name-plate data on the various system equipment.

Messrs. Evans and Harder have commented on the fact that of the remedial measures listed in the paper only two have been discussed in detail. Due to the space requirements of the paper it was not practicable to discuss all the remedial measures available. Since data on the remaining measures listed had already been published, the detailed discussion was confined to the items on advance planning and frequency selective devices, subjects which had not been covered in previously published material. The authors agree that there is no single method of coördination to be applied universally, but that the most practicable solution in a given case can be arrived at only by a study of all the coördinative measures available. This conclusion has been brought out in the paper (item 5, page 55, of "Summary of Conclusions" and under "Coördinative Measures," pages 60 and 61).

Joint Use of Poles With 6,900-Volt Lines

Discussion of a paper by W. R. Bullard and D. H. Keyes published in the December 1933 issue, p. 890–8, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 489–95.

D. H. Keyes: P. H. Chase's discussion of the paper brings up several interesting and important factors which require consideration in any study of joint use of poles between power and telephone companies.

The foreign systems coördination committee of the former Natl. Elec. Light Assn. made an extensive, although not complete, survey in December 1932 which indicated approximately 1,400 miles of joint use in the United States between communication plant and higher voltage distribution circuits. Of this approximately 53 per cent was with the Bell System companies, 37 per cent was with the independent telephone companies, and 10 per cent could not be identified from the answers given. In general these represent specific situations where joint use was considered to be the most satisfactory over-all solution in particular situations usually involving a limited number of poles.

While this represents a considerable amount of construction, few systematic records of over-all performance were previously kept. Experience in one area where high voltage joint use has existed for a number of years indicates that in the absence of such records it is unjustifiable to conclude that such joint use is entirely satisfactory. In this particular instance, for example, after a systematic routine for investigating contacts between power wires and telephone plant had been established it was found that the frequency of contact and the extent of damage exceeded that expected, based on the cases which had previously come to the engineers' attention.

Both the power and telephone engineers on the Joint Subcommittee several years ago took steps to secure information on any contact which occurred between higher voltage distribution circuits and telephone circuits so that such cases could be promptly investigated and all of the pertinent facts obtained. As a result of this a large amount of data has already been secured and a number of investigations have been made. These include contacts involving not only joint use but also crossings and conflicts of the two classes of facilities. The data secured in these investigations have furnished a large amount of the basic material upon which the relative hazard studies have been carried forward.

Provisional Report No. 6 of the Joint Subcommittee on Development and Research referred to in the paper and also the paper on Joint Use presented before the A.I.E.E. by Messrs. Huber and Martin in February 1931, discuss the various factors which enter into the problem of relative safety and point out the necessity for obtaining coördination of protection of power and communication facilities in order to provide satisfactory over-all situations. Possible improvement in the telephone fuse referred to by Mr. Chase has been investigated, but an over-all appraisal does not appear to show that satisfactory protection could be obtained by relying solely upon an improved fuse.

It would be expected that a system engineered and operated with the high service standards employed in Philadelphia would naturally have a minimum number of contacts per year on the average. Furthermore, the method of grounding and the excellent relaying of the system would tend to minimize the effect of any contact which did occur. Experience has shown that the power companies are seldom, if ever, advised of contacts by the communication engineers unless material damage results.

The authors are of the opinion that the relative safety of joint use involving the higher voltage distribution is largely affected by the circumstances of the systems, such as the character of construction and the nature of the protective and other electrical features. It was a coördination study of these factors which brought a satisfactory solution in Staten Island.

An Economic Study of Suburban Distribution

A. H. Sweetnam and C. A. Corney, January 1934 issue, p. 97–102.

Radial Versus Primary Network Distribution

H. E. Wulfing, January 1934 issue, p. 38–42.

Fundamentals of Design of Electric Energy Delivery Systems

J. Allen Johnson and R. T. Henry, December 1933 issue, p. 831–8.

Discussion of a group of papers presented for oral discussion at the session on power distribution of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of these papers were published in the March 1934 issue, p. 489–95.

R. E. Hellmund: After a great many years, during which the Institute records have shown a preponderance of interest in transmission problems, the present meeting and also some of the preceding ones have given the problems in distribution the attention they well deserve. However, the papers presented have dealt essentially with the broad problems in distribution having reference to the relative merits of radial and various kinds of network systems, location of substations, etc. The purpose of my discussion is to invite increased attention to the somewhat neglected ends of the distribution system, such, for example, as the leads and wiring to and on the customers' premises and the smaller distribution transformers. Technically, the problems connected with these items perhaps are or at least appear to be the simplest, and possibly this is the very reason why they have received the least attention. In addition, they may have been neglected because the layout and responsibility for them is divided among the utilities, the electric contractors, and the users.

The reason why increased attention to these ends of the distribution system is desirable is that more and also larger capacity motors are continuously being installed for motor-driven appliances, domestic and commercial refrigeration, air conditioning, etc., in districts which previously had rather light and uniform loads. The present practice is in general to install any type of commercial distribution transformer in more or less arbitrarily chosen locations, to install wiring meeting the underwriters' requirements, and motors of various standard types, and then to expect everything to work satisfactorily. If such is not the case, the stand is frequently taken that the connected equipment is at fault and possibly should be taken off the line.

Following are a few illustrations of this: With a relatively small compressor outfit, flickering of the lights was noticed when the equipment was running. An analysis indicated that with the particular ratio of the pulleys of the belt drive, the piston impulses caused load variations of a frequency of about 15 to 20 cycles a second, which with the line drops existing caused the lights to flicker. In another case trouble was experienced from a commercial refrigerating equipment due to low voltage during starting; in fact, the voltage drop was so large that the starting voltage was away below

established standards, and as a consequence improper functioning of the control resulted in a great deal of trouble and expense.

It is true that in each of these cases the connected equipment could have been changed to remedy the trouble. In the first case, a change from a low-power-factor, repulsion-start, induction-run motor belted to the compressor to an equipment with direct-connected capacitor motor would have corrected the trouble, or possibly a compressor with a larger number of pistons could have been used. The larger number of pistons and the direct-connected motor would have resulted in the frequency of the impulses being so high as not to be noticeable, and the higher power-factor of the capacitor motor would have reduced the variations of the line drop. In the second case, just the opposite change, that is, from the capacitor motor used in this case to a repulsion-start, induction-run motor, would have reduced the starting current and consequently the line drop during starting.

It should be realized, however, that insistence upon such changes and possibly upon additional and more exacting regulations with regard to the characteristics of the connected equipment, would not exactly prove beneficial to load building, especially since in either of the 2 cases a better planning of the wiring installation would have led to satisfactory results at a much lower expense. In the case where the voltage drop during starting was too high, it was found that the network to which the motors were connected had excellent voltage regulation and that somewhat heavier leads from the network to the motors would have taken care of the situation at an almost negligible increase in cost.

Although it may be impracticable for the utilities to engineer each individual motor installation, these problems should nevertheless be given increased attention. In many cases the use of low-impedance transformers may help out greatly in such situations. Again, it may be advisable in some cases to use larger distribution transformers serving a somewhat greater area, as a result of which any connected motor will represent a smaller percentage of the transformer capacity and thus cause lower voltage drops during starting or during variations in loads. Leads from such larger transformers serving larger areas will, of course, be longer and therefore may have to be made somewhat heavier, but the total cost of the installations may not be increased as one large transformer is usually cheaper than several small ones. At any rate, these or similar solutions may be more economical than any insistence upon features which unnecessarily increase the cost of the connected equipment, a practice which in many cases may retard the installation of additional load-consuming equipment.

E. W. Oesterreich: In analyzing the papers presented in the symposium on "power distribution" it was found that it was practically impossible to reconcile the apparent discrepancies in the basic conclusions, due to the absence of supporting cost data, or to the different basis of cost determination.

We can readily understand why topographical conditions may have a great influence on the relative unit capacity costs of the various distributing systems between the substation and the point of customer utilization. However, in this morning's presentation, the outstanding difference appeared to be that for the cost per kilovoltampere of firm capacity for distribution substations. Take for example the substation cost estimates when compared to the equivalent network unit estimates as presented by Messrs. Johnson and Henry, and Messrs. Sweetman and Corney. The Johnson and Henry paper shows the network unit installations as being approximately 75 per cent higher in capital investment cost than the equivalent substation installations. Messrs. Sweetnam and Corney indicate the opposite of this condition in that their network unit installation costs are approximately 42 per cent below the corresponding substation investment requirements. In another study recently completed by a company, which study involved an area of 11 square miles and a 1931 peak load demand of 32,000 kva, the analysis showed that for a distribution substation which incorporates the most recently proposed practices in economical substation design, the estimated investment cost could be lowered to a point where the total investment for the substation capacity would be approximately equal to the investment required for the network unit installations.

This wide spread in substation investment cost data would indicate not only a decided difference of opinion as to operating and engineering design requirements for a presupposed similar service requirement, but a large differential in the installation costs of the equipment.

Mr. Wulfing shows in his paper in "Table IX—Comparative Load-Capacity Table" that in the network plan the transformer units are installed as the load growth within the area under consideration and in the surrounding station area, requires the additional capacity while existing substation capacity is utilized to its fullest extent for the maximum period of time. In the radial feeder plan, the initial installation of the new substation appears to immediately release to the surrounding area, substation capacity of 4,000 kva in excess of that released, or rather unloaded, in the network plan. According to the table this additional released capacity amounts to a total of 14,500 kva in the first 6 years considered, or roughly, an average capacity of 2,500 kva for 6 years. To make the annual cost comparison applicable, it would appear that the annual cost of the equipment released, which is not used or useful in supplying capacity for the growth in load in the surrounding area, should be charged to the plan creating the idle investment condition. Or if all of the surrounding station capacity made available by the radial plan is necessary to supply immediate load requirements of the surrounding area, then it would seem more equitable if the cost of the difference in the amounts of this capacity used under the 2 plans should be charged to the network plan.

Messrs. Johnson and Henry present a worth while contribution to the industry by clarifying the fundamentals involved in the problem of economic design of distribution systems. Unfortunately, their presentation of comparative capital costs as shown in Table II is of such a general nature that the lack of data relative to items of the subdivisions prohibits comparisons with conditions as they exist on other properties.

A system composed of small increments of capacity, installed at or near the concentrated loads when needed, and feeding into a distribution system which does not require frequent, costly circuit revision work to adequately serve the increasing demands brought about by normal growth of load and the addition of new circuits, presents economic advantages which are apparent. But local conditions, construction practices, operating and service standards may impose such restrictions that the ideal condition cannot be obtained. The papers presented force us to recognize the engineering, economic, and operating phases of distribution as a problem which cannot be effectively subdivided into component parts such as transmission, substation, and distribution. For each of the related phases and for the composite system there is a solution which results in the lowest annual costs over a reasonable period of time. It is this solution which we must strive for regardless of precedence, and existing functional jurisdictions.

The officers and contributing authors of the power transmission and distribution committee are to be congratulated on their courage in presenting a symposium on a subject so controversial in nature as this one. The importance of the effect of differences in operating requirements and engineering design practices on distribution costs has been emphasized in the presentations. It is to be hoped for that this session will provide the necessary stimulus to distribution engineers so that the attendants at future Institute conventions will be able to derive the benefits of further thought and analysis of this problem.

William Shuler: In comparing the relative merits of the radial system with the primary network systems, there are 2 elements which are very important, one of which has already been touched upon, but the other has not been mentioned.

The possibility of improving the reliability of the radial system has been mentioned, but I do not think sufficient emphasis has been placed on this point. The interconnection of the lightning arrester ground with the secondary neutral apparently benefits the whole line performance rather than just the transformer; that is, with these lightning arresters, interconnected, there will be fewer flashovers on the line itself than when the arrester ground is separate.

Furthermore, we have made marked progress in improving our line construction. Also, the improvements in operating practices, such as high-speed relaying and instantaneous reclosure, are all tending to give to our radial system a degree of continuity which, in some cases, might be superior to a primary network. I am referring to the fact that in such a set-up, the dip in voltage on a radial system relayed for instantaneous tripping and closing may, as a matter of fact, permit customers' apparatus to continue in operation where the prolonged dip necessitated by network relaying might cause an outage.

The other point I wish to emphasize is that we must undoubtedly look forward

to the use of higher voltages for distribution circuits. When the time comes for making such a change, there will be less expense involved on systems employing radial distribution, than there would be where primary network installations have been made. I think, in the past, a great many of our decisions regarding fundamentals in system design have been made without giving sufficient weight to this point. Surely, our experience has demonstrated that the constancy of change confronts our industry to a greater extent possibly than any other.

Fundamentals of Design of Electric Energy Delivery Systems

Discussion of a paper by J. Allen Johnson and R. T. Henry published in the December 1933 issue, p. 831–8, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 489–95.

J. A. Johnson and R. T. Henry: The discussion of this paper, together with the other papers presented in the symposium, indicates the need of extreme care in making comparative studies to avoid drawing unwarranted conclusions from comparison of systems which are not truly equivalent. Much of the confusion which has existed, and still exists, could be avoided if more attention were paid to the fundamentals involved and if greater care were used to recognize differences between the operating characteristics of the systems compared.

In the latter part of D. K. Blake's discussion he states that for a large area the network will save money on cable and conduit, substations and even on transmission cable. We feel that this is not necessarily true. The principal factor in determining the ratio of "spare capacity" to "firm rating" is the probability of failures in the subtransmission circuits. A network with a low ratio of "spare" subtransmission circuits is not necessarily equivalent in reliability to a radial system with a higher ratio of spare circuits. While it is true that in the Buffalo system each group of subtransmission circuits depends entirely on the circuits within that group for spare capacity, it is a fact that in a large network the number of subtransmission circuits available as reserve for any particular subtransmission circuit is quite limited, unless excessive "interleaving" is provided. This is one of the elements of the problem which is not readily apparent in studies of small networks and it is much more apparent with 22 kv than with 13 kv subtransmission. In its practical effect it means that a network must have about the same number of subtransmission circuits and in turn about the same total transformer capacity as a system like the one in Buffalo in order to make it truly equivalent to such a radial system.

W. R. Bullard's suggestion that the subtransmission voltage be used as the primary voltage may result in very real economies but we believe it is not generally applicable.

In Buffalo, at least, local ordinances do not permit the use of overhead lines of such voltages, and there are many other objections to such a practice which will occur to anyone familiar with the subject, but which cannot be adequately discussed here. At present its principal field of application would seem to be in high density areas using underground feeders and low voltage networks, and in very low density areas (rural lines) where the higher voltages have been found less objectionable for overhead use.

John S. Parsons suggests that the use of aerial cable will materially decrease the cost as compared with underground subtransmission but we feel that the aerial cable also has only a rather limited application. It probably would not help the situation in Buffalo where there is a very definite program for the removal of overhead wires from city streets and where there are no alleys available.

Mr. Parsons also mentioned the advantage of air blast on the network transformers in order to provide emergency capacity. Air blast will undoubtedly provide emergency capacity in transformers but it will not help underground cables and is therefore of limited value in a network system where the subtransmission capacity is one of the controlling factors.

C. A. Corney raised several questions regarding the studies made in Buffalo. In these studies various sizes of network transformers were considered, including several different sizes between 1,500 and 4,000 kva. Double network units were also considered. The figure of 10 per cent which was published in the *Elec. World* in July 1931 was based on earlier studies with large network units whereas the figure of 36 per cent given in our paper was based on more recent and more detailed studies with 1,500 kva network units. These later studies were made principally because of suggestions that the use of smaller units would be more favorable to the network than the larger units considered in the earlier studies.

It is of interest to note the striking similarity between the system employed in Somerville with double unit substations and without tie feeders between substations which our Boston friends seem to identify with a primary network, and the system used in Buffalo which we call a radial system. Possibly the definitions suggested in our paper should be extended to include definitions of a "primary network" system and a "radial" system. There seems to be a tendency for some to identify the radial system with large substations and large transformer units and to call any system using small transformer units a network system. There appears to be general agreement as to the economy of small units. The point at issue, therefore, as between the two systems is whether it is better to group these small units and make the distribution feeders radial or disperse the units and interconnect them into a network through the distribution feeders.

We feel it will be helpful in arriving at correct conclusions if, in further studies and discussion of this subject, these fundamentals be kept firmly in mind.

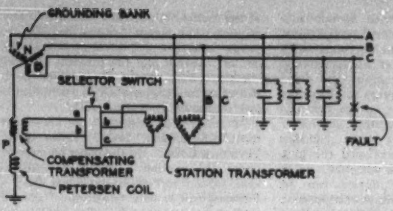
Petersen Coil Tests on 140-Kv System

Discussion of a paper by J. R. North and J. R. Eaton published in the January 1934 issue, p. 63–74, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 462–5.

J. R. Eaton: In the tests described in the paper it was found that corona and other system losses caused a fault current of approximately 45 amp, which could not be balanced out by the Petersen coil. On the assumption that losses in the system during fault would be proportional to the length of connected transmission line, it was anticipated that in case the Consumers Power Company 140-kv transmission system consisting of over 800 miles of overhead line were to be tied into one Petersen Coil system, the losses would produce a fault current of approximately 200 amp. With no definite information at hand, the question arose as to whether arcs of this current magnitude would be self-extinguishing. A method was worked out in 1932 which provided for compensating this loss current, thereby reducing the current in the fault to a very low value.

A schematic diagram of this loss compensating arrangement is shown in Fig. 1. The additional equipment required is a compensating transformer connected between the grounding bank neutral and the Petersen coil terminal, and a selector switch by means of which the compensating transformer may be energized from any desired phase of the transmission system. With a fault on phase C as shown in the diagram, the compensating transformer is connected to phase AB, the voltage E_{ab} is then added to the voltage between the transformer neutral and ground E_{np}, giving a total voltage across the Petersen coil of E_{pp}. As current through the Petersen coil lags its voltage 90 deg, the current in the Petersen coil assumes the position I_p. By a suitable choice of the ratio of compensating transformer and the proper tuning of the Petersen coil, the horizontal component of the Petersen coil current may be made equal to the charging current I_c, while the vertical component of the Petersen coil current may be made equal to the loss current due to corona I_{cor}. Under these conditions the current in the fault would theoretically be zero. Obviously with this arrangement, a relay scheme must be provided which will cause the selector switch to apply to the compensating transformer a voltage taken from between the 2 unfaulted conductors.

On January 7, 1934, this scheme was tried out on the Petersen coil system described in the paper, making use of equipment available in the Saginaw River substation. Calculations showed 40 kv to be required for complete loss current compensation. However, the facilities available for test permitted obtaining a maximum potential of only 29 kv. In Fig. 2 is shown the results of these tests. The upper curve shows the current in the fault with the Petersen coil system operating normally. With the



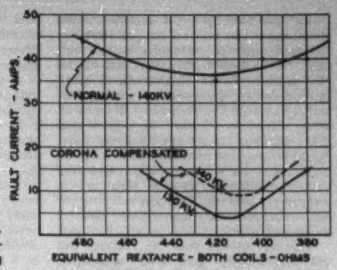
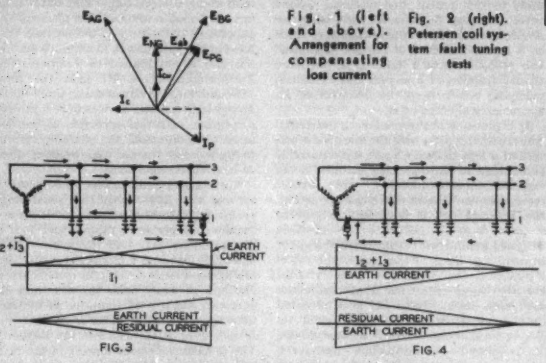


Fig. 1 (left and above). Arrangement for compensating loss current

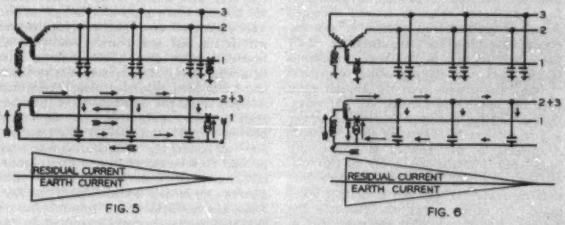
Fig. 2 (right). Petersen coil system fault tuning tests



Figs. 3 (left) and 4 (right). Isolated neutral system

corona compensating scheme in effect, the fault current was reduced from 35 amp to 10 amp. At 130 kv the corona losses were considerably reduced and the loss current was almost completely compensated by the current through the Petersen coil. The remaining 5-amp fault current was of higher harmonic characteristics.

In general, the scheme performed as anticipated, and apparently affords a method of holding ground fault current to a low value regardless of the magnitude of system losses due to corona or other causes.



Figs. 5 (left) and 6 (right). Petersen coil system

J. M. Dunham: The authors have pointed out in their paper that the information given in Table IV, p. 69 (ELECTRICAL ENGINEERING, January 1934) on the relative magnitudes of voltage induced in exposed telephone lines is applicable only to this particular system with a fault at Alcona. Some further discussion of these relative magnitudes with particular reference to the distribution of residual or earth current, for several types of grounding, may be of interest.

The distribution of residual current for faults to ground on an isolated neutral system is shown in Figs. 3 and 4. In Fig. 3 the fault is assumed at a point remote from the generating source and the residual current appears as a maximum at the point of fault dropping to zero at the source. If the fault occurs at the source, the residual current is again a maximum at the point of fault but is 180 deg out of phase with that for the previous fault location.

Considering the same system as above but connecting a Petersen coil in the neutral, the residual current distributions for faults at the source and at the end of the line are shown in Figs. 5 and 6. For simplicity, only the reactance offered by the Petersen coil and the capacitance to ground of the lines will be considered. To simplify the analysis of these circuits further, 2 currents will be considered, namely, that due to the presence of the Petersen coil, neglecting the capacitance to ground and the capacitance current neglecting the Petersen coil. These currents are then combined to give the residual current distribution. In this system the distribution of residual current is identical for both fault locations; in fact it is independent of fault location.

The measurements of induced voltage from which Table IV of the paper has been prepared are, of course, proportional among other things to the earth current in the exposure. In Figs. 3 and 5 it can be seen that if an exposure is located near the fault, the induced voltage for the isolated system will be greater than for the Petersen coil system. If, however, the exposure is near the source, the induced voltage will be greater for the Petersen coil than for the isolated system. Similarly the induced voltage will be affected by the location of the exposure if the system is grounded through a high neutral resistance. It is apparent from the above that the location of the exposure will exert an effect in determining whether the induced voltage will increase or decrease, in changing from an isolated neutral system to a Petersen coil or high neutral resistance system.

Table IV shows that the induced voltage for the Petersen coil system is less than that for the isolated neutral system, which follows from the fault and exposure locations. The grounding bank condition, for this particular fault location, is equivalent to a Petersen coil system about 50 per cent undertuned and the value of the induced voltage would be expected to fall between that for the isolated system and the Petersen coil system as shown in Table IV. With the system grounded through resistance (about 800 ohms) the induced voltage was higher than for the isolated neutral system. Although the total fault current is less in this case than with the system isolated, the effect of the neutral resistance is to change the distribution of earth current so that a larger percentage of the fault current appears in the exposure.

C. L. Fortescue: The Petersen coil has a vogue in Germany where I think it is safe

to say that there is not a single important transmission line which is not provided with Petersen coils for protection against outages. During my short stay in Germany for the World's Power Conference, I heard commendatory statements regarding the performance of the Petersen coil from all sides. However, it must be remembered that lightning storms are relatively infrequent in Germany as compared to what we get in this country. Nevertheless, according to my recollection, ground wires are in general use and the Petersen coil may be said to supplement the protective effect of the ground wires.

It is my opinion that the Petersen coil will undoubtedly have small application in this country, this application being for lines below 110 kv rather than for high voltage lines. Present information indicates that a 132-kv line with 2 overhead wires designed along modern lines will give practically as good performance from an outage standpoint as the authors' 140-kv lines with Petersen coils. A report by the Great Lakes Division of N.E.L.A. made on the performance of 132-kv lines equipped with 2 ground wires covering the Great Lakes District indicates an average performance over 5 years of the order of $1^1/_2$ outages per 100 miles per year, which it must be admitted is a very fair performance from a line outage standpoint. Lines are being built in the 230-kv class and higher from which a performance of one outage every few years per 100 miles of the line is expected. It is hardly to be expected that the addition of Petersen coils would substantially improve such performance.

A point I wish to emphasize is that the Petersen coil does not protect the apparatus from lightning, whereas a well designed overhead ground wire system is also excellent protection for the substation. As I have pointed out in lightning discussions in the past, the surge passing to ground through the towers from the ground wires does not materially involve the line wires; that is to say, the surge appearing on the line wires after the lightning surge has been dissipated in the ground is exceedingly small and is negligible as far as the substation apparatus is concerned provided that no failure of the line insulation takes place. In other words, the effect of the ground wires is to localize the stress due to lightning so that beyond the few towers that are affected by the direct lightning stroke a surge of only a moderate magnitude will travel over the line. The purpose of the Petersen coil is merely to prevent a lightning surge which may flash over a line insulator from developing into a fault to ground and it must be admitted that it performs this task with a fair degree of efficiency when in proper tuning and when corona losses are not excessive.

It would appear that the most favorable field for application of the Petersen coil in this country is on lines for rural distribution of power. These lines are usually simple single circuits and Petersen coils can easily be designed to operate with such lines. In these lines it is generally found that an adequate ground wire protection is uneconomical. In such lines while a number of lightning strokes terminate on the line and produce a large number of flashovers, the Petersen coil will insure that the majority of these flashovers will not become outages and the customer's service is not substantially impaired as a result of lightning. However, the Petersen coil has rivals which perform this service just as effectively. I have in mind, for example, the deion tube which not only prevents the lightning stroke from becoming an outage but also reduces the duty on arresters and other protective devices. For more complex circuits there may be developed the high speed circuit breaker with automatic quick reclosing means. This device can be used with the higher voltage transmission lines to supplement the overhead ground wires. It may be expected that with this device even the few outages that may occur as a result of failure of the line insulation will probably have a duration of not more than a fraction of a second and customers receiving power from the line will be inappreciably affected by it.

It is probable that except when horizontal construction is used with the line conductors spaced a long distance apart a considerable percentage of all lightning strokes to an exposed transmission line will involve more than one wire in which case, of course, the Petersen coil is powerless to prevent a phase-to-phase outage. The properly designed ground wire system will shield the transmission lines so that the likelihood of 2 phases of the conductors being involved is quite remote even when insulation failure does take place. It should also be noted that deion protectors or high speed reclosing breakers are effective against double line-to-ground or line-to-line flashovers, whereas the Petersen coil is limited to single phase-to-ground flashovers.

To sum up, I feel that while the Petersen coil may have a field in our systems it will not take the place of the good line protection which has been developed to a high degree within the last few years. You have all heard a great deal about making lines lightning proof. The reason that so much effort has been expended along these lines is that when the lightning-proof line has been achieved such a line can be loaded up nearly to the static stability limit without fear of instability and firm power may be sold to a customer over a single transmission line without having another line reserve to insure continuity of service. Thus the investment in transmission in lines will be very materially reduced for the same delivery of power.

J. R. North: J. E. Clem's explanation of the meaning of the term "zero sequence capacitance" is correct and in the definition of the term "Cg" given in the appendix, the words "with one conductor grounded" are unnecessary.

As C. L. Fortescue has pointed out, Petersen coils would have little application on systems consisting entirely of lightning-proof lines. However, there are many cases where Petersen coils would be applicable on systems where lines, because of structural, economic or other limitations, will not be equipped with ground wires or Deion tubes.

Messrs. Schnyder and Sidler in their discussions have mentioned the possibility of operating with lines grounded. In this country, it is generally customary and desirable to take out of service, as rapidly as possible, high voltage circuits which have become permanently faulted, irrespective of the method of neutral connection. This requires that means be provided for the proper selection and disconnection of the circuit involved and the problem becomes complex where several ground fault compensating coils are installed on a metallically interconnected system network.

Mr. Sidler has suggested the use of the term "Extinction Coils" rather than "Petersen Coils." In the paper on page 64 under the caption "Theory of Petersen Coil Operation," it is explained that a Petersen coil is only one form of ground fault compensating coil. This latter term has been used in several other places in the paper and the nature of the analysis outlined in the appendix is, as stated, a general one and is not limited to Petersen coils. Furthermore, it is felt that the term "Ground Fault Compensating Coil" is the proper term for such devices since it is more descriptive of actual operation as the coil tends to compensate the charging current to ground and the arc then becomes more or less self-extinguishing.

With regard to dissonance tuning, analyses and tests have shown that satisfactory operation of these Petersen Coils does not require 100 per cent tuning, and this is illustrated by Fig. 4 in the paper. As a matter of fact with a practical coil the taps are selected to cover certain increments of line and in many cases the coils may be operating slightly off tune due to the fact that the theoretical in-tune point of the system setup is between two tap positions. The unbalance current flowing in the neutral under normal conditions is extremely small. The tuning of the coils, contrary to certain expressed opinions, is very simple and may be easily determined by calculation or by test.

The statement referred to on page 70 of the paper to the effect that Petersen coils are only effective for clearing momentary faults is true without regard to the continuous current rating of the coil since by definition faults are cleared only when they no longer exist.

Automatic Reclosing of Oil Circuit Breakers

Discussion of a paper by A. E. Anderson published in the January 1934 issue, p. 48–53, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 466–7.

Robert Treat: A. E. Anderson has called attention to a matter which should be of vital interest to many operating companies. At a time when the utilities are under fire from so many directions, anything which permits even a minor reëstablishment of public esteem is of importance. Not a minor, but a major improvement in service is possible in many cases by adopting the operatiug procedure described.

Some pioneering spirits in a few operating companies have demonstrated by actual experience on their own systems that:

1. It is entirely feasible to reclose *im-*

mediately a breaker which has been tripped automatically, and about 9 times out of 10, the circuit has cleared up so the breaker stays in.

2. Customers who have made necessary modifications in their control equipments, ride through the 9 short circuits in which immediate first reclosure is successful with so little effect on their operations that they are not even aware that there has been a disturbance.

Thus, so far as the customer is concerned, by this simple and inexpensive modification in operating procedure, the power company eliminates 9 interruptions out of 10.

Certainly this is no general panacea for all interruptions. The nature of some loads is such that a 15-sec or even a 2-min outage is of no great concern. The nature of other loads and drives is such that possibly they cannot be benefited—at least with equipment now available.

One company, wishing to gain experience with immediate reclosing, decided to make a trial installation on 1 or 2 circuits. The first feeder selected was found upon investigation to average about one interruption a year, and the loads served by it were such that an outage of 15 sec, or even of 15 min, was of no consequence whatever. Obviously, it would require a very enthusiastic person indeed to justify the application of immediate reclosure to this feeder.

However, experience has demonstrated that many types of load can be benefited by immediate reclosure. Utilities having such loads, if they are now subject to too frequent interruptions cannot afford to overlook this important means of regaining some lost public favor by furnishing greatly improved service.

It used to be felt that the one way of assuring continuous service to important loads was to provide 2 feeds. This does help, especially if the 2 feeds are from separate sources, and supported on different structures. However, experience has shown that 2 overhead circuits on the same pole or tower are sometimes not sufficiently immune to simultaneous troubles as to guarantee the desired degree of freedom from interruptions. One company reports that it has a double circuit line, on which 10 per cent of the outages involve only one circuit, 90 per cent both circuits. It is entirely conceivable that sometimes a single circuit line provided with immediate reclosure may give fewer interruptions to loads that can take advantage of it, than a double circuit line can without immediate reclosure.

D. W. Ellyson: The Kansas City Power and Light Company has been operating automatic reclosing oil circuit breakers on a 15–30–75 sec cycle since 1922, and at the present time the following breakers are in service:

255	Single-pole 2,540/440 volt Y (one for each phase)
24	Single-pole 6,950/11,950 volt Y (one for each phase)
1	Three-pole 13,500 volt
6	Three-pole 19,050/33,000 volt Y
286	Total

Our experience has been that these reclosing breakers give better service than was obtained from the manually operated stations and that they have materially reduced the time required to restore service. A summary of tripouts of 2,540/4,400-volt Y, oil circuit breakers from April 1926 to November 1932 showed a total of 424 tripouts divided as shown in Table I.

The percentage of lockouts is 13 per cent, which is considerably higher than the figures shown in Mr. Anderson's paper. This may be due in part to the fact that our figures were obtained from regular log sheets where all the lockouts are carefully noted but in cases of general trouble it is possible for the dispatcher to overlook a breaker opening and then closing and remaining closed.

From an examination of these figures it is seen that in 77 per cent of tripouts the breaker remained closed after the first reclosure. If instantaneous first reclosing had been used, it would have in effect cut out 77 per cent of the outages, as the great majority of the load is lighting, and all the customer would have noticed would have been a dip in his lights. This lead to the adoption of instantaneous first reclosure on all the 19,050/33,000 Y outgoing circuits for our new 13,500–33,000 Y step-up transformer substation.

This includes a total of 7 equipments, 2 transfer breakers, 3 for radial feed circuits and 2 for feeding a 19,050/33,000 Y loop, so that our entire 33,000 Y load is handled by instantaneous first reclosure breakers.

The final installation of these breakers was made only a few weeks ago so that we do not have any operating data to make any comments on just what will occur. However, we did have one case where a cat short-circuited the 33,000-volt bus in the loop station containing the sectionalizing breaker, and this breaker and one of the loop breakers at the substation opened, killing one section of the loop, and then both breakers reclosed instantaneously. A coal mine using one 500 hp and one 800 hp shovel was in operation at this time and the operators did not know that our breakers had opened.

Our equipments require approximately 55 cycles (determined by means of a cycle counter) from the time the main contacts break contact to the time they make contact again.

Due to the fact that the synchronous motors connected to our lines are of relatively small capacity as compared to the lines which feed them, we have not at present had to take into consideration any possible feed-back to the short circuit from synchronous equipment. However, there is a cement plant connected to our lines and having synchronous motors of rather large capacity, and the breakers supplying these motors have been equipped with low voltage devices that trip these breakers before the instantaneous breakers have time to reclose.

A. E. Anderson: E. E. George points out advantages that have been experienced where certain large synchronous motors were operating in conjunction with induction motors, all being installed in the same plant. Although the synchronous motor (after a power interruption) tends to maintain normal voltage, which will delay the dropping out of instantaneous undervoltage devices, this same characteristic will also tend to maintain arcs on the feeder system. As pointed out in the paper further operating information is required before the overall effect of the synchronous motor can be evaluated for general application.

H. A. P. Langstaff describes the extended application of a-c reclosing equipment to tie-lines on the system of the West Penn Power Co. where 137 equipments operate as stub feeders (44 on interconnections) and 33 equipments operate when the line is energized from the other end, resulting in approximately 20 per cent of the equipments on this system, functioning as multiple feeders.

Another important item referred to is the proper coördination of fuse and relay characteristics, which is essential if the equipment is to give the desired degree of selectivity required for system operation.

Mr. Langstaff concurs with Mr. George in the opinion that a third reclosure is a decided advantage. As pointed out in the author's paper, the third reclosure can be obtained in the conventional design of a-c reclosing relay, with practically no additional expense or complication.

In the case that Mr. Langstaff cites, illustrating the possible application of automatic reclosing relays (to an attended station) the number of outages per year was extremely small. However, there are many installations where service requirements or a sufficiently large number of operations warrant the installation, in attended stations, of a simple relay of the type shown in Fig. 5, giving one immediate reclosure, followed by one or two reclosures under the control of the station operator.

The data submitted by Mr. Ellyson, covering the period from April 1926, to November 1932, gives a higher percentage of lockouts as compared with the values in the author's paper. Mr. Ellyson gives one possible explanation for this higher value. It has been noted that faults on an underground system are more often of a permanent nature as compared with those on overhead systems. When systems of the latter type are installed in localities subjected to frequent thunder-storms, the percentage of lockouts would presumably decrease, due to the transitory effect of the

Table I—Summary of Tripouts

	Breaker Remained Closed After							
	1st Recl		2nd Recl		3rd Recl		Lockout	
	No.	%	No.	%	No.	%	No.	%
Total single-phase	180	42.4	31	7.31	4	0.94	31	7.31
Total 2-phase	117	27.60	4	0.95	0		12	2.83
Total 3-phase	31	7.31	1	0.24	1	0.24	12	2.83
Grand total	328	77.3	36	8.50	5	1.20	55	13.00

disturbance. Other transitory disturbances would also tend to decrease the percentage of lockouts.

Lightning Measured on 4-Kv Overhead Circuits

Discussion of a paper by Herman Halperin and K. B. McEachron published in the January 1934 issue, p. 33–7, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 465.

Edward Beck: The paper by Herman Halperin and K. B. McEachron is timely and important because here are presented for the first time field test data on a distribution system. The writer agrees with the order of the lightning arrester currents mentioned by the authors for this system, but we would like to point out that even on this system higher currents may occasionally occur. The probability of this occurrence appears to be so low that the authors consider it negligible. Certain observations and experience indicate that on some distribution circuits the occurrence of surge currents of several thousand amperes is not negligible, and that currents of the order of 80,000 to 100,000 amp are possible although very rare.

Of considerable interest in the paper are the results secured on transformers with interconnected lightning arresters which show the considerable benefits to be secured by the application of protection around the transformer thereby limiting the voltage which may be applied across the transformer to the lightning arrester voltage even though the potential from the primary leads to ground may be of considerable magnitude as indicated in the authors' Table II. Of further interest in this table is the fact that the field tests produced records of the voltage across interconnected transformer and therefore across the lightning arrester itself which are in good agreement with the voltage measured across terminals of lightning arresters in laboratory tests.

With increased attention being given to the reliability of distribution circuits, the collection of data of the kind presented by Messrs. Halperin and McEachron is very valuable and it is hoped that this paper will stimulate further investigation by others, particularly on some exposed rural distribution lines.

C. L. Fortescue: This is the first case of a systematic investigation of surges on distribution circuits that has ever to my knowledge been carried out. While the tests have resulted in a large amount of statistical data on low potential surges that occur on distribution lines, the set-up was such that potentials above 500 kv would not be recorded because they would cause flashover of the potentiometer used in connection with the surge recorders. In like manner, large surge currents through the lightning arresters would not be recorded because an instrument and potentiometer to record the potential of the surge always accompanied these installations.

If we consider a section of distribution line 0.5 mile long, the probability of strokes above 2,000 kv terminating on the line within this section is only about 0.15 per year or about one every 7 years. The probability of strokes of 8,000 kv and above is about $^1/_{10}$ of this or 0.015, about once in 70 years. In considering the possible potential that may arise on such a line due to being hit by a stroke of lightning, the resistivity of the earth and the resulting resistance at the pole must be considered. The probability of strokes of the order of 20,000 kv terminating in the half mile section is about 0.003 per year and the probability of a particular transformer in this half mile section receiving such a stroke is still smaller, being probably of the order of 0.0002 per year. If there are 1,000 such sections, each containing a transformer, the probability of a transformer receiving such a stroke is of the order of one every 5 years out of the 1,000 transformers. If the value of current due to such a surge will destroy an arrester and both arresters will be involved, and if there are 1,000 transformers with neutral connections each using 2 arresters, about the same number, namely, one out of 1,000 every 5 years, will be lost.

The above figures are rough and simply indicate the order of the magnitudes encountered and apply to suburban circuits. The presence of a large number of guyed poles will materially reduce the hazard to transformer and lightning arresters due to lightning, and the hazard will be much less for urban lines. They, however, show how small is the probability even in 4 years testing of obtaining high potentials in the sections where measuring instruments were installed.

The idea quite generally held that the flashover of the line insulation including wood poles determines the magnitude of the potential of the surge on the wires is erroneous except when the footing resistance is very low. In some parts of the country footing resistance may reach values of several hundred ohms. Under such circumstances, most of the potential appears locally in the earth. I think that pole shattering due to direct strokes will take place whenever a severe lightning stroke hits a pole, but it will be more severe where the footing resistance is low, and the extent of travel will be reduced. A pole having a length of 40 ft between ground and cross arm has a probable minimum flashover under long surges of about 2,000 kv. It probably begins to flash over at this value even with steep waves but complete breakdown does not occur probably for 8 or 10 μsec at this potential. At higher potential, breakdown is accelerated but the surge potential will have time to build up to considerably higher potential than 2,000 kv before the complete breakdown takes place. With high resistance in series with the pole complete breakdown may never be reached because the small current required to raise the potential of the ground will be readily supplied by partial breakdown of the wood pole, and, therefore, the pole top potential will be high and the surge will be propagated over the line with attentuation due to corona and also due to partial breakdown to the high resistance ground at each succeeding pole.

It should be evident, therefore, that the test reported in this paper includes none of the surges that is likely to injure transformers or destroy arresters, as the potentials recorded are not sufficiently high and should be well within the capacity of even the poorest types of lightning arrester.

I was fortunate enough to witness a direct stroke to the distribution line supplying my house a couple of years ago. I was outside on the veranda watching the lightning storm when the stroke took place about 2 blocks from my house. Streamers issued from all the wires for the full length of the 2 blocks, of the type encountered in the laboratory and known as suppressed discharges. The pole these discharges appeared to enter showed evidence of surface corona at spots along the pole. Unfortunately, this stroke happened in daylight and the full extent of corona over the pole surface was not visible, but the streamers issuing from the line wires would indicate a value of the surge traveling over the wire of at least 1 or 2 million volts and the surge was evidently sharply suppressed by the discharge to ground. The station circuit breaker opened and the telephone cable on the same poles was injured putting the telephone service out of commission until repairs were made.

My conclusion after reading the paper is that the majority of surges recorded in these tests are induced surges which would be expected to be large in number. The higher potentials that were encountered may have been due to side flashes or small strokes which may have been reduced in magnitude due to having occurred near an arrester. To give due credit to the authors of this paper, it must be pointed out that this data which they have procured are the statistical data that are lacking in our lightning statistics and while this type of surge is not likely to cause outages or injury to apparatus, it is likely to be the cause of other troubles not so serious from the operating company's point of view but which on account of its frequency of occurrence must be considered.

J. K. Hodnette: The authors have presented some interesting data on the voltages and currents produced in low voltage urban distribution circuits by discharges of lightning. They form a valuable indication of the frequency of occurrence and approximate magnitude of surges in these circuits.

From the data obtained, the authors have reached the interesting conclusion that the surge currents usually expected on urban circuits are 300 amp or less and the surge voltages considerably less than 200 kv. These values agree with the general conception of the values that would be expected for induced surges in metropolitan districts where the lines are largely shielded by buildings and other tall structures and where direct strokes are indeed improbable. However, the same does not apply to distribution circuits in general as evidenced by the fact that on the short, 1,600 ft, sections of exposed line, the authors obtained 82.5 per cent of their measurements of voltages in excess of 50 kv. On rural and village lines, the expectation of high surge voltages would be increased as well

as the frequency of occurrence. Also on such lines direct strokes would be expected to occur more often.

Two years' field experience with several thousand distribution transformers with lightning protection around the transformers, on lines throughout the country have indicated that high surge currents occur relatively often (See "Heavy Surge Currents—Generation and Measurement," P. L. Bellaschi, ELECTRICAL ENGINEERING, January 1934, p. 86–94). This experience is not interpreted as establishing the probability of direct strokes on distribution circuits on account of the diversity of locations, etc. It does indicate, however, that each year approximately 0.5 per cent of such transformers are subjected to very high surge voltages, or their protective devices to surge currents many times higher than those measured by the authors.

In addition, a direct stroke does not have to hit the line very near a transformer to give rise to these high currents. High surge currents may be conducted along the line for a relatively long distance—possibly as far as 1,000 to 2,000 ft under usual conditions of line construction and ground resistances. Although the enormous voltage attending a direct stroke of lightning on a line is sufficient to flash over the pole insulation, where the ground resistance at the base of the pole is high, a voltage of high magnitude will still remain on the line until it is shunted to earth by other contacts or a low resistance connection such as the multiple grounds of a secondary neutral.

On exposed lines, as indicated by the above field experience, heavier surge currents than these indicated by the authors must be taken into account.

Herman Halperin: The experience in Philadelphia, as reported by H. N. Ekvall, gives further evidence of the operating and economic advantages of the use of the interconnection in urban territory. For such applications, all available data indicate that these improvements obtain with no increased hazard to customers' premises and with no very serious accompanying disadvantages. The only disadvantage found in the Chicago experience was that with the interconnection, the rate of failure of arresters during lightning was about twice the rate for the arresters grounded only to a driven pipe. This increase means that with our complete use of the interconnection the number of arrester failures would increase from about 25 to about 50 per year. On the other hand, annual removals of arresters due to all causes in Chicago are several times these figures.

Referring to Mr. MacCarthy's remarks, while 2 high voltages, i. e., 30 and 37 kv were measured across the secondary lead of the transformers, the practically complete absence of troubles in customers' premises indicates that such voltages are not maintained for an appreciable time nor exist very far out on the services to the customers. In addition to his point that the lower rate of transformer failure near open ends of lines may be due to the smaller primary exposure for such installations, the lower rate could be due to the lower voltages that are incident to draining surge current from practically one direction as compared to the surge voltages that appear with surge current drainage for two directions. As Mr. MacCarthy remarks, with reference to Fig. 6 of the paper, conditions at the end of the line opposite the arresters shown may have affected the voltage distribution along the line. In reply to his inquiry, the distances to the nearest equipment, shown in Fig. 7 as 750 ft and 1,600 ft, also represent distances to the nearest arresters.

We agree with Messrs. Beck, Fortescue, and Hodnette that very high surge currents probably do occur on distribution lines—rarely in urban districts and more frequently in rural territory. It is interesting to observe that Mr. Fortescue's analysis of severe surge currents, apparently derived on a probability basis, is in good agreement with statistical records in Chicago. For transformer burnouts due to direct strokes about one transformer failure occurs per 200,000 transformers per storm, or roughly one transformer per 1,000 transformers every 5 yrs. The rate of failure of arresters installed in the normal manner, during thunder-storms has been about three failures per 1,000 arresters every 5 yrs. This, while somewhat higher than the figure given by Mr. Fortescue, probably includes also failures due to voltages lower than the values assumed by him, which are not only approximate, but also probably high. His statement that the surges recorded were not of dangerous proportions is questionable in view of test data and operating experience showing that many distribution transformers in service will fail at surge voltages of about 100 kv or even considerably less.

K. B. McEachron: As pointed out by Messrs. Beck, Fortescue, and Hodnette, direct strokes will be a more important factor in connection with exposed lines than it will be for unexposed circuits. This means that high impulse currents may be expected to be encountered more frequently on rural circuits than on those circuits where considerable shielding exists. That this is true in Chicago is shown by the comparison between the so-called "long" distribution circuits and the urban circuits.

The data obtained do not shed any light on the frequency of occurrence of discharges of great magnitude on rural circuits. Data of this sort should be obtained in order that the proper valuation may be placed upon the necessity for direct stroke protection on rural circuits. The experience with a large number of arresters on rural circuits does not seem to indicate that direct strokes of great magnitude are a predominant factor in rural protection. However, as I have already indicated, more data are necessary before any conclusions can be drawn.

I am somewhat surprised to note that Mr. Fortescue believes that none of the surges reported in the paper are likely to injure transformers. It is interesting to note in this connection that distribution transformers do fail in Chicago during lightning storms without any evidence of damage either to poles, cross-arms, or arresters. The very great reduction of transformer failures, due to interconnection, indicates clearly that most of these failures are not due to the inability of the arrester to perform its intended functions, but rather due to the circuit arrangements which permit the effects of ground resistance and length of ground lead to seriously influence the protection afforded the transformer.

With transformers and arresters in proper condition, it seems that it ought to be possible to reduce the number of transformer failures to those cases associated with severe direct strokes, in which the current magnitude is of the order of several thousand amperes.

It is to be hoped that statistical data, relating to the performance of arresters on rural circuits so arranged as to show the relation between pole damage and these failures, will be gathered and presented to the Institute, to help clarify this whole question of the requirements of protection for the distribution transformer.

Control of Distance Relay Potential Connections

Discussion of a paper by A. R. van C. Warrington published in the January 1934 issue, p. 206–13, and presented for oral discussion at the protective devices session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 465–6.

A. R. van C. Warrington: E. E. George is correct in his assumption that at present the automatic potential switching means described in the paper are not generally applicable for use with bushing potential devices.

Both Messrs. George and Neher brought up the point that the nature of the fault may change before the distance relays have operated which might result in incorrect distance measurement. The type of change which would necessitate a change in potential connections is the spreading of a single-phase ground fault to one or both of the other phases. The single-phase ground fault requires wye voltage while delta voltage is required for multiphase faults if residual current compensation is not employed as in Fig. 5. In Fig. 8 residual current is added when the relay is supplied with wye potential, and the zero sequence component of the current eliminated during multiphase faults, so that the distance relay operation is correct with either position of the transfer switch if the ground fault involves more than one phase. In Figs. 9 and 10 wye voltage and residual-compensated current are supplied to the distance relay on all ground faults regardless of the number of phases involved.

Mr. Neher has pointed out that distance relays in which the ohmic and starting units are supplied with potential from different phases will require separate switching for the two units. This means duplicate contacts on the switching relays in Figs. 1, 2, and 3, which would therefore seem more applicable to distance relays with single-phase potential with amplifying means for insuring reliable operation on low voltage. Where 3 relays are used for phase and for ground faults (Figs. 5, 8, 9, and 10) there are 2 alternatives. Either single-phase potential can be used or the ohm units only can be switched, their starting units being supplied with excitation suitable for response to both interphase and ground faults.

Portable Schering Bridge for Field Tests

Discussion of a paper by C. F. Hill, T. R. Watts, and G. A. Burr published in the January 1934 issue, p. 176–82, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 478–81.

F. C. Doble: The discussion of this paper by Messrs. Sporn, Gross, Balsbaugh, and others has been of great interest and constitutes a valuable addition to it. It is especially gratifying to have the Westinghouse Company put the stamp of its approval on power-factor and loss measurements as reliable indices of the insulating integrity of bushings and other insulation. Mr. Sporn referred to the work he has been doing for the last 4 years in service up-keep using the Doble power-factor test set. To complete the record it would be well to state that this test set and the method of field testing using power factor which was developed by the Doble Company was quite thoroughly described at a special meeting before the N.E.L.A. at Harvard University in April 1931. Again a paper was presented in October 1932, before the National Research Council in Baltimore covering the results obtained from 3 years of field service.

In designing the Doble power-factor test equipment some 5 years ago a great deal of thought was given to the selection of the design and type of apparatus to be used in order to get the maximum of practical results from field testing. It was decided to employ the wattmeter method and direct-reading indicating meters. Some difficulty was experienced at first in adapting the meters to this use because no existing instruments were suitable but a special solution was worked out which leaves very little to be desired from that standpoint.

In this connection it may be noticed that the wattmeter method measures directly and effectively the resistance values of wood members in oil circuit breakers. Here the variable resistance that is sometimes encountered introduces no difficulty because the direct-reading instrument is able to follow changes as they occur which is not the case with the bridge where it is necessary to get a reading by seeking a balance. This balance method requiring an appreciable amount of time is ill-adapted to follow up a constantly changing value even though the magnitude of the change be not very great.

As might be expected, the authors do not attempt this kind of reading with the apparatus which they describe but recommend the substitution of the megger for that purpose. There is another point which no doubt influences them also and that is the practical impossibility of making resistance measurements with this bridge as designed where the capacitances involved are extremely small as is necessarily the case with wood members.

In the field, high electrostatic effects are apt to be present. Such effects as they produce are, in the case of the wattmeter type of test set, effectively averaged out by taking additional readings with reversed source connections.

It seems as if the bridge would not lend itself so effectively to this means of eliminating objectionable inductive effects and, in point of fact, in the field such a situation is known to have arisen.

B. L. Goodlet: I notice that the work described in this paper is stated to be "probably the first application of the Schering Bridge to field tests."

I would therefore contribute the information that the company with which I am associated has employed a portable Schering bridge for field tests for something like 5 years.

The first portable Schering bridge was constructed by my firm in 1928, after several years' experience of power factor tests in the works had proved the value of the method. A photograph of this early instrument is reproduced in Fig. 1. The test voltage is 5 kv, the transformer and bridge being both contained in a single wooden box 18 × 21 × 17 in. The small box on the right is a ratio transformer to allow the bridge to be fed from any a-c supply from 100 to 500 volts.

This instrument was first employed in field tests carried out under my supervision in the London district in 1929, and has been in regular use ever since. The development has not to my knowledge ever been described in print but is alluded to on p. 17 of a paper "A Contribution to the Better Knowledge of Resin Paper Insulation" read by the writer at the last International High Tension Conference (Paris, June 1933).

Figure 2 of this paper (taken from a still earlier one) is the same as Messrs. Hill, Watts, and Burr's Fig. 6, while Figs. 3, 4, and 5 support their statement that the majority of bushing troubles are due to moisture entering the bushing.

For the last 5 years every paper bushing made in our works has been given a power-factor test at maximum rated voltage and temperature. Each bushing passed is marked with an identity number from which its manufacturing history can be traced. This information being available, the results of field tests can be immediately assessed. No trouble has been experienced since this practice was adopted.

I. W. Gross: The authors have summed up the bushing testing problem quite correctly when they say: "Dielectric loss measurements detect deterioration of insulation which might later cause failure." This principle was made use of in the portable insulation tester we have been using. In fact, the set reads "watts" and "current" directly, and from these values the power factor is obtained by one setting of a slide rule, since the applied test voltage is 10,000 volts. In detecting defective conditions internal to the oil circuit breaker, we put entire dependence on the watts loss readings, and a correct interpretation of these easily locates trouble external to the bushings. It seems to us, if excess dielectric loss is the cause of insulation failure, a test set should, if possible, measure this loss directly and not measure everything except this loss.

The field technique of testing described by the authors, such as measuring power factor on oil circuit breaker bushings with the breaker open and closed, and testing transformer bushings with and without windings, we have been making use of ever since we first used the power factor method of test, that is, over a period of some 5 years. It is interesting to note that the authors suggest little in the way of improvement in test methods with their test set.

The idea of applying power-factor measurements to oil was, to our knowledge, first brought out for field use about 2 years ago. Since that time we have used this test repeatedly. Our experience has been that where defective insulation was found the oil frequently had a high power factor, although in some cases the oil has tested good on the breakdown test. It would be interesting to know what the authors' experience has been in this respect, and at what value of power factor they recommend reconditioning the oil.

There is one feature of power-factor testing on which the authors have placed some emphasis. That is, disconnecting the leads from an oil switch to the bus or disconnecting switch. Leaving the lead attached.

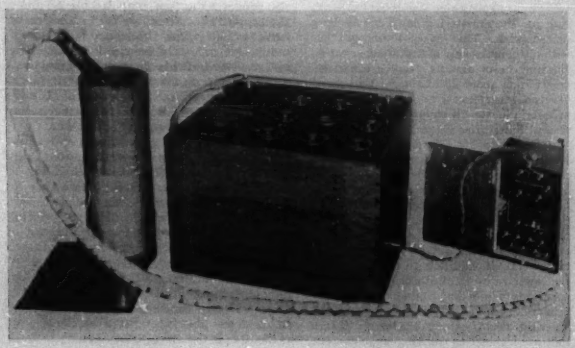


Fig. 1. Portable Schering bridge constructed in 1928

Fig. 2. Laboratory test set-up for determining bushing temperature-power factor characteristics

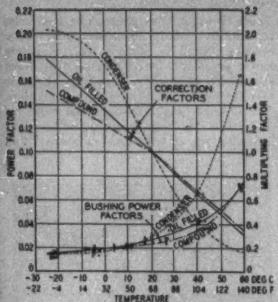


Fig. 3. Power-factor temperature characteristics of bushings

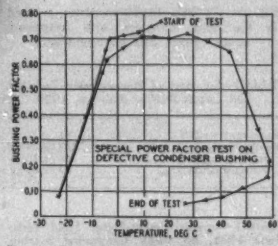


Fig. 4. Power-factor temperature characteristics of a very bad bushing

they claim "has disadvantages which lessen the value of the bushing test." We have found, on the contrary, that there are in most cases, distinct advantages in leaving the lead attached, provided the test set is capable of detecting defects under these conditions. With the lead attached all switch and lead insulators are included in the test circuit. We have, in some cases, actually found defective insulators by this method of test which would not otherwise have been found. Pickup interference due to this lead has never given us any trouble in our testing work.

It is also stated in the paper, that if the test is made with the lead attached, the bushing capacitance is not obtained, and that this should be watched as closely as the power factor. We have never used the capacitance characteristic of a bushing in any of our tests on condenser bushings to determine a bad bushing, although it is easily obtainable from the measured field current, and yet, we have been able to pick out defects in condenser bushings the same as in any other bushing.

One of the important features of bushing testing is locating the trouble. In testing some 15,000 bushings of all types, and over 2,000 oil circuit breakers, we have run down in detail a great many cases of trouble. One typical example may be of interest. An oil circuit breaker was found with bushings having a high power factor; and the insulating wood inside the breaker showed defective. In one bushing bad oil was found with 5.4 per cent power factor, but having a breakdown test of 31 kv. This oil was changed. A heavy carbon deposit was also found inside the breaker. Cleaning the inside of the breaker failed to remove all the trouble, so the wood guide and lift rod were checked for resistance by the power factor test set. One guide, in different sections of its length, showed a resistance from 21 to 270 megohms, while a corresponding new guide had 1,540 megohms resistance. The old lift rod had a resistance from 63 to 200 megohms, while a new lift rod had 3,000 to 10,000 megohms. The old lift rods and guides were baked and finally brought back to a resistance of 2,000 to 10,000 megohms. These megohm readings were all taken on the test set, and not by the ordinary d-c instrument. Eleven months later, when the breaker was retested, the power-factor readings were normal, showing that the trouble which had been removed had not recurred. This type of detailed investigation in definitely locating and clearing up trouble is typical of some of the work we have done with the test set, beyond the mere routine testing of bushings.

Although our testing of transformer bushings has not been so extensive as on oil circuit breaker bushings, recent results indicate the desirability of testing transformer bushings, if costly failures are to be avoided. On one of our properties where systematic testing of transformer bushings has recently been started, out of 100 transformers tested, 11 "defective" conditions, and 7 "remove" conditions of insulation were found. This indicates faults considerably higher than the average found on oil circuit breakers, although the extent of the transformer tests is still too limited to draw this as a definite conclusion.

In carrying out our field testing through an entire year, we noted the power factor readings of bushings were affected by the temperature, but not sufficiently, at the time, to cause any concern. As the test work proceeded, however, and the test set had definitely proved its ability to find insulation faults, refinements in the testing technique were made. One of these was the determination of bushing power-factor values with temperature variation. Test equipment for this work was made available by the Doble Engineering Company, and several bushings of different types were obtained from the field and taken to the laboratory for detailed tests. The laboratory set-up for carrying on these tests is shown in Fig. 2. The bushings were enclosed in a cubicle and the temperature altered from −23 to approximately 60 deg C.

The power-factor temperature characteristics of the condenser, oil filled, and compound filled bushings tested are shown in Fig. 3. These power-factor curves have been converted to correction factors for use in reducing all field power-factor readings to a 20 deg C reference basis. Although the tests were carried out with care and precision, it is not maintained that the correction factors can be used indiscriminately as a hard and fast basis to eliminate temperature effects entirely on power-factor readings. Many more such tests will be required on a large number of bushings before an accurate average representative curve for each type of bushing can be obtained. But even then, it should be kept in mind that all parts of a bushing in the field are rarely at the same temperature, so that the data presented in the figure is probably sufficient for the purpose intended, which is, to correct observed power factors, on a practical basis, to a given reference basis.

In Fig. 4 is shown the power-factor variation of a very bad bushing as the temperature was lowered from 17 deg C to −23, then raised to 58 deg, and again lowered to 28 deg over a period of about 5 days. At the end of the test the bushing, which then had a power factor of 0.055, was flashed over once on 60-cycle test, but on the second application of voltage, the bushing punctured. The deduction we have drawn from this special test, as well as from field tests on other types of defective bushings, is that if the bushing is found very bad, it is doubtful if its insulation can be satisfactorily rejuvenated.

There are several points in the last 2 paragraphs of the authors' paper that are not entirely clear. The implication that a bushing with high power factor (that is, with defective insulation) will give satisfactory service, provided it has a somewhat higher voltage rating than the rated voltage of the circuit on which it is used, does not seem sound. We have found several bushings defective by the power-factor test in the field, which later successfully withstood a 60-cycle high voltage test, and then failed on impulse tests. Such bushings even though they have a voltage rating in excess of the circuit rating, are a potential hazard, unless their impulse strength is in excess of other nearby apparatus, or unless other protection to limit impulse voltages is supplied. Even where a defective bushing has a high rated voltage in comparison to the circuit voltage, such a bushing may fail in service if it is not carefully watched for rapid progressive deterioration. We believe bushings in the above class, except in rare cases, can be justly classified as a general nuisance on a power system.

The paper states "the number of faults will materially decrease with repeated tests." This is a rather optimistic general

conclusion. Decrease in bushing faults and failures is the goal of every operating man, but repeated tests to locate and remove insulation faults must also be supplemented by effective work in reducing the cause of the fault, if a worth while reduction is to be secured. While power-factor tests have demonstrated their ability to detect faults in existing bushings and similar insulation, we need, for the future, more careful thought and intelligent design in rendering such insulation immune to trouble, and serviceable under the conditions which must be met in service.

Philip Sporn: The authors state that "a portable instrument for the measurement of dielectric loss was not available for purchase and use by the power companies until the Schering bridge here described was developed." As a matter of fact the idea was first proposed and a test set made available some 5 years ago. Although the method was viewed with skepticism at the time, the situation today is entirely different. The power-factor method of testing bushing and similar insulation is now a generally accepted practice.

Bushing testing with a portable power-factor tester has been carried out on the properties of the American Gas and Electric Company system for the past 5 years. In Fig. 5 there are shown 2 views of the type of test set that has been employed. You will note the compactness of the set which includes a transformer, control panel, and test instruments. This test set was designed and built by the Doble Engineering Company. In Fig. 6 is shown the use of this equipment for testing bushings, in this case the test being made on a 33-kv transformer. In Table I is shown a summary of results of bushings tested in 1929. You will note that out of some 3,880 bushings tested there were found 122 cases, or 3.15 per cent, of faulty conditions. These, when further analyzed, showed 58 bushing faults totaling 1.5 per cent, and 64 external faults, or 1.65 per cent. Because of this comparatively large percentage of faults, and because of the damage that a bushing failure, particularly a failure of a bushing connected to the bus side of a high voltage heavy power bus invariably results in, it was decided to continue, and further develop, this method of testing. It was felt, for example, that when faced with a situation such as is shown in Fig. 7, which shows 7 44-kv bushings that failed on one property during one storm, or when faced with a situation of defective insulating material like the one shown in Fig. 8, which shows the bracing material and operating rod on a 66-kv breaker, that something more than merely replacement with another insulating member of the same kind, or something more than merely waiting until the actual damage occurred and then mopping up, was necessary. Proper operating and proper engineering dictated the digging down and finding out what was causing these troubles, and if possible, setting up standards for safe equipment and standards of unreliable and unsafe equipment, so that the unsafe equipment could be taken out, serviced, and replaced before the damage was actually done.

The extent to which the problem was studied can perhaps be seen by Fig. 9 and Table II which show diagrammatically the results of a study of a particular 44-kv bushing found in service with a power factor of 0.076. On the basis of previous standards established, it was found that this represented a poor insulating condition. The bushing was then dissected piece by piece and the results of this dissection, including the power factor and watts loss readings shown progressively in the table, until finally the defect was definitely located. The felt washers which were used between the individual skirts of the porcelain had absorbed moisture, and gave a power factor anywhere from 0.36 to 0.98. This wet felt had apparently resulted in moisture and other deleterious effects communicating themselves to the condenser layers of the bushing, and resulted in bringing the insula-

Fig. 5. Portable insulation tester as used in the field, complete with transformer control panel, and instrument case

Table I—Summary of Power-Factor Tests on Oil Circuit Breaker Bushings, 1929

Bushings tested	3,881
Faults found	122 (3.15%)
Bushing faults	58 (1.50%)
External faults	64 (1.65%)

Table II—Special Power-Factor Field Tests, June 1931, on 44-Kv Transformer Bushing Shown in Fig. 9

Test condition	% P. F.	Watts
Bushing in transformer tank (as found)	7.6	1.21
Bushing out of transformer tank	8.0	1.27
Bushing out—low end wiped	8.1	1.29
Bushing—top porcelain shell removed	7.5	1.13
Bushing 2—top porcelain shells removed	8.0	1.19
Bushing 3—top porcelain shells removed	8.2	1.24
Bushing 4—top porcelain shells removed	8.2	1.23
Felt washers between porcelain	36–98	0.21–1.45
Individual condensers (1 to 8)	6.9–15.0	1.07–6.7

NOTE: Felt washers between porcelain water-soaked insulation deteriorated.

Fig. 6. Testing a 33-kv potential transformer in the field with the portable insulation tester

Fig. 7. Seven 44-kv bushings which failed during one lightning storm, June 1931

Table III—Power-Factor Tests in 1931 on 44-Kv Bushings

	Field Tests			Factory Tests			
					60 Cy.	Impulse	
Ref.	% P. F.	Watts	Megs.	% P. F.	Kv-F. O.	Kv (1 1/2 x 40)	Remarks
1.	4.6	0.25	Inf	6.43	190	400	O. K.[2]
2.	6.2	0.31	Inf	8.6	180	438	O. K.[2]
3.	5.5	0.76	1,000	4.65	160[1]		Failed
4.	5.8	0.45	1,000	3.75	175	410[1]	Failed
5.	8.0	1.13	900	3.7	185[1]		Failed
6.	9.5	1.93	Inf		60[1]		Failed
7.	10.5	1.42	500	3.55	190	350[1]	Failed

1. Bushing failed.
2. This bushing had bad insulation in outer condenser, but enough good insulation left to withstand puncture.

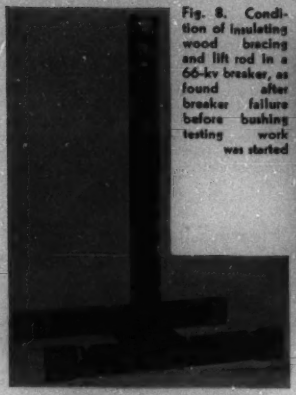


Fig. 8. Condition of insulating wood bracing and lift rod in a 66-kv breaker, as found after breaker failure before bushing testing work was started

Fig. 10. Field testing a 37-kv oil circuit breaker

Power-factor test set is located inside specially fitted light delivery truck

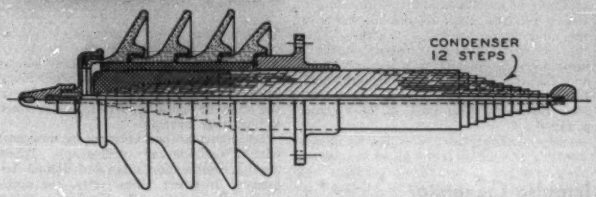


Fig. 9. A 44-kv bushing

Table IV—Analysis of Defective 37-Kv Oil Filled Bushing September 1932. (See Fig. 11)

	Per cent	Watts
Field test power factor	19.5	1.91
Test 24 hours after removal	42.0	....
Bushing oil (top)	17.1[1]	2.0
Stud insulation	46.0[2]	5.2
Insulating sleeve (top)	100.0[2]	5.8
Near bad spot in sleeve	95.0	11.0
Bushing after disassembling and filling with new oil	35.5	2.1
60-cycle test	broke down at 180 kv. Insulating sleeve punctured — creepage along stud insulation	

1. Oil Tested 19 kv.
2. Good insulation should be 2 to 3% approximately.

tion of some of them down to a point where they had a power factor as high as 0.15.

Some of the other early results that pointed to the absolute necessity of continuing power-factor testing can be gathered from Table III which shows the results of some power-factor tests made in 1931 on a group of 44-kv bushings. In this table there are shown both field and laboratory tests of 7 bushings, all of which had indicated defective condition by power factor tests in the field. On being found defective by field test, they were taken to the laboratory, power-factor tested by the laboratory test set, given 60-cycle flashover tests, and later, when they survived the 60-cycle test, given impulse tests with a $1^1/_2 \times 40$ wave. The interesting thing in connection with this table is that 5 of the 7 bushings failed on voltage test, and No. 4 and No. 7, although passing the 60-cycle test, both broke down under the impulse test. This, of course, is not in agreement with the expectation of the authors that a bushing which would meet the standard one-minute test, by which I presume is meant to be a 60-cycle test, would be expected to be a satisfactory bushing. Of course all of those who have gone into the problem of insulation coördination over the past 8 years or so, have found out a long time ago that a 60-cycle test is not adequate as a sole reliance of insulation strength.

The result of all of this work throughout 1929, and 1931, definitely led to the conclusion that:

(a). Periodic testing of bushings by power factor methods was essential in the present stage of the bushing art.
(b). That a satisfactory method and satisfactory instruments for carrying out such tests were available and could be relied upon to give consistent and reliable results. This does not check the authors' statements as to availability of equipment prior to the set they have described.

It might be interesting in this connection to show how our test equipment is being handled in the field. In Fig. 10 is shown a standard light $^1/_2$-ton truck with a delivery body, which is used by the test man to transport the test equipment to and in the field. In the rear of this truck all the necessary test equipment is carried, and is frequently used without removing the test transformer or instruments from the car. The equipment is shown at one of the substations with the test being carried out on a 37-kv breaker bushing. Note the simplicity of the arrangement and the fact that the test set has not been moved out of the car for obtaining the readings. The particular test equipment that we have used in the past 5 years is, of course, suitable for testing any type of bushing, and with proper application, to a great deal of insulation, some of which we have already started testing and on others of which we are feeling our way.

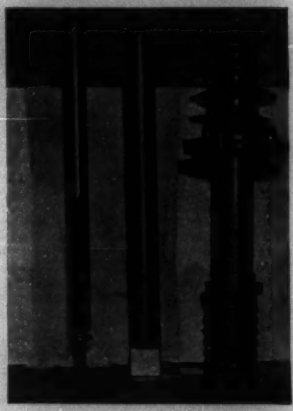


Fig. 11. 37-kv oil filled bushing found defective on field power-factor test

Note defective spots in insulation which broke down with 160 kv 60 cycles applied to bushing

In Fig. 11 is shown a standard oil filled 37-kv bushing which, through the use of

Table V—Summary of Field Power Factor Tests on 8,376 Bushings (1932–33)

Type of Bushing	Oil Filled	Comp. Filled	Condenser	Solid Porc.	Totals & Per Cent
Bushings in service					
Number tested	4,210	2,344	936	146	7,636
"Defective"	270	218	124	27	639
"Remove"	247	106	74	17	444
% "defective"	6.4	9.3	13.2	18.5	8.4
% "remove"	5.9	4.5	7.9	11.6	5.8
Spare bushings					
Number tested	334	302	102	2	74.6
"Defective"	14	19	15[1]	0	48
"Remove"	11	10	43[1]	0	64
% "defective"	4.2	6.3	14.7[1]	0	6.5
% "remove"	3.3	3.3	42.1[1]	0	5.7

1. All rather old bushings stored in position in oil circuit breaker, in oil.

the test equipment, had the trouble definitely diagnosed. The history of this bushing is shown in Table IV. It will be noticed that this bushing was found on field test with a power factor of 0.195 and a watts loss of 1.91. The bushing was torn down and the insulation around the conductor was found to have a power factor of 0.46. The insulating sleeve had a power factor of approximately unity. The normal power factor of this insulation when tested separately should be in the order of 0.02 to 0.03. The bushing was then flushed out with clean oil and reassembled with the same insulating parts, and was found to have a power factor of 0.355 and a watts loss of 1.2. The 60-cycle test was then made on the bushing and the bushing broke down at 180 kv. The breakdown, which is clearly shown in Fig. 11, resulted in a puncture of the conductor and sleeve insulation. This is only one of a number of cases where bushings found defective on field tests, were actually investigated and the trouble definitely located.

In the past 5 years there have been tested on the American Gas and Electric Company system, some 15,000 bushings. A summary of the results found on over 50 per cent of these bushings is given in Table V. It will be noted that the percentage of defects which averaged 8.4 per cent, varied from 6.4 per cent to 18.5 per cent and the percentage which was recommended for removal averaging 5.8 per cent, varied from 4.5 per cent to 11.6 per cent. What is even more striking is that spare bushings, which are generally considered by the operator as his second line of defense, did not stand up a whole lot better. All of this goes to show that there is no such thing, apparently, as insulation, and particularly composite insulation subjected to exposure and action of the elements, that can be safely forgotten.

In closing, I think we ought to say that we know that as a result of our own work and the work of a number of other operating companies, power-factor bushing testing and general power-factor testing of insulation is no longer in the pioneer stage, and that it has a well established and solid background at the present time. In our own case, testing with the equipment described, reading watts loss and current, and calculating power factor has given most practical and excellent results.

We have found, too, that carrying on our tests entirely independently of the designers of the equipment has had its advantages, and that we have been able in doing that to set up perhaps more definite standards of safe and unsafe operating practice. Further information on the results obtained in our system has been given by Gross and Turner. (See "Testing Bushings and Insulation by Power-Factor Method," *Elec. World*, v. 103, 1934, p. 68–72 and p. 110–6.)

Impulse Generator Circuit Formulas

Discussion of a paper by J. L. Thomason published in the January 1934 issue, p. 169–76, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934.

P. H. McAuley: The author has made a rather complete tabulation of impulse circuit formulas. He states that their primary value is to prove that cathode ray oscillograms actually record test-piece voltages. Unquestionably, it is gratifying to be able to justify mathematically, established laboratory practices and measuring equipment. But it is to be regretted that reliable circuit analyses do not precede the working out of these relations in the laboratory. If the calculations had kept pace with practice, our impulse testing literature would not have so many inaccuracies and disagreements.

The author has based most of his results on a generator capacity of 0.01250 μf. This is a practical value quite likely to be found at least up to the 2,000-kv class. In Fig. 3 of the paper it is shown that, for the conditions assumed, a smooth wave voltage of only 50 per cent of the rating of the generator can be obtained. About 3,000 ohms series resistance is required to damp out the oscillations. These oscillations, occurring with inadequate series resistance, have caused many errors in voltage values in the past, particularly where the sphere gap has been used for voltage measurement. The sphere gap measures the crest value of the oscillation which may be as much as 25 per cent higher than the equivalent smooth wave flashover voltage of the test piece.

Another conclusion that follows for the wide range of conditions which the author has assumed concerns the wave front. The minimum wave front shown, Fig. 8 of the paper, is 0.9 μsec. This is further evidence of the impracticability of a wave with a $^1/_2$ μsec front.

Heavy Surge Currents—Generation and Measurement

Discussion of a paper by P. L. Bellaschi published in the January 1934 issue, p. 86–94, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 481–2.

W. G. Roman: A high current surge generator similar to that described by P. L. Bellaschi has been used for several months in the impulse laboratory at East Pittsburgh. It has been found very valuable in the study of lightning arrester performance at high surge currents.

Surge currents and voltages are measured with a cathode ray oscillograph. When making combination surge and normal frequency, or power follow tests, the surge generator can be synchronized with either crest of the normal frequency voltage. A galvanometer type oscillograph and a ballistic wattmeter are used to measure the normal frequency power follow. The ballistic wattmeter is valuable in statistical studies or in routine arrester tests. The capacitor units are arranged in 2 banks of 10 units each and can be used all in parallel at 100 kv or as a 2-stage generator at 200 kv. The physical arrangement of the capacitors, discharge gap, and test cell is shown in Fig. 1.

The compact arrangement of the circuit, and the use of several parallel discharge paths where possible, has resulted in a low equivalent inductance for the circuit. Therefore, although the surge generator is physically small, the current output is high. The discharge is a damped sine wave, the period being 19 μsec. At a charging voltage of 92 kv the current reaches a crest of 125,000 amp the first half cycle. The oscillating current decays to half value in approximately 40 μsec.

A surge current shunt with a very low ratio of inductance to resistance was developed. A sketch of this shunt is shown in Fig. 2. The resistance elements are twisted resistance wires spaced around the circumference of the concentric brass tubes. One of the resistance elements is shown in the sketch. The resistance elements have a slight amount of inductance and at high frequencies a voltage component leading the current by 90 deg will be induced. By looping one of the leads to the current measuring cable back through holes in the concentric tubes, as shown in the sketch, a voltage lagging the current by 90 deg is induced. By making this loop the proper

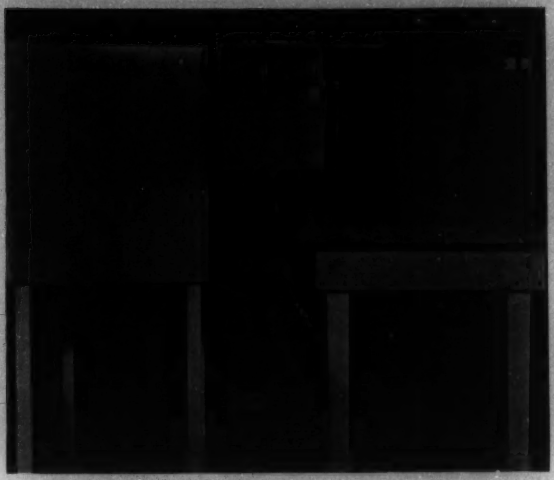


Fig. 1. High current surge generator showing capacitors, discharge gap, and test cell

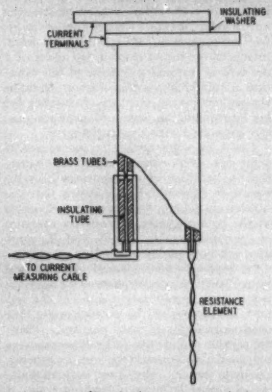


Fig. 2. Sketch of surge current shunt

size the leading and lagging components of voltage can be made to cancel and the shunt will have nearly a pure resistance characteristic. When thus compensated a typical shunt has a time constant of 0.07 μsec and the error at 100,000 cycles is less than 0.5 per cent.

P. L. Bellaschi: A review of the paper along with the interesting discussions which this paper has stimulated indicates clearly that the technique of heavy surge currents can now be considered well established for all practical purposes. The various points brought out in the discussions are either fully treated or summarized in the paper by specific as well as general statements, these statements being based on lengthy analysis and experiments that could not have been incorporated in minute detail in the paper without unduly lengthening the paper.

Theoretically speaking, there are various methods of securing a surge generator of low impedance. In fact a number of arrangements have been considered by the author, such as the fan-type arrangement of parallel condenser groups, the ring-type arrangement, etc. But, in addition to the ideal theoretical lay-out, other important practical considerations need be taken into account, such as for example: (1) The utilization of any apparatus already installed may be economically desirable; (2) the space requirements at the discharge gap is another consideration, particularly where the purpose of the test is to produce a direct-stroke current discharge to the fully assembled apparatus, excited and operating under conditions closely simulating service, and similar other practical considerations. It will be noted from Fig. 6 in the paper that the parallel condenser groups comprise substantially a fan-type arrangement. This arrangement meets the theoretical requirements of a heavy surge current generator, as well as the practical requirements in the way of physical space and facilities, required for conducting with full control and safety, tests on completely assembled apparatus, such as transformers with de-ion gap protection, fuse cutouts, lightning arresters, etc. The apparatus tested is enclosed in a steel tank (see Fig. 6) and is excited at normal operating voltage from a power source capable of supplying unusually heavy power current in the case of short circuit.

With the surge current generator described in the paper (see Fig. 6), the amplitude and duration of the currents attained (see Figs. 9 and 10) and used to test surge-proof distribution transformers with de-ion gap protection, simulate in severity the currents in the direct stroke of lightning. This surge current generator, as well as the one mentioned by Mr. Roman, may truly be considered *lightning current generators*. The surge currents that have been obtained and mentioned by Mr. Brownlee are more appropriately classified as of moderate severity.

The symmetrical aperiodic waves which are referred to by Mr. Brownlee may also be obtained with an autovalve block or element. The heavy surge current generator at Sharon is of sufficient capacity to generate and discharge through de-ion gaps unidirectional currents of durations as great as 40 μsec from crest to half-crest value (see oscillogram C, Fig. 10 of the paper).

The discussion presented by Mr. Brownlee on shunts is in accord with the analyses and experience of the writer. However, Mr. Brownlee has confined himself practically with the less difficult problem of low-current capacity shunts. The shunt B, Fig. 11 in the paper, is simple and rugged in construction, and is capable of measuring a surge current up to 150,000 to 200,000 amperes. This shunt can readily be replaced in case of damage and at a low cost. Calculated values of the resistance and inherent inductance for this type of shunt, given in Appendix II, if substituted in a numerical example will indicate that for all practical purposes this type of shunt is amply good; extensive experience confirms this. For slightly greater accuracy in reproducing the wave form of very fast waves, flat strips of thin ribbon separated by a few mils of insulation will give somewhat better results than the wire conductor, and for still more exact reproduction it is even desirable to compensate for the inherent inductive drop as mentioned by Mr. Roman (for illustration of compensated shunt, see "Generating 130,000 Amperes for Laboratory Testing," by P. L. Bellaschi and W. G. Roman, *Elec. J.*, March 1934, p. 96–100). These latter precautions become useful in extremely accurate or what may be termed scientific investigations, and also for waves much faster than are at present used.

The effects of skin and proximity effects were analyzed in sufficient detail by the writer and for conductors of high resistivity material these effects are of no practical importance. Similarly, the shunt capacity is of no importance.

Appendix III of the paper analyzes the physical problem of fusion of conductors and this analysis is well substantiated by experiments with actual surge currents. For further information on the laboratory investigations on heavy surge currents, Mr. Thomason is referred to the *Elec. J.*, issue of March 1934 and letters by the author published in *L'Elettrotecnica* during November 1933 and subsequently. The reference given by Mr. Thomason is of interest but no mathematical studies or analysis of the fusion characteristics of conductors are given therein. For some previous studies and analysis on this subject mention may be made to Reference (9), published as early as 1928.

As to the practical and fundamental knowledge of lightning currents, obtained in the laboratory, the extensive investiga-

tions on heavy surge currents described in the paper and correlation of these laboratory findings with field experience have now brought to practical realization a degree of protection of electrical apparatus against lightning which a few years ago was only to be hoped for. These laboratory investigations have also enhanced materially our fundamental knowledge of lightning phenomena observed in the field.

An A-C Potentiometer

Discussion of a paper by S. L. Burgwin published in the January 1934 issue, p. 108–13, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934.

C. L. Fortescue: Some 18 years ago there was considerable activity in the Institute in connection with potentiometer devices. Dr. Clayton Sharp at about that time wrote a paper in which he described various potentiometer methods for measuring the ratio and time lag of current transformers. I was particularly taken with the method using mutual inductance because it showed prospects of obtaining an absolute measuring device. Accordingly, I set out to build a potentiometer for the purpose of measuring the ratio and phase angle of current transformers using this scheme.

The instrument which I developed has been described (see "The Calibration of Current Transformers by Means of Mutual Inductances," by C. L. Fortescue, TRANS. A.I.E.E., v. 34, 1915, p. 1599–1615) and consisted of 2 main mutual inductances and auxiliary mutual inductances for fine adjustments. One of the mutual inductances had a current range of from 10 to 5,000 amp. All the mutual inductances were wound on toroidal marble coils, which had been accurately machined to within a few ten thousandths of an inch of the specified dimensions. However, in winding these toroids, which was done very carefully on a dividing machine, I overlooked one thing and that was the fact that in making a complete circuit with the solenoid around the toroid an extra turn is added at right angles to the other windings so that the mutual induction between this extra turn and the other windings passing through the toroid must be taken into account in the mutual induction. Consequently, when I came to check up the mutual induction of the coils, I found a small error from the calculated values which I could not account for as I had not taken into account this extra turn. As I recall, it was Dr. G. A. Campbell of the American Telephone and Telegraph Company who called my attention to this extra turn during the discussion of my paper.

The error due to this extra turn was exceedingly small and the mutual inductances were found to be almost perfectly astatic. Using this device, we were able to measure the ratio and phase angle of current transformers with great accuracy. We also used it experimentally to measure the resistance and reactance of reactors with a high degree of accuracy. In fact, the device was so delicate that a man passing within a few feet of the reactor and having a bunch of keys in his pockets would throw the instrument off zero. This device could also be used for measuring iron loss.

This device was designed principally to be used as an absolute standard for measuring ratio and phase angle of current transformers, and it has been used for this purpose and has given satisfaction during the past 18 years. The instrument used in connection with this device is a separately excited needle galvanometer so that the separate winding can be excited in phase and in quadrature by means of a phase transforming device. A remarkable thing about this potentiometer is that it is in continual use on our commercial testing floor at Sharon and has been found to be perfectly satisfactory and is unaffected by the regular commercial testing that is being carried on within a few feet of it.

I should like to point out also that the a-c calculating board is nothing more than a very large potentiometer in which 250 or more circuits are involved and by which the voltage and current distribution in these circuits can be measured accurately. The device for measuring voltage on the a-c board is a potentiometer device which gives in-phase and quadrature components of voltage. This a-c board has been in continual use for solving complicated network problems and has proved to be very satisfactory.

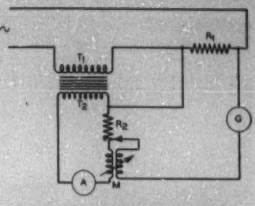


Fig. 1. A potentiometer circuit for the precise determination of ratios and phase angles of current transformers

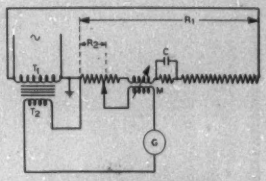


Fig. 2. A potentiometer circuit for the precise determination of ratios and phase angles of potential transformers

I. M. Stein: In the opening statement of his paper, Mr. Burgwin says "while the a-c potentiometer may not be adapted as well to a particular test as a more specialized meter or bridge circuit, its chief advantage is that it can be used satisfactorily for a very wide range of measurements." He then goes on to say "However, the use of the a-c potentiometer has been restricted greatly, probably because of several practical difficulties which never have been eliminated satisfactorily in spite of the many types of a-c potentiometers that have been developed."

The first quotation says in effect that the a-c potentiometer is a jack of all trades and a master of none. I think that that brief statement gives, as accurately as can be done in a brief statement, the real reason for the restricted use of the general purpose a-c potentiometer in this country.

To attribute the restricted use to slide wire difficulties is, I believe, definitely erroneous. Slide wires are very generally used in potentiometers having a limit of error in the order of 0.01 per cent, and I am confident that an actual count would show that there are more precise potentiometers of the slide wire type in successful general use than there are of all other types combined.

Mr. Burgwin refers to a paper by Thomas Spooner in the *Review of Scientific Instruments*. Spooner's paper refers to an a-c potentiometer of foreign manufacture and of recent design. It may be that in this recently designed instrument the slide wire construction was faulty.

The paper gives no statement of the accuracy attainable with the instrument described. I think that a summation of the various limits of error involved is an essential part of the description of any measuring instrument. On the other hand, the author refers several times to the use of his instrument in iron testing. In such measurements, a limit of error in the order of 1 per cent is customary because of the variation in individual samples of iron. Perhaps the author has no intention of claiming for his instrument the degree of accuracy usually associated with a potentiometer.

I wish to call attention to one source of error not even considered in the paper, that is, variation of temperature. For instance, in Appendix I it is shown that the quadrature relation between the 2 elements of the potentiometer depends on the sum of the resistances R_1, R_3, R_5 and R_4, some of which presumably are copper windings.

In contrast with general purpose a-c potentiometers, special purpose a-c measuring circuits, incorporating some of the important features of the potentiometer, are used extensively in this country. These are capable of the same order of accuracy as precise d-c potentiometers and, in general, are quite simple. Moreover, they all make use of a more or less standardized group of precise a-c measuring units so that having available a reasonably complete group of such units nearly any of the special purpose potentiometer circuits may be set up.

Figure 1 shows such a special-purpose circuit for the precise determinations of the ratio and phase angle of current transformers. This circuit has been in use for many years at the U.S. Bureau of Standards and in many other laboratories in this country. Figure 2 is a similar circuit for testing potential transformers.

Figure 3a shows a very simple special-purpose potentiometer circuit for core loss and permeability tests of iron cores. It will be seen that this circuit is similar to Fig. 6 in the paper, but that most of the apparatus in the a-c potentiometer has been eliminated. Measurements made in accordance

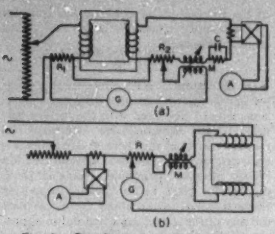


Fig. 3. Simple potentiometer circuits for core loss and permeability tests on iron cores

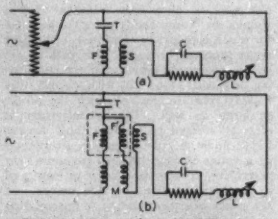


Fig. 4. A simple zero-deflection method for making the measurements indicated in Fig. 7 of the Burgwin paper

with Fig. 3*a* are more direct and therefore less subject to error. The Fig. 3*a* arrangement was selected not because it is best for the purpose, but because it is similar to, but much simpler than, the arrangement shown in the paper. The Fig. 3*a* arrangement may be improved and simplified further by transferring the ammeter and the primary of the mutual inductance to the exciting circuit, by eliminating resistance R_3 and compensating unit C and then connecting the secondary winding of the test specimen, the secondary of the mutual inductance and the galvanometer all in series and across a portion of resistance R_1; this arrangement is shown in Fig. 3*b*.

Figure 4 (upper) shows a very simple zero deflection method (although not a null method) for making the measurements indicated in Fig. 7 of the paper. This is generally known as the "phase-defect" method. Only 2 units are required, the astatic dynamometer and a variable standard of self-inductance. The scale of the latter may be calibrated to read directly either phase-defect angle or power-factor.

The circuit of Fig 4 (upper) and also the circuit of Fig. 7 in the paper result in some error because of the losses in the coil in series with the condenser being measured. By adding a compensating winding F', a small fixed compensating mutual inductance M and changing one potential connection, all as shown in Fig. 4 (lower), this error may be eliminated when using the Fig. 14 circuit.

May I conclude with a statement which differs somewhat from Mr. Burgwin's opening statement. That is, while potentiometer principles may be well adapted to precise special-purpose a-c measuring circuits, the general purpose a-c potentiometer is a relatively inflexible high-cost investment and is not capable of the accuracy and convenience of operation usually associated with the name "potentiometer."

A New Demand Meter

Discussion of a paper by B. H. Smith published in the January 1934 issue, p. 94–5, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934.

P. M. Lincoln: The paper by B. H. Smith describing "A New Demand Meter" is a very interesting one. Not the least interesting feature of this paper is the evidence given therein of the recognition on the part of the Westinghouse engineering department that a demand meter which responds to the loads imposed thereon in accordance with an exponential law is a suitable one for any demand meter.

As Mr. Smith so clearly points out in his paper, the device which he describes has exactly the same law of response as does the thermal wattmeter, i. e., the exponential law. This raises the broad question as to the relative merits of demand meters having an exponential law of response compared to other devices that have been used in the past for measuring demand. It is to this question that I wish to confine my remarks, and particularly to compare the thermal wattmeter with other types.

The so-called "block interval" type of demand meter has been used from the very beginning of the measurement of demand, and has been accepted in the United States as the standard method of measuring demands. There are certain loading conditions for which the thermal meter and the block interval meter do not give the same indications, and it has been tacitly assumed in the past, particularly among United States meter users, that under these conditions it is the block interval type of meter that gives the correct results while the thermal type is in error. Searching analysis does not support this tacit assumption. Although this matter has been briefly discussed before (see "The Character of the Thermal Storage Demand Meter," TRANS. A.I.E.E., v. 37, 1918, p. 189–210) it may be well to point out again that where the loading conditions are such as to cause a difference in the indications of the 2 types, it is the thermal type and not the block interval type that gives the dependable indication.

In Fig. 1 is shown the relative indications of the block interval and the thermal types of demand meters. So long as the load is steady or the blocks of load drawn are of relatively long duration, the 2 types indicate the same value. As the blocks of load decrease in time of duration, the 2 types begin to differ and the shorter the time of load duration, the greater will be this difference. With a block of load lasting exactly 2-meter periods, the thermal type is exactly one per cent low compared to the block interval. As the block of load drawn becomes shorter than 2-meter periods, the difference in indication becomes greater. Also, the indication of the block interval type begins to become indefinite; this, as is well known, is because the block interval meter may "split the peak," that is, the whole of the block of load may occur within a single meter period or only a part of it. On the other hand, the indication of the thermal wattmeter is perfectly definite. As a given block of energy decreases in time and correspondingly increases in watts, the thermal meter continues to recognize the increased heating effect of these higher loads for shorter durations while the block interval meter does not. There is a very definite and accurate mathematical expression for the indication of a thermal meter when there is applied to it any given amount of energy (kilowatt-hours) during any given time. This expression is:

$$\text{Thermal meter indication} = \frac{\text{watts-minutes}}{t}\left(1 - e^{\frac{-2.302t}{t_1}}\right)$$

where

e = base of Napierian logarithmus
t_1 = time in minutes for thermal meter to reach 90 per cent of final
t = time in minutes of load duration

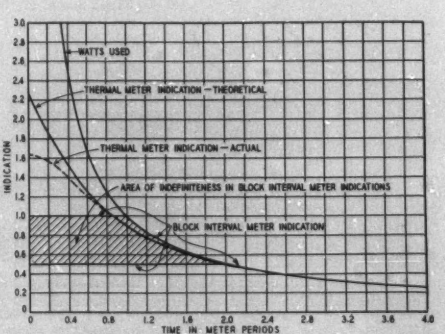


Fig. 1. Positive indications of block interval and thermal type demand meters when an isolated block of a given amount of energy (kilowatt hours) is applied during time intervals varying from zero to 4 times the time period of the block interval meter

From this expression it is readily seen that as t approaches zero and therefore the watts drawn approach infinity, the indication of the thermal wattmeter approaches a value that is 2,302 times the maximum indication of the block interval meter or 4,604 times its minimum indication. In Fig. 1 is shown the relative indications of the 2 types for all load duration intervals from zero to 4 times the time period of the block interval meter. The higher indication of the thermal type of meter for short load durations is quite defensible since it is obvious that a user of electric service who takes for instance his entire 15-min supply of energy in, say, so short a time as one minute, should pay more for taking his service in that abnormal manner than another user who spreads the same block of load over a longer period of time.

To express in words the relative characteristics of the thermal and block interval types of demand meters shown in Fig. 1, it may be said that the thermal meter recognizes in a consistent and accurate manner the "demand principle" for blocks of load of *all* time durations from zero to infinity. The block interval meter recognizes the "demand principle" reasonably accurately for load durations in excess of 2-meter periods, inaccurately to a high degree for load durations from one meter period to 2, and not at all for load durations of less than one meter period. The term "demand principle" may be defined as the effect of the loads drawn upon the heating of the equipment used to supply that load.

In Fig. 2 is shown another comparison between the thermal and block interval types of demand meters. This is essentially the same as Fig. 1. In Fig. 1, a given block of *energy* is assumed to be applied to each type during time intervals ranging from zero to 4 times the time period of the block interval meter. In Fig. 2, a given value of *watts* is assumed. The mathematical expression for the indication of the thermal meter under the conditions of Fig. 2 is

$$\text{Thermal meter indication} = \left(1 - e^{2.302\frac{t}{t_1}}\right)$$

$$= \left(1 - 10^{-\frac{t_1}{t}}\right) = \left(1 - \frac{1}{\text{anti}\log_{10}\frac{t}{t_1}}\right)$$

where

t_1 = time in minutes for thermal meter to reach 90 per cent of final or the time period of the block interval meter

t = time in minutes of load application

It will be noted that the mathematical expression for the thermal meter response in Fig. 2 is the same as the parenthetical part of that in Fig. 1.

An analysis of Figs. 1 and 2 can lead to only one conclusion, viz., that the fundamental principle underlying the block interval meter is unsound. For load durations of less than 2 meter periods, its indication is a matter of chance; its indication depends upon the instant that the meter happens to reset. Fortunately, most loads have a time of duration during maximum of more than 2 meter periods, so that in general the block interval meter gives an acceptable measure of demand. But there are exceptions to this general rule. Any device which is used to determine the amount which a user of electric service should pay for that service should, like Caesar's wife, be above suspicion in *every* case, not simply in the majority of cases. That the block interval meter is indefinite and inaccurate, at least on some loads, may easily be demonstrated by installing 2 on the same load, so adjusted that their time periods "break joints," that is, so that the time period of each overlaps the other by one-half. On some loads, 2 block interval meters so installed will show a very considerable difference in indication. Which of these 2 is the correct indication? The answer is neither.

The wide use and general acceptance of the block interval meter during the past 25 years or more do not alter the fact that its underlying principle is unsound. Up to 1917 it was the only available method of measuring demand and under these circumstances its use was quite justified. With the advent of demand measuring devices having an accurate principle of operation, there is no longer any excuse for continuing in use a device with an inaccurate principle of operation.

Why, may I ask, is it necessary to use the complicated mechanism described by Mr. Smith when the thermal meter is available? In this connection it is only proper to point out that the thermal demand meter is now in almost universal use in Canada, having been introduced there in 1918, and is in rapidly increasing use in the United States, having been introduced into the United States in 1928. The simplicity of the thermal meter is in marked contrast to the complexity of the device that Smith is now proposing.

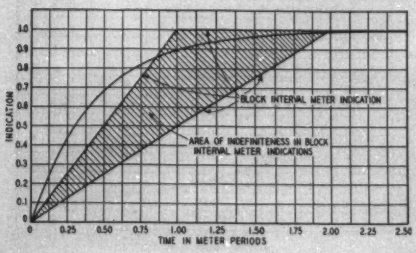


Fig. 2. Relative indications of block interval and thermal demand watt-meters when a given isolated load is applied during time intervals from zero to 2.5 times the time period of the block interval meter

R. E. Hellmund: With reference to Professor Lincoln's remarks, I recall several occasions when I discussed with the meter engineers of the Westinghouse Company the relative merits of the thermal demand principle proposed by Professor Lincoln and the "block interval" principle; some of these discussions dated as far back as twelve or thirteen years. On none of these occasions did any of the meter engineers fail to appreciate fully that, from a purely theoretical point of view, there was a great deal of merit in the Lincoln meter. The only reason why the "block interval" principle was considered more favorable for commercial work at that time was that it was simpler and more readily understood, a factor which is of great importance in handling meter problems because in this work we are by no means concerned with the engineering profession alone, but with various rate-making commissions and with the public at large as well. The manufacturer is after all obliged to produce those devices which find the greatest public acceptance, irrespective of what his own engineers may prefer from a theoretical point of view, and it was considerations of this nature and not a lack of understanding or appreciation of the principles propounded by Professor Lincoln which in general favored the development of the block interval demand meter in comparison with the thermal demand meter.

While the principles advocated by Professor Lincoln have naturally found some market acceptance in the past, only experience will show to what extent their acceptance can be increased, and only time will tell which of the 2 principles will find the most general acceptance. The users and customers, and not the manufacturers, will be the final judges in this matter.

B. H. Smith: I agree with Mr. Lincoln that it probably will be 15 years before this matter is settled to the satisfaction of all concerned. But 15 years is not a long time. The earth is said to be one hundred million years old or more. I can remember 15 or even 30 years ago—and it seems but yesterday.

As to the mechanical mechanism, the Westinghouse company has a very large number of kva meters in service with a ball mechanism which is very similar to the mechanism in the new demand meter. In this demand meters there is still a synchronous motor, always a difficult problem in former demand meter; but with the new mechanism there is practically no load on the motor and, consequently, the problem is much easier and I believe we have it solved.

Here, in my hand, is the complete demand attachment. It fits into existing watthour meters and thus avoids the installation expense of a separate demand meter. This expense with present thermal meters is one of the reasons why they have not been more extensively used. As I told Mr. Lincoln some time ago, he should design his thermal meter to go into existing watthour meters as an attachment.

News
Of Institute and Related Activities

North Eastern District to Meet at Worcester

THE TENTH annual meeting of the North Eastern District of the American Institute of Electrical Engineers will be held at Worcester, Mass., from Wednesday, May 16, to Friday, May 18, 1934. On Friday the meeting will be combined with the District Student Branch Convention.

Headquarters will be at the Bancroft Hotel, corner of Franklin and Portland Streets. This is one of the most comfortable hotels in Massachusetts with most adequate facilities for meetings of this character. The service is excellent, and the prices extremely reasonable. Special arrangements have been made with the management to provide rooms for the students on a dormitory plan at $1 per day.

The City of Worcester

Worcester is located in the heart of the Commonwealth of Massachusetts. It is a city of 200,000 population, the third largest in New England, centrally located for industry and commerce. It is connected by rail and super-highways to the principal markets of the Atlantic seaboard.

Its industry is diversified covering over 500 different items of manufactured articles. Included in this long list are: American Steel and Wire Company, manufacturers of wire and cables; M. J. Whittall Associates, rugs and carpets; Norton Company, grinding wheels and machinery; Crompton and Knowles Loom Works, textile machinery; Heald Machine Company, automatic machines and tools; Leland-Gifford Company, crank shafts and forging; the Royal Worcester Corset Company; and the United States Envelope, all internationally known.

Historically, Worcester is rich in interest. Twice, once in 1654 and again in 1683, the settlement was abandoned after the inhabitants sustained savage attacks by the Indians which reduced their numbers and destroyed their homes and crops. It was not until 1713 that a permanent settlement was established. From Worcester went forth General Artemas Ward, the first American to receive the commission of General under American authority; Colonel Timothy Bigelow, commander of the "Minute Men"; Isaiah Thomas in whose publication *The Massachusetts Spy* was printed the first copy of the Declaration of Independence to appear in a New England paper; General Rufus Putnam, Eli Whitney, George Bancroft, Elias Howe, Clara Barton, Edward Everett Hale, and a long list of names known to every child in the nation. The whole of New England abounds in historic shrines and natural beauty spots, all within an easy automobile ride of Worcester.

Worcester and the surrounding territory is served by the high voltage lines of the New England Power Company with local distribution made by companies operating under the New England Power Engineering and Service Corporation.

Wednesday's Activities

A most interesting program has been mapped out for the meeting. Immediately following the address of welcome by Vice-President J. Allen Johnson at 9:30 a.m. on Wednesday morning, 4 technical papers will be presented. After recess for luncheon another group of technical papers will be read and discussed. No special arrangements are being made for dinner on the first day of the meeting so that members may be free to look up acquaintances and dine with them. The evening entertainment will start at 8 p.m. and will consist of moving pictures with other feature entertainment.

Thursday's Activities

On Thursday morning 3 most interesting papers of a non-technical or a semi-technical character will be presented. This session is made short in order to provide sufficient time for the meeting of the District executive committee during the luncheon period. The afternoon will be given over to an inspection trip at the South Works of the American Steel & Wire Company. A most interesting visit is assured. In the evening a buffet lunch will replace the usual dinner. This will be followed by an informal dance and get-acquainted period.

Friday's Activities

The morning session on Friday will feature the student convention, as usual. This

The building on the left is the Bancroft Hotel on the corner of Franklin and Portland Streets, Worcester, Mass., which will be the headquarters for the Institute's North Eastern District meeting May 16–18, 1934. On the right is the Worcester Telegram-Gazette Building, and in the middle the Chamber of Commerce Building

will be under the direction of Prof. L. W. Hitchcock of the University of New Hampshire, who is chairman of the Branch counselor committee.

The scene of activities of the day will be transferred from the Hotel Bancroft to the campus of the Worcester Polytechnic Institute. Plans in addition to presentation of student technical papers in the morning include a trip to the Millbury dispatching station of the New England Power Company in the afternoon.

Annual Dinner

The annual dinner and presentation of prizes will be held at the Sanford Riley Dormitory of Worcester Polytechnic Institute at 6:30 p.m. on Friday. Following dinner both the student and senior sections will meet in the lecture room of the engineering laboratories where Dr. Robert J. Van De Graaff will give an illustrated lecture on "High Voltage and Its Application to Atomic Disintegration." If time permits, following Dr. Van De Graaff's lecture the local Student Branch will carry out some interesting experimental demonstrations of electrical apparatus.

Student Conference

After the morning session, the annual luncheon conference of the Branch chairmen and counselors will be held at the Sanford Riley Dormitory.

Saturday's Activities

For those who can stay over on Saturday arrangements have been made for a visit to the substation of the New England Power Company at Tewksbury, Mass. This is a 220-kv station, and will be of considerable interest to both the senior and student members.

Inspection Trips

Worcester is particularly rich in features for entertainment of members and guests. In addition to the plant of the American Steel & Wire Company, Worcester is the home of the Norton Company, manufacturer of abrasive materials, grinding wheels, tools, etc., the Heald Machine Company, manufacturer of precision tools and automatic machinery, and the Worcester Pressed Steel Company, manufacturer of pressed metal pieces as the name implies. Those wishing to do so may arrange for visits to any one or all 3 of these plants. The John W. Higgins Armory at the Worcester Pressed Steel Company will be of special interest. This is one of the most famous collections in the United States of armor from medieval time to the last of the armored knights. John W. Higgins, president of the Worcester Pressed Steel Company is an ardent student of arts in metals and has secured for his museum an elaborate collection depicting artistry in metal work from the 4 corners of the world.

In addition to these features of interest to the engineers in Worcester is found the internationally famous Worcester Antiquarian Society, a historical society of great interest to lovers of New England and an art museum exhibiting some of the world's famous masterpieces in painting and sculpture. As previously stated opportunity will be given to visit all of these points of interest.

South Works of the American Steel and Wire Company, Worcester, Mass., to which an inspection trip is scheduled on Thursday afternoon of the Institute's North Eastern District meeting to be held in Worcester May 16–18, 1934

Table I—Hotel Rates

Hotels	Single Room Running Water	Single Room With Bath	Double Room Running Water	Double Room With Bath
Bancroft*	$2.00	$2.50, 3.00, 3.50	$4.00	$4.50, 5.00
Aurora	$1.75, 2.00	$2.50, 3.00	$3.00, 3.50	$4.00, 5.00
Worcester	$1.75, 2.00	$2.50, 3.00	$3.00, 3.50	$4.00, 5.00

* Headquarters. Special rates for Students only—4 or more in room, individual cot beds, with bath, $1 per person

Women's Entertainment

A special women's committee has prepared a fine program for the entertainment of women visitors. On Wednesday afternoon a visit will be made to the Worcester Antiquarian Society and the Worcester Art Museum. A luncheon or tea at the John W. Higgins Armory, followed by bridge for those who desire, is planned for Thursday afternoon. On Friday there will be a luncheon at the Worcester Country Club with an opportunity to play bridge, tennis, or golf as desired.

Sports

Sports tournaments have not been scheduled but the committee will be glad to make arrangements for golf and tennis at any of the local clubs during the meeting.

Registration and Hotel Reservations

All planning to attend this meeting should register in advance, if possible, by writing to L. S. Leavitt, 11 Foster St., Worcester, Mass. Members should complete their registrations after arrival so as not to miss the opening session. There will be no registration fees.

Hotel reservations should be made directly with the hotel preferred. Rates for the headquarters hotel, Hotel Bancroft, the Aurora Hotel, and the Worcester Hotel are given in Table I. Both of the last 2 named hotels are under the same management.

An information desk will be open all day Wednesday and Thursday and during the morning of Friday for the convenience of members.

Parking

Ample parking space will be found in the vicinity of the Bancroft Hotel. Special arrangements have been made whereby A.I.E.E. members, and visitors, will be able to park their cars in the Bancroft Garage, 24 Portland Street (just around the corner from the hotel) at $0.75 per day. This includes the privilege of taking the car out as often as desired without additional charge. Open air parking space on Federal Street at the rear of the hotel also is available at a small fee.

Program

Most of the technical papers to be presented for discussion at the meeting have been published in this and preceding issues of Electrical Engineering. For those papers which have been published, reference to the issue and page is given with the title in the following program. Members who wish to follow the presentation in detail and discuss the papers are urged to take the necessary issues to the meeting with them.

Because it is contemplated that the May 1934 issue of Electrical Engineering will be devoted to the fiftieth anniversary of the A.I.E.E., those papers which have not been made available in time for inclusion in the April issue will not be published in advance. For this latter group, arrangements are being made with the authors to supply mimeographed copies.

All technical sessions, with the exception of those scheduled on Friday, will be held at the Bancroft Hotel. The sessions on Friday will be held in the lecture rooms of the Worcester Polytechnic Institute.

Wednesday, May 16

9:00 a.m.—Registration

9:30 a.m.—Opening Session

Opening Address, J. Allen Johnson, vice-president, North Eastern District, A.I.E.E.

Selected Subjects—T. A. Worcester, *chairman*

A New Type of Warble Tone Oscillator, W. H. Bliss, University of Maine. April, p. 547–50

A Vacuum Tube Controlled Rectifier, C. B. Foos, General Electric Co. April, p. 568–70

Thyratron Tube Control of High Speed Resistance Welders, W. C. Hutchins and O. W. Livingston, General Electric Co. Not published

The M.I.T. Power-Factor Bridge and Associated Oil Cell, and the Power-Factor Measurement of Small Oil Samples, J. C. Balsbaugh, N. D. Kenney, and Alfred Herzenberg, Massachusetts Institute of Technology. Not published

Future AIEE Meetings

North Eastern District meeting,
Worcester, Mass., May 16–18, 1934

Summer convention,
Hot Springs, Va., June 25–29, 1934

Pacific Coast convention,
Salt Lake City, Utah, Sept. 3–7, 1934

2:00 p.m.—Transmission and Distribution, I. E. Moultrop, *chairman*

SHUNT RESISTORS FOR REACTORS—II, F. H. Kierstead and L. V. Bewley, General Electric Co. March, p. 411–8

THEORY OF PRIMARY NETWORKS—PART II, F. M. Starr, General Electric Co. March, p. 426–31

DOUBLE UNBALANCES IN 3-PHASE NETWORKS AND THEIR SOLUTION ON THE A-C CALCULATING BOARD, E. W. Kimbark Not published

EXPERIMENTS IN FATAL ELECTRIC SHOCK, A. G. Conrad and H. W. Haggard, Yale University. March, p. 399–402

8:00 p.m.—Special Entertainment Feature

Thursday, May 17

9:00 a.m.—General Session, Louis S. Leavitt, *chairman*

FIFTY YEARS OF THE A.I.E.E., by C. F. Scott, Yale University.

THE INSIDE WORKINGS OF THE A.I.E.E., J. Allen Johnson, vice-president, North Eastern District, A.I.E.E.

SPEED CONTROL PROBLEMS OF INTERCONNECTED OPERATION, Robert Brandt, New England Power Engineering and Service Corp.

12:00 noon—District Executive Committee Luncheon

1:30 p.m.—Assemble for transportation to South Works, American Steel and Wire Co.

2:00 p.m.—Inspection trip through South Works of the American Steel and Wire Co.

6:30 p.m.—Buffet luncheon followed by informal dancing

Friday, May 18

9:00 a.m.—Student Technical Session, Professor L. W. Hitchcock, chairman Student counselors' committee

Meeting held at Electrical Engineering Laboratory, Worcester Polytechnic Institute, corner of West and Salisbury Streets

12:00 noon—Luncheon Conference of Counselors and Branch Chairmen

2:00 p.m.—Student Inspection Trips

2:00 p.m.—Electrical Machinery, C. A. M. Weber, *chairman*

IRREGULAR WINDINGS IN WOUND ROTOR INDUCTION MOTORS, R. E. Hellmund and C. G. Veinott, Westinghouse Electric and Mfg. Co. Feb., p. 342–6

STRAY LOAD LOSS TEST ON INDUCTION MACHINES, T. H. Morgan, Worcester Polytechnic Institute, and P. M. Narbutovskih, Graduate Student, Stanford University. Feb., p. 386–90

SOME PROBLEMS INVOLVING ADJUSTED SYNCHRONOUS REACTANCE, H. B. Dwight, Massachusetts Institute of Technology. April, p. 566–8

TRANSFORMER REACTANCE AND LOSSES WITH NONUNIFORM WINDINGS, H. O. Stephens, General Electric Co. Feb., p. 346–9

6:30 p.m.—Dinner at Sanford Riley Dormitory, Worcester Polytechnic Institute

8:00 p.m.—Illustrated lecture—HIGH VOLTAGE AND ITS APPLICATION TO ATOMIC DISINTEGRATION," by Dr. Robert J. Van De Graaff.

Saturday, May 19

The committee will be glad to make arrangements for a visit to the 220-kv substation of the New England Power Company at Tewksbury Mass., for any desiring to make this trip.

Floodlighting of this building in Worcester, Mass., the city selected for the Institute's North Eastern District meeting to be held May 16–18, 1934, makes possible the flying of the flag 24 hours a day. The building is the Soldier's Memorial on Lincoln Square

RULES ON PRESENTING AND DISCUSSING PAPERS

At the technical sessions, papers will be presented in abstract, 10 min being allowed for each paper unless otherwise arranged or the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion.

Any member is free to discuss any paper when the meeting is thrown open for general discussion. Usually 5 min are allowed to each discusser for the discussion of a single paper or of several papers on the same general subject. When a member signifies his desire to discuss several papers not dealing with the same general subject, he may be permitted to have a somewhat longer time.

It is preferable that a member who wishes to discuss a paper give his name in advance to the presiding officer of the session at which the paper is to be presented. Each discusser is to step to the front of the room and announce, so that all may hear, his name and professional affiliations. Three typewritten copies of discussion prepared in advance should be left with the presiding officer.

Other discussions to be considered for publication should be typewritten and submitted in triplicate to C. S. Rich, secretary of the technical program committee, A.I.E.E. headquarters, 33 West 39th St., New York, N. Y., on or before June 1, 1934.

COMMITTEE

The District meeting committee in charge of this meeting consists of: J. Allen Johnson, *chairman*, vice-president, North Eastern District; A. C. Stevens, secretary-treasurer, North Eastern District; L. W. Hitchcock, chairman of Student Counselors, North Eastern District; and L. S. Leavitt, R. P. Bullen, W. H. Timbie, J. S. Henderson, B. K. Northrop, and W. B. Hall.

North Eastern District to Hold Student Convention

The student Branch convention for the Institute's North Eastern District is to be held on Friday, May 18, 1934, at Worcester, Mass., in conjunction with the tenth annual meeting of this District, as announced in an item appearing on preceding pages of the news section of this issue. The Bancroft Hotel is to be the headquarters for the District meeting on Wednesday and Thursday, but all activities scheduled for Friday and including those of Friday evening are to be at the Worcester Polytechnic Institute.

The Branch counselors are in a key position to insure the success of this annual Student activity by encouraging the presentation of Student papers and by arranging for Student attendance. Inspection trips can well be planned with Worcester as the objective either on Thursday, May

17, when a visit is already scheduled in the afternoon to the South Works of the American Steel and Wire Company, or Friday, May 18, for participation in the student technical session, and the usual afternoon trip to one of the industries. The banquet, heretofore held on Thursday evening, is planned for Friday evening. It is to be followed by an illustrated lecture "High Voltage and Its Applications to a Disintegration" by Dr. Robert J. Van De Graaff of Massachusetts Institute of Technology. A visit to the New England Power Company's station at Tewksbury is planned for Saturday.

L. W. Hitchcock (A'11) professor of electrical engineering, University of New Hampshire, Durham, is chairman of the Branch counselors committee.

A.I.E.E. Executive Committee Meets

A meeting of the executive committee of the American Institute of Electrical Engineers was held at Institute headquarters, New York, on March 9, 1934, in place of the regular meeting of the board of directors.

Present: John B. Whitehead, chairman; H. P. Charlesworth, J. Allen Johnson, Everett S. Lee, E. B. Meyer, and W. I. Slichter, members of the committee; A. E. Knowlton and L. W. W. Morrow, members of the board of directors; and H. H. Henline, national secretary.

Report of a meeting of the board of examiners held February 28, 1934, was presented and approved. Upon the recommendation of the board of examiners, the following actions were taken upon pending applications: 2 applicants were transferred to the grade of Fellow; 7 applicants were elected and 17 were transferred to the grade of Member; 47 applicants were elected to the grade of Associate; 153 students were enrolled.

The Finance committee reported expenditures for the month of February amounting to $18,181.74. Report approved.

Financial reports of the 1934 winter convention, held in New York, January 23–26, were presented, and the committee voted its appreciation of the effective arrangements made by the convention committee and of the successful financial outcome.

The dates, September 3–7, inclusive, were approved for the 1934 Pacific Coast Convention, in Salt Lake City, Utah.

Col. William B. Jackson was reappointed a representative of the Institute upon the Commission of Washington Award for the 2-year term beginning June 1, 1934.

Dr. John B. Whitehead was nominated for appointment as a member, representing the Institute, of the divison of engineering and industrial research, National Research Council, for the 3-year term beginning July 1, 1934, succeeding H. P. Charlesworth, whose term expires at that time and who is ineligible for immediate reappointment.

Approval was given to the appointment by the president of the following committee of tellers to canvass, count, and report upon the election ballots cast for Institute officers: W. E. Coover, chairman, J. T. Binford, A. Hagstad, Henry Kurz, W. C. Plumer, W. B. Snow, and H. B. Stoddard.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

To Institute Members Planning Trips Abroad

Members of the Institute who contemplate visiting foreign countries are reminded that since 1912 the Institute has had reciprocal arrangements with a number of foreign engineering societies for the exchange of visiting member privileges, which entitle members of the Institute while abroad to membership privileges in these societies for a period of 3 months and members of foreign societies visiting the United States to the privileges of Institute membership for a like period of time, upon presentation of proper credentials. A form of certificate which serves as credentials from the Institute to the foreign societies for the use of Institute members desiring to avail themselves of these exchange privileges may be obtained upon application to Institute headquarters, New York. The members should specify which country or countries they expect to visit, so that the proper number of certificates may be provided, one certificate being addressed to only one society.

The societies with which these reciprocal arrangements have been established and are still in effect are: Institution of Electrical Engineers (Great Britain), Société Française des Electriciens (France), Association Suisse des Electriciens (Switzerland), Associazione Elettrotecnica Italiana (Italy), Koninklijk Instituut van Ingenieurs (Holland), Verband Deutscher Elektrotechniker E. V. (Germany), Norsk Elektroteknisk Forening (Norway), Svenska Teknologforeningen (Sweden), Stowarzyszenie Elektrykow Polskich (Poland), Elektrotechnicky Svaz Ceskoslovensky (Czechoslovakia), The Institution of Engineers, Australia (Australia), Denki Gakkwai (Japan), and South African Institute of Electrical Engineers (South Africa).

Pacific Coast Convention Dates Selected

The dates of September 3–7, inclusive, have been approved by the Institute's executive committee for the 1934 Pacific Coast convention to be held in Salt Lake City, Utah. This convention takes the place of that originally scheduled to be held in Salt Lake City, September 4–8, 1933, but subsequently postponed.

The 1934 Pacific Coast convention committee has been appointed by President Whitehead, and plans are now actively progressing toward the arranging of a successful meeting.

It is planned that technical papers to be discussed at this convention will have been published in ELECTRICAL ENGINEERING in advance of the convention, in accordance with the Institute's newly adopted publication program. Details of the convention, including the technical program, entertainment features, and other events, will be given in future issues of ELECTRICAL ENGINEERING.

Tentative Plans for Summer Convention Are Announced

THE FIFTIETH annual summer convention of the A.I.E.E. will be held at Hot Springs, Va., June 25–29, 1934, with headquarters in the Homestead Hotel. This picturesque setting with its excellent facilities for sports and recreation together with a well-rounded technical program offers an ideal opportunity for members and their guests to enjoy a very pleasant and profitable week. As an additional feature this year, the opening session will be devoted partly to a special program commemorating the 50th Anniversay of the Institute, in which prominent members will take part.

The technical program which has been tentatively arranged calls for 7 sessions: education, insulators, power generation, automatic stations, electrical machinery, instruments and measurements, and communication. Technical papers for these several sessions will have been published in ELECTRICAL ENGINEERING so that any member interested will have ample opportunity to prepare thoughtful written discussion on any paper or papers of importance to him. The treatment of the subject of education will consider industry demands, present economic conditions, and the encouragement of initiative in the engineering student. Power generation will treat a hydroelectric survey of broad scope and the New York generating system as it aids network operation. The communication session is expected to present several papers dealing with the wide-band open-wire system of program transmission and shielding against inductive exposure. In addition other sessions will offer a number of papers which will outline some of the latest developments in theory, design, and the fabrication of electrical apparatus.

The general convention committee for the 1934 summer convention consists of the following members: W. S. Rodman, chairman; C. A. Robinson, vice-chairman; R. C. Bailey, secretary; E. P. Coles, R. N. Conwell, F. M. Craft, S. A. Flemister, J. T. Graff, E. L. Lockwood, W. R. McCann, and I. Melville Stein.

More complete information in regard to the program for the summer convention will be announced in subsequent issues of ELECTRICAL ENGINEERING. Arrange your plans now so as to be able to attend the annual summer convention at Hot Springs, Va.

Technical Committee Activities Proposed for Sections and Districts

This statement from I. Melville Stein, chairman of the A.I.E.E. Sections committee outlines a proposal that merits the thoughtful attention of every member of the Institute in order that the subject may be discussed thoroughly and constructively at the annual conference of officers, delegates, and members that will be an important part of the program of the fiftieth annual summer convention, to be held June 25–29, 1934, at Hot Springs, Va.

THREE of the most important activities of the American Institute of Electrical Engineers are: (1) its technical meetings, (2) its publications, and (3) the work of its technical committees.

It hardly can be questioned that the greatest mutual benefit to the membership and to the Institute as a whole comes with the participation in these activities by the maximum number of members. The function of the Institute is to provide the opportunity for such initiative on the part of individual members, and each member should take full advantage of the opportunities offered.

About a third of a century ago, it was realized that the Institute was not providing for its members remote from headquarters adequate opportunity to participate in technical meetings. Due largely to the foresight and efforts of Dr. Charles F. Scott, then president of the Institute, the idea of establishing Sections in many parts of the country, was given a great impetus. As a result, many Institute Sections were organized during and shortly following President Scott's term in office. The effect was quite remarkable. The membership of the Institute, which had been the smallest among the four Founder Societies increased abruptly until it became the largest. While an increase in Institute membership is in itself not a measure of success, it is an excellent index of the interest and participation in Institute activities, which are the real objectives.

Somewhat later, further opportunity for general participation in technical meetings of the Institute was offered by the formation of Districts and the provision for District Conventions.

Very recently, opportunity for all members to gain greater advantages from the Institute publications was established by the new publication policy, which provides for printing promptly and in full in ELECTRICAL ENGINEERING all papers and discussions accepted by the Institute.

Opportunity for Membership Participation

Up to the present time the opportunity for general participation in the third important activity of the Institute, namely, technical committee work, has not been provided. This, of course, is not intentional. On the contrary, the matter has been discussed many times over a considerable period of years, with the hope of finding a satisfactory plan which would provide for more general participation in the work of the technical committees. Always there appeared some important obstacle in the nature of something which would have made general participation by the membership a handicap rather than a help to the technical committees. Recently the study that has been devoted to this problem has brought forth a tentative plan which aims to provide for general participation in technical committee work in a way that should be a help rather than a handicap to the work of these committees.

As in the case of the technical meetings and publications of the Institute, the plan aims to provide full *opportunity* for general participation in technical committee activities, leaving it to each individual member to take the *initiative* in actually participating.

The proposed plan has been reviewed carefully by the technical program committee and by the committee on coördination of Institute activities. These 2 committees are in agreement that the plan should be presented for consideration by the delegates at the annual conference of officers, delegates, and members to be held during the forthcoming summer convention at Hot Springs, Virginia. It is the purpose of this article to give the proposed plan advance publicity, so that each member of the Institute may have the opportunity to discuss it with his Section delegate prior to the conference.

Details of Proposed Plan

Briefly, the tentative plan proposed is as follows:

1. Each Fellow, Member, and Associate of the Institute would be asked to communicate, to a duly appointed officer in his Section, his wishes with regard to becoming affiliated with one or more of the Institute's technical committees. There are 18 technical committees at present. Of course, no member would be under obligation to affiliate with any technical committee.

2. If in any Section there were a reasonable number of members, for instance 5, desiring to affiliate with a particular technical committee, the authorized Section officer would call a meeting of that group for the purpose of organizing that particular *Section Technical Committee*. The members so assembled would elect their own chairman. Thus in large Sections there probably would be set up as many Section technical committees as there are national technical committees. In smaller Sections, it is likely that the full number of technical committees would not be organized.

3. From among the elected Section chairmen of a particular technical committee in each District, there would be appointed a District chairman of that particular technical committee. Each District chairman so appointed automatically would become a member of the corresponding national technical committee. Probably each vice-president would appoint the District chairman in his District.

4. Thus, included in each national technical committee, there would be 10 members, who, in the first instance, had been elected to serve as Section chairmen of that technical committee and then appointed to serve as District chairmen of the same committee. Also on each national technical committee, there would be at least an equal number of members appointed at large in the usual way.

The ways in which these Section technical committees could coöperate in the technical committee activities of the Institute are many, but space in which to enumerate them is not available here. Of course, those members who for some time have favored an expansion of the Institute's technical committee activities are well aware of the advantages to be gained.

Comments Wanted

In addition to discussing this plan with his Section delegate prior to the delegate's conference at the summer convention, June 25–29, it is suggested that any member wishing to comment on this proposed plan send his comments to I. Melville Stein, chairman of the A.I.E.E. sections committee, at 4901 Stenton Avenue, Philadelphia, Pa.

Southern District Holds Student Conference

The seventh annual student activity conference of the Southern District of the A.I.E.E. was held at North Carolina State College, Raleigh, January 11–13, 1934. About 200 students and faculty members, from 16 colleges, attended this conference. At the morning session, a group of student papers was presented. These were "Determination of Sequence Constants of a Synchronous Motor," by William E. Dean, Jr., student, University of Tennessee; "Electrically Tied Synchronous Motors," by C. W. Trieste, student, University of Florida; "The Selection and Application of Photoelectric Cells," by R. B. Shores, student, Clemson Agricultural College; "Mercury Vapor Process of Generating Power," by R. S. Wellons, student, Georgia School of Technology; "Public Utility Regulation in Southern States," by William L. Ridenhour, student, University of North Carolina; and "Kindling of Electric Impulse Sparkover," by A. J. McCullough, student, University of Alabama.

The afternoon meeting was called to order by Prof. R. S. Fouraker, as chairman, who appointed Joseph Weil as secretary. Prof. Claudius Lee was elected chairman of the eighth students activities conference to be held at Virginia Polytechnic Institute, Blacksburg, Va., in 1935. Professor Lee was also named as the delegate to represent the southern Branches of the Institute at the annual summer convention for 1934.

At the discussion of student activities during the afternoon the students themselves participated actively, notwithstanding the fact that there were many visitors and counselors present. Representatives from different Branches told of the projects that have been used by their Branches to

increase attendance at meetings. Plans were discussed which might be used most effectively for arousing and maintaining the interest of the students in the Institute.

Interest was shown concerning the question of vocational guidance. The value of guidance and examples of where this work has been beneficial were discussed.

A banquet was held Friday evening at which H. M. York, chairman of the North Carolina State College Branch, was toastmaster. During the banquet prizes for the winning student papers were announced and presented as follows:

First prize, $25 to R. B. Shores
Second prize, $10 to R. S. Wellons
Third prize, $5 to W. L. Ridenhour

Inspection trips were made on Saturday to Duke University at Durham, and to the University of North Carolina at Chapel Hill.

In addition to F. M. Craft, vice-president A.I.E.E., the following student counselors were in attendance:

W. W. Hill	Alabama Polytechnic Institute
F. R. Maxwell, Jr.	University of Alabama
S. R. Rhodes	Clemson Agricultural College
W. J. Seeley	Duke University
Joseph Weil	University of Florida
T. W. Fitzgerald	Georgia School of Technology
S. A. Bureau	University of Kentucky
J. M. Houchens	University of Louisville
L. H. Fox	Missisippi State College
R. S. Fouraker	North Carolina State College
William Hand Brown	North Carolina State College
W. J. Miller	University of North Carolina
R. F. Stainback	University of North Carolina
J. E. Lear	University of North Carolina
T. E. Ball	University of South Carolina
J. E. Tarboux	University of Tennessee
Claudius Lee	Virginia Polytechnic Institute
J. S. Miller, Jr.	University of Virginia

Electronic Show Conducted by Students

The meeting of the Institute's Student Branch at Pennsylvania State College, held February 21, 1934, was on the subject of vacuum tubes, and included an exhibit of vacuum tubes and an electronic show. The meeting also took on the nature of a celebration of the Institute's 50th anniversary, inasmuch as a brief ceremony at the beginning of the meeting was devoted to this purpose.

The papers and demonstrations were conducted by senior electrical engineers. A discussion of electron tubes entitled "The Electronic Age" by D. Robertson was given. Following this, the more important types of tubes were described and exhibited by F. C. Schwerer, and the fundamental principles of the construction and operation of the more common types were then given by W. C. Johnson. In the electronic show which followed, the demonstrations and the names of the students conducting these were:

1. Mobile Color Control	J. K. Walter
2. The Senaitron	D. T. Costa, W. E. Ferry and L. H. Wurster
3. Motor Speed Control	R. W. Barnitz and H. J. West
4. Futuristic Lighting Control	J. F. Giampiltro and D. M. Hutchinson
5. Electronic Eyes	R. C. Hollobaugh, M. J. Petscavage and F. W. Sell
6. Grid Glow Stroboscope	C. N. Bushey, D. S. Dietz and M. A. Sayland
7. Electronic Accordion	S. W. Smith, D. J. Troup, and P. S. Young
8. Electronic Bars	R. A. Bradford, J. N Fogg and R. C. Schlaack
9. The Coloraudio	C. E. Disney, L. E. Fredrickson, and F. S. Miller
10. Sequence Control	E. Heath and E. V. Osterhout
11. The Vocalite	N. S. Young
12. Music Transmitted Over Light Beam	J. D. Colvin
13. Rotating Disks and Neon Glow Lamp	F. W. Sell

Engineering Foundation

Outline of Joint Engineering Organizations

A brief résumé of the organization and objects of United Engineering Trustees, Inc., and its 3 departments, namely, the administrative department, The Engineering Foundation, and the Engineering Societies Library, follows:

United Engineering Trustees, Inc., was organized in 1904 under the name of the United Engineering Society "to advance the engineering arts and sciences in all their branches, to further research in science and in engineering, to maintain a free public engineering library, and to advance in any other manner the profession of engineering and the good of mankind." It is now the joint agency of the 4 national societies representing the civil, mining and metallurgical, mechanical, and electrical engineers.

Administrative Department

United Engineering Trustees, Inc., as the agency of these 4 societies, owns and administers the Engineering Societies Building at 33 West 39th street, New York, N. Y., and the funds related thereto. It also administers the following trust funds: Engineering Foundation fund, library endowment fund, Henry R. Towne engineering fund, Edward Dean Adams fund, John Fritz Medal fund, and depreciation and renewal fund (for the Engineering Societies Building). Management of the building and all trust funds is in the hands of the administrative department of United Engineering Trustees, Inc., under the direction of its board of trustees.

The American societies of civil, mining and metallurgical, mechanical, and electrical engineers, through United Engineering Trustees, Inc., have equal interests in the ownership, occupancy, and administration of the building, which is run on a cooperative plan. The Engineering Societies Building houses also several other organizations in which engineers are interested.

The Engineering Foundation

The Engineering Foundation, founded by Ambrose Swasey (HM'28) is entrusted with the expenditure of the income of endowments and other funds "for the furtherance of research in science and engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind." Its present preferred activity is engineering research. The Engineering Foundation coöperates with the 4 national engineering societies of which United Engineering Trustees, Inc., is the joint agency, with other organizations, and with individuals, in seeking additional knowledge through active, wisely directed research. It issues Research Narratives and other publications. It also has aided in establishing other research organizations.

Engineering Societies Library

The joint library of the national societies of civil, mining and metallurgical, mechanical, and electrical engineers is a free public library, which, with its numerous activities, is operated for users at a distance as well as for those who visit its rooms in the Engineering Societies Building. The library maintains a staff of technically trained searchers and translators, as well as reference assistants. It makes photoprints of any material in its collection and through a card service keeps subscribers informed of articles in periodicals on subjects in which they may be interested.

Election Held by Engineering Foundation

At its annual meeting February 15, 1934, the Engineering Foundation's board reelected as its chairman George W. Fuller, consulting engineer, former vice-president of the American Society of Civil Engineers, New York, N. Y., and a member of the firm of Fuller and McClintock. H. P. Charlesworth (M'22, F'28, and junior past-president) assistant chief engineer, American Telephone and Telegraph Company, New York, N. Y., was reelected a vice-chairman. D. R. Yarnall was also elected a vice-chairman. These members, together with E. R. Fish and J. V. N. Dorr, constitute the executive committee. Dr. A. D. Flinn continues as secretary and director.

Members of The Engineering Foundation's board whose terms began at the annual meeting on February 15, 1934, and expire at the annual meeting in February 1937, are: D. R. Yarnall, nominated by The American Society of Mechanical Engineers to serve as trustee to succeed E. R. Fish; G. D. Barron, nominated by the American Institute of Mining and Metallurgical Engineers to succeed H. C. Bellinger; W. H. Fulweiler, nominated by The American Society of Mechanical Engineers, to succeed D. R. Yarnall; W. I. Slichter (A'00, F'12, national treasurer, and past vice-president) by the A.I.E.E. to succeed himself. Other members of the Engineering Foundation's board elected at this meeting are R. M. Roosevelt, trustee to succeed G. D. Barron of the American Institute of Mining and Metallurgical Engineers; and H. V. Coes, *ex-officio*, president of United Engineering Trustees, Inc. Other members of the Engineering Foundation's board holding over from previous election are: A. S. Tuttle, H. P. Charlesworth (M'22, F'28, and junior past-president), G. W. Fuller, O. E. Hovey, E. DeGolyer, A. E. White, C. E. Skinner (A'99, F'12, and past-president), G. G. Crawford, E. R. Fish, and J. V. N. Dorr.

An outline of the organization and objects of The Engineering Foundation is given in a companion article in this section of this issue.

Annual Report Issued by Engineering Foundation

In the annual report of The Engineering Foundation submitted by George W. Fuller chairman for 1933, and by Dr. A. D. Flinn, director, the following brief summary of activities during 1933 was given:

"Activities in 1933 included, with others, investigations of concrete and reinforced concrete arches, earths and foundations, steel columns for bridges and buildings, arch dams, and plastic properties of concrete, in the civil engineering field; critical review of the world's literature on alloy iron and alloy steels since 1890, and mining and strata research, both sponsored by the American Institute of Mining and Metallurgical Engineers; in coöperation with committees of The American Society of Mechanical Engineers, studies of boiler feed water, a critical pressure steam boiler, effects of temperature on properties of metals, cutting of metals, lubrication, cottonseed processing, and wire rope; under sponsorship of the American Institute of Electrical Engineers, 2 electric welding researches, one on pure iron electrodes and the other on nitrogen in welds.

"Assistance was given also to summer schools for engineering teachers, studies of objective types of tests for entrance to engineering colleges and other uses, vocational guidance in relation to engineering; to Engineers' Council for Professional Development, coördination committee of engineering societies, the library fund committee, Personnel Research Federation, and lecture courses for disengaged engineers.

"Reports can be found in the publications of the societies and in other journals to be seen in the offices of the societies, in Engineering Societies Library or in other libraries.

Throughout the recent years of financial difficulty, progress on the enterprises to which the Foundation has been contributing, although reduced, has been well maintained considering the handicaps. Already the signs for the future are encouraging. For coöperation and for opportunities to be helpful the Foundation expresses appreciation."

Annual Report Issued by United Engineering Trustees, Inc.

In the annual report of United Engineering Trustees, Inc., for 1933, it is pointed out that properties for which the corporation is responsible (real estate at cost, "funds" at book value, and library as appraised) total approximately $4,000,000. The corporation closed the year without deficit, by close economy, but for the library this is achieved only with the aid of special contributions.

Table I—Summary of 1933 Financial Report

Operation of Building		
Gross Operating Revenue	$94,770.21	
Less Operating Expenditures	93,719.42	
Net Operating Revenue	1,050.79	
Transfer of Revenue to Depreciation and Renewal Fund	0.00	
Appropriation from General Reserve Fund	3,934.40	
Total	4,985.19	
Loan written off	1,700.00	
Remainder	3,285.19	
Credit Balance in Activity Account Jan. 1, 1933	9,990.89	
Credit Balance in Activity Account Dec. 31, 1933		$13,276.08
Operation of Library		
Maintenance Revenue	$41,262.35	
Maintenance Expenditures	40,606.05	
Credit Balance for year 1933	656.30	
Transferred to Search Bureau	155.22	
Net Credit Balance for year 1933	501.08	
Credit Balance from previous year	2,921.11	
Credit Balance Dec. 31, 1933		3,422.19
Service Bureau Revenue	8,903.50	
Service Bureau Expenditures and Adjustments	10,135.27	
Debit Balance	1,231.77	
Transferred from Library	155.22	
Debit Balance for year 1933	1,076.55	
Credit Balance from previous years	1,076.55	0.00
Total net operating credit balance cumulated to December 31, 1933		$16,698.27
Funds and Property		
Funds held by U.E.T., Inc., Dec. 31, 1933 (book value)		
Henry R. Towne Eng. Fund		$49,243.13
*Combined Fund:		
Depreciation and Renewal	$331,458.03	
General Reserve	0.00	
Engineering Foundation	783,049.13	
Library Endowment	174,544.32	
Edward Dean Adams	100,000.00	1,389,051.48
Real Estate, cost to Dec. 31, 1933		1,987,793.92
Operating Cash: On Deposit	$11,467.04	
Petty Cash	250.00	11,717.04
Accounts Receivable		6,836.04
Fire Insurance Reserve		1,444.48
Due from John Fritz Medal Fund Corp.		12.85
Library as appraised for fire insurance		480,800.00
Total		$3,926,898.94
John Fritz Medal Fund (Custodian)		3,500.00
		$3,930,398.94

* A group of funds managed as if one for convenience and economy in investment transactions.

In this report it is pointed out that United Engineering Trustees, Inc., continues to be treasurer and accountant for the Professional Engineers Committee on Unemployment of the New York–New Jersey metropolitan district; and for a national relief fund; also custodian of funds for the John Fritz Medal Fund Corporation.

Among numerous other activities of the year, the flag of the 11th Engineers, American Expeditionary Forces, was committed to the care of United Engineering Trustees, Inc., in June 1933, with impressive ceremonies, by Mrs. William Barclay Parsons, widow of General Parsons, who had been colonel of the regiment.

A summary of the account's financial report for the administrative department for 1933 appears in Table I. In a companion article in this section of this issue, an outline of the organization and objects of United Engineering Trustees is given.

Election of United Engineering Trustees, Inc., Held

At the annual meeting of the United Engineering Trustees, Inc., which was held January 26, 1934, officers to serve for the year 1934 were elected. H. V. Coes, representing The American Society of Mechanical Engineers, was reelected president. G. L. Knight (A'11, F'17), representing the A.I.E.E., was elected vice-president, as was H. P. Charlesworth (M'22, F'28, and junior past-president) also a representative of the A.I.E.E. Dr. A. D. Flinn was elected to continue as secretary, and C. P. Hunt to continue as treasurer. A. S. Tuttle was elected to continue as assistant treasurer.

Appointments to the board of trustees for the 3-year term expiring January 1937, were announced to be as follows: J. P. Hogan (M'31), H. G. Moulton, D. R. Yarnall, and H. R. Woodrow (A'12, F'23). Mr. Woodrow is the representative of the A.I.E.E. Other members of the board of trustees for the year 1934 (the first 4 having terms expiring in 1935, and the last 4 having terms expiring in 1936), are as follows: A. S. Tuttle, R. M. Roosevelt, W. L. Batt, and G. L. Knight (A'11, F'17), C. W. Hudson, W. H. Bassett, H. V. Coes, and H. P. Charlesworth (M'22, F'28, and junior past-president).

An outline of the organization and objects of United Engineering Trustees, Inc., is given in a companion article in this section in this issue.

Home Study Course in Air Conditioning Analyzed. The advantages of a home study course have been brought out by an analysis made by the officials of Rutgers University, New Brunswick, N. J. The course analyzed was in air conditioning, technical training in this subject being given to an adult group by the university extension division. Students from 36 states and 5 foreign countries were registered. It was found that former education seems to have little correlation with the degree of effectiveness with which a student acquires both the fundamental and advanced principles of air conditioning. The majority of students are employees of public utility companies, and range from executives to mechanics. The group has been able to maintain an average performance rating of slightly more than 90 per cent. The course shows a remarkably high percentage of completions, and the students in this course received grades among the highest 3 groups in all home study courses offered by the university.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Limiting Reactances of 2-Terminal Reactance Arms

To the Editor:

Texts on circuit theory show that all irreduceable 2-terminal pure reactance arms of a given number of elements may be divided into 2 distinct groups. Any arm will be potentially equivalent to all other arms in its own group and potentially inverse to all arms of the other groups. Furthermore, any such arm, having n elements, will have n-1 finite resonant and anti-resonant frequencies. Also, the reactance must be either zero or negative infinity at zero frequency and must be either zero or plus infinity at infinite frequency. If we know the number of elements and the reactance at either zero or infinite frequency we can symbolically sketch the reactance curve.

There are 2 methods of determining these limiting reactances without the use of mathematics. These 2 methods are simple and direct, and yet they seem not to have been mentioned in the literature.

To find the reactance at zero frequency, inspect the arm for a d-c path. If there is a d-c path the reactance will be zero, if not it will be a negative infinity. A d-c path between terminals can only exist through a chain of inductance elements, all of which will have zero reactance at zero frequency.

To find the reactance at infinite frequency, inspect the arm for a direct capacity path. If such a path exists, the arm will have zero reactance at infinite frequency; if not, the reactance will be a plus infinity. If a path can be traced between terminals, traversing only capacity elements and broken by no inductance elements, the reactance of each capacity element, hence of the total path, will be zero at infinite frequency.

These methods can be easily and rapidly applied to the most complicated reactance arms and serve as a valuable check on the mathematical calculation of the reactance curve. They may also be used to detect possibilities of reduction in supposedly irreduceable arms. For example, suppose an arm had an even number of elements but the above tests showed the limiting reactances to be opposites, one zero and one infinite. This would immediately indicate that somewhere in the arm there were 2 or more elements which could be combined without changing the type of reactance curve.

Very truly yours,

S. G. LUTZ (ENROLLED STUDENT)
(Purdue University, Lafayette, Ind.)

Early Development of the Transformer

To the Editor:

In the abstract of the address "A Century of Development in Industry and Engineering" given by the writer before Section M (engineering) of the American Association for the Advancement of Science, Chicago, Ill., June 27, 1933, and published in the October 1933 issue of ELECTRICAL ENGINEERING, p. 666–71, the following statement appears:

"The use of alternating current for other than local electric lighting purposes was not visualized until the serious development of the transformer took place. In 1882 Gaulard and Gibbs developed a power transformer, which invention was exploited by Westinghouse, who was quick to perceive the possibilities of the transformer in connection with long distance transmission."

I would like to add to this the following statement:

"In 1884 a transformer, which for the first time embodied a closed iron core and thus became suitable for economical practical employment in power distribution by means of alternating current, on which the whole of modern electrical engineering is based, was built by the Ganz Company of Hungary under the Zipernowsky-Déri-Bláthy patents. By 1886 such transformers were operating in a number of power stations in Europe and South America. The Ganz Company can thus claim to be the pioneers in modern power distribution by means of alternating current."

Very truly yours,

A. P. M. FLEMING (M'14)
(Local Hon. Secy. A.I.E.E.; and Director and Manager of Research and Educational Depts., Metropolitan-Vickers Electrical Co., Ltd., Manchester, England)

Personal Items

PHILIP SPORN (A'20, M'26, F'30) for the past year chief engineer of the American Gas and Electric Company, New York, N. Y., has been appointed vice-president in charge of engineering. Mr. Sporn, after receiving the degree of electrical engineer from Columbia University, spent 2 years in the testing department of the Crocker Wheeler Electric Manufacturing Company. Following this he did some postgraduate work at Columbia, and then spent one year with the Consumers Power Company, Jackson, Mich., on station and substation design, joining the American Gas and Electric Company in 1920. Since that time his promotion has

PHILIP SPORN

been rapid. In 1920 he was made assistant to the electrical engineer. In 1921 he was also given the added responsibility of handling relay engineering for the company, and in 1922 station design was added to these other duties. In 1923 he was placed in active charge of the electrical engineering department. After directing the engineering division of the electrical engineering and construction departments he was promoted to chief electrical engineer, and last year was appointed chief engineer in charge of both the electrical and mechanical engineering activities of the American Gas and Electric Company and its subsidiaries. Mr. Sporn has been active in the A.I.E.E., the Edison Electric Institute, and the Association of Edison Illuminating Companies, as a member and chairman of a number of technical committees and subcommittees. He has contributed many papers and discussions to the A.I.E.E. in addition to his activities on its committees. Mr. Sporn is also a member of the Franklin Institute and Sigma Xi, and a fellow of the American Association for the Advancement of Science.

EDGAR KOBAK (A'21, M'22) vice-president and general sales manager, McGraw-Hill Publishing Company, Inc., New York, N. Y., has resigned. Mr. Kobak has been associated with this organization for the past 18 years, having been a vice-president of the company since 1926. Mr. Kobak, widely known in the electrical industry as a result of his diversified activities for the organization in the course of his rise from subscription representative to vice-president has not yet announced his future plans. He early contributed to the progress of the *Electrical World*, published by the McGraw-Hill Company, both as an editor and advertising salesman. After 2 years as an assistant editor, he joined the advertising and business division, and as a salesman for *Electrical World* and *Electrical Merchandising* covered the Chicago territory for 2 years. He spent one year in St. Louis, Mo., in a similar capacity. Upon his return to the New York headquarters of the publishing company, Mr. Kobak acted as promotion manager for *Electrical World* before becoming a vice-president in the McGraw-Hill Company. He was a member of the executive committee and of the board of directors. Mr. Kobak is president of the Advertising Federation of America. Prior to entering the publishing business, he was associated with the Georgia Railway and Power Company.

C. A. MAYO (A'13) assistant manager, The Eastern Massachusetts Electric Company, Salem, Mass., has been appointed manager of this company. In 1911 Mr. Mayo joined the Charles H. Tenney organization, entering the meter department of the Malden (Mass.) Electric Company at that time. He was superintendent of the Peoples Gas and Electric Company, Oswego, N. Y., for 3 years and from 1916 to 1931 was electrical engineer of the Malden company. The Eastern Massachusetts company, of which he is now manager, is the wholesaling and interconnecting organization of the Tenney properties north of Boston, and is now a part of the New England Power Association.

L. V. BEWLEY (A'27) engineer in the power transformer department of the General Electric Company, Pittsfield, Mass., has received one of the awards of The Charles A. Coffin Foundation for "a revolutionary new mathematical theory which greatly aids engineers in safeguarding transmission lines from lighting." Mr. Bewley is a frequent contributor of articles to the A.I.E.E. The Charles A. Coffin Foundation has been making awards each year since 1922, when it was established by the board of directors of the General Electric Company as a tribute to the late Charles Albert Coffin, founder of the company and its first president.

F. B. JEWETT (A'03, F'12), and past-president) vice-president, American Telephone and Telegraph Company, and president, Bell Telephone Laboratories, Inc., New York, N. Y., was elected a member of the board of trustees of the Carnegie Institution of Washington, D. C., at its annual meeting on December 15, 1933. Doctor Jewett has also been named by the Federal Transportation Coördinator as the chairman of the scientific research committee which will make a survey to determine "whether railroads are securing the maximum benefits from the utilization of modern science and invention."

T. M. HUNTER (A'15, M'28) engineer and sales manager, American Transformer Company, Newark, N. J., has been elected president of that organization. Mr. Hunter has been connected with the American Transformer Company for 20 years, and has been intimately identified with many of its various activities. After holding the position of manager of the industrial division of the company for several years, he was made general sales manager in 1933. Since 1929 he also has been a vice-president.

L. W. ROBERT, JR. (A'31) who for a number of years has been president of Robert and Company, Inc., consulting engineers and architects of Atlanta, Ga., and who, as announced in ELECTRICAL ENGINEERING for July 1933, p. 515, was appointed assistant secretary of the treasury in charge of public buildings about a year ago, has been removed from supervision of public building construction to the U.S. Bureau of Engraving and Printing and the Mint.

P. J. KENT (A'19) who has been chief system operator of the Edison Electric Illuminating Company of Boston, Mass., for many years, and has had 47 years of service with that company, retired from active service March 1, 1934. Mr. Kent is widely known in the eastern central station field for his activities in connection with the New England System Operators Club and for his handling of local and interchange facilities in eastern Massachusetts.

J. H. FERRY (A'20) chief engineer, Potomac Electric Power Company, Washington, D. C., was recently appointed vice-president of that organization. Mr. Ferry has been with the Potomac Electric Power Company since 1906, progressing through various positions in the engineering department and finally becoming chief engineer, a position which he still retains. He is a past-chairman of the Washington, D. C., Section of the Institute.

F. M. CLARK (A'24) physicist in the laboratory of the Pittsfield (Mass.) works of the General Electric Company, has received one of the Charles A. Coffin Foundation awards for "his development of pyranol, a non-inflammable and non-explosive liquid used as a substitute for oil in the insulation of transformers." Mr. Clark previously received an award from the Charles A. Coffin Foundation in 1931.

J. A. DARLING (A'21) assistant chief system operator, Edison Electric Illuminating Company of Boston, Mass., has been appointed chief system operator of the company, succeeding P. J. Kent (A'19). Mr. Darling entered the company's employ in 1902, becoming a load dispatcher in 1914. Three years later he was made assistant chief system operator.

S. R. Bergman (A'04) consulting engineer at the river works of the General Electric Company, West Lynn, Mass., is the recipient of one of the Charles A. Coffin Foundation awards for devising a new type of bucket manufactured by the General Electric Company for rayon manufacturers, which has banished previous failures in this piece of equipment."

E. J. Doyle (M'30) has resigned as president of the Commonwealth Edison Company, Chicago, Ill. He has served the Edison company for 38 years, having begun as Samuel Insull's office boy. It is stated that Mr. Doyle will perform, without title, his former duties, the position of president remaining unfilled.

Vannevar Bush (A'15, F'24) vice-president of Massachusetts Institute of Technology, Cambridge, and dean of engineering of that institution, has been appointed assistant treasurer. Brief biographical sketches of Doctor Bush, who has long been active in the Institute, were published in Electrical Engineering for April 1932, p. 286, and September 1932, p. 672–3.

T. C. Clark (M'27) sales engineer, W. N. Matthews Corporation, St. Louis, Mo., has recently been elected a vice-president of the James R. Kearney Corporation, St. Louis. Mr. Clark was for 13 years engaged on system operation with the Union Electric Light and Power Company of St. Louis, where his last position was division superintendent of overhead construction.

H. A. Morss (A'11, M'11) treasurer and recently-elected president of the Simplex Wire and Cable Company, Cambridge, Mass., has been appointed acting treasurer of the Massachusetts Institute of Technology, Cambridge. He has been a life member of the corporation since 1914, and assistant treasurer for many years.

R. W. Lamar (A'15) formerly general manager of the Tennessee Public Service Company, Knoxville, has been elected vice-president of that company. Mr. Lamar entered the public utility business upon graduation from Washington University, St. Louis, Mo., in 1907.

P. J. Myler (A'07) president of the Canadian Westinghouse Company, Hamilton, Ontario, Can., has been elected chairman of the company to succeed the late H. H. Westinghouse. Mr. Myler also will retain the presidency of the company.

B. S. Rodey, Jr. (A'22, M'26) assistant auditor, United Electric Light and Power Company, New York, N. Y., was recently appointed auditor of this company. Mr. Rodey also holds an identical position with the New York Edison Company.

Mark Eldredge (A'14, M'20, F'33) chief engineer, Memphis Power and Light Company, Memphis, Tenn., has been elected president of the Memphis Engineers' Club for the year 1934.

D. C. Barnes (A'04, M'20) vice-president of the Engineers Public Service Company, New York, N. Y., has resigned this office to become vice-president of the Stone and Webster Engineering Service Corporation.

F. D. Weber (A'09, M'30) chief electrical engineer, Oregon Insurance Rating Bureau, Portland, has been elected president of the Electric Club of Portland for the year 1934.

Obituary

William States Lee (A'04, M'05, F'13, and past-president), vice-president and chief engineer, Duke Power Company, Charlotte, N. C.; president of W. S. Lee Engineering Corporation of New York, N. Y., and Charlotte; and past-president of American Engineering Council, died March 24, 1934. News of Mr. Lee's death was received as this issue was going to press. A biographical sketch of Mr. Lee is scheduled for inclusion in the May 1934 issue of Electrical Engineering, as one of the group of sketches on the past-presidents of the Institute.

William Joseph Hammer (A'87, M'87, F'12, life member, past vice-president), consulting electrical engineer, New York, N. Y., and an early associate of Thomas A. Edison, died March 24, 1934. As notice of his death was received as this issue was going to press, a biographical sketch of Mr. Hammer is scheduled for inclusion in the May issue.

George Owen Squier (A'91, F'19, and member for life) retired, major-general, U.S. Army, Washington, D. C., died March 24, 1934. As notice of his death was received as this issue was going to press, a biographical sketch of Major-General Squier is scheduled for inclusion in the May issue.

Walter D'Arcy Ryan (A'02) for many years head of the illuminating laboratory of the General Electric Company, Schenectady, N. Y., and since June 1932, consulting engineer for the company, died at Schenectady, March 14, 1934. He was born at Kentville, Nova Scotia in 1870. Following private instruction, he attended Memramcoock College, in New Brunswick, and King's County Academy, Kentville, Nova Scotia. He then spent 3 years at the Royal School of Cavalry at Quebec. After a 5-year commission with the 18th Hussars, Royal Engineering, he subsequently came to the United States, and in 1891 accepted a position in the Lynn, Mass., works of the Thomson-Houston Electric Company, which subsequently became the General Electric Company. In 1896 he was promoted to the position of superintendent of test men in the West Lynn works of the General Electric Company, and shortly after this was made a commercial engineer and served as secretary of the Lynn factory committee. In 1903, he was formally designated illuminating engineer, and became one of the pioneers in this field. He was subsequently transferred to research, and was placed in charge of the commercial engineering department which is stated to have developed under his supervision to the first illuminating engineering laboratory in the world. In 1908, when the company organized the lighting laboratory in Schenectady, Mr. Ryan was given supervision of this laboratory. Here he started a series of experiments which, to a large measure, are responsible for present-day methods of floodlighting. In 1932 he was made a consulting engineer, being a consultant for the illuminating engineering laboratory. Mr. Ryan's engineering tendencies were early observed, when, in 1885, at the age of 15, he invented an ice velocipede, and 2 years later invented a rotary valve steam engine. In 1890 he developed and constructed a $^1/_8$-hp d-c motor and other small electrical devices. It was these tendencies which directed his interest to the Thomson-Houston Company at Lynn. Among the many famous striking floodlighting effects which were worked out under his direction were those for the Pan-American Exposition at Buffalo, N. Y., in 1901, the St. Louis Exposition in 1904, the Hudson-Fulton Exposition in New York City in 1909, the Panama-Pacific International Exposition in San Francisco, Calif., in 1915, and finally the Century of Progress Exposition in Chicago, Ill., in 1933. The exterior lighting for this latter exposition was designed by a corps of engineers from different companies all working under his direction. Many other lighting exhibits in this and foreign countries were designed by him, and he was frequently called upon to arrange illuminating effects for special occasions. Mr. Ryan was a charter member of the Society of Illuminating Engineers and was active in its affairs.

George Marshall Yorke (A'02, F'29) vice-president in charge of engineering, Western Union Telegraph Company, New York, N. Y., died March 18, 1934. He was born at Lowell, Mass., in 1870. In 1893 he graduated from Massachusetts Institute of Technology, Cambridge, with the degree of B.S. in E.E. From 1893 to 1911 he was employed by the American Telephone and Telegraph Company, spending the first year at Boston as inspector, the second at New York in a similar position, the third at Philadelphia, Pa., as district inspector, and the next 2 years, terminating in 1898, at Chicago as district inspector. The next year he was again at Boston, as district inspector, and in 1899 was transferred to New York as assistant electrician. He subsequently became assistant general superintendent of plant for the company, being the assistant in charge of construction engineering for the long lines department of the company. During the latter part of the period terminating in 1911, he had charge of the design of long distance central offices and of such special undertakings as the first long distance underground conduit and cable systems of the company, between New York and Philadelphia, and other points. In 1911 he became associated with the Western Union Telegraph Company at

New York, as an engineer, being appointed general superintendent of plant in 1913. In 1916 he was elected a vice-president of the company, holding this position until the time of his death. During this period he has been in charge of the engineering work of the company, including the design of all parts of the physical property, and the development of many new devices and methods in relation to both land and ocean cable telephony. Mr. Yorke was a director of the following companies: American District Telegraph Company (N. J.), Gold and Stock Telegraph Company, Stock Quotation Telegraph Company, and Teleregister Corporation. In 1918 he was appointed a member of the operating board of the U.S. Telegraph and Telephone Administration. He was a major in the Signal Officers Reserve Corps, being attached to the staff of the chief signal officer of the army, 1917–18. He was a member of the Franklin Institute of Philadelphia, the Technology Club of New York City, and the Metropolitan Museum of Art, American Museum of Natural History, and the New York Zoological Society, all of New York. He also was a member of the Machinery Club and the City Club, of New York, and the Manasquan River Golf and Country Club.

Harry Thomas Edgar (A'03, M'28) who had been division manager for Stone and Webster, Inc., Boston, Mass., for many years, died February 15, 1934. He was born at Griggstown, N. J., in 1869. Following 2 years spent in a lawyer's office at New Brunswick, N. J., he entered the employ of the Edison Electric Illuminating Company at New Brunswick in 1886 as office boy and night switchboard operator. Between 1886 and 1893 he was engaged in the installation of electrical apparatus in central stations throughout the country, and for the Edison Electric Light Company (now the General Electric Company), in New York, N. Y. From 1893 to 1897 he was secretary and general manager of the Georgia Electric Light Company at Atlanta. From 1897 to 1899 he was engaged in selling arc lamps, incandescent lamps, and carbon lamps in New England and New York. Since 1899, his work was entirely executive, managing properties under the executive management of Stone and Webster, Inc. From 1899 to 1901 he was manager of the Lowell (Mass.) Electric Light Corporation, and from 1901 to 1905 held a similar position with the El Paso (Texas) Electric Railway Company. In 1905 he became vice-president and manager of the Northern Texas Traction Company at Fort Worth, holding this position until 1910 when he became manager of the Seattle (Wash.) Electric Company. In 1912 he became district manager and division manager in charge of groups of properties under the executive management of Stone and Webster, Inc., with headquarters in Boston, holding this position for many years. Mr. Edgar was a brother of the late Charles L. Edgar (A'96, F'12) president and general manager of the Edison Electric Illuminating Company of Boston, and was an uncle of L. L. Edgar (A'12) first vice-president of the Edison company.

Norman Nelson Ross (A'93, M'94, F'12 and member for life) district turbine specialist, General Electric Company, Cleveland, Ohio, died November 1933. He was born at Washington, D. C., in 1869. He was educated principally by private tutors, and studied mechanical engineering and physics. His first position was that of telegraph operator. After serving in this position for about 2 years he was employed by the Bell Telephone Company on instruments and construction work for about 2 years, following which he was in business on his account in Montreal, Quebec, doing general electrical work for about $1^1/_2$ years. He next entered the employ of the Edison company in the works of E. Chanteloup, Montreal. He then went to the Royal Electric Company, subsequently going to Sherbrooke, Quebec, with A. J. Lawson, building Edison apparatus. After a few years in business for himself and in teaching, he reentered the employ of the Canadian Edison Manufacturing Company at Sherbrooke, being in charge of the testing departments. After a period as foreman of construction, installing lighting in railway plants in different localities, he became district engineer for the district from Port Arthur, Ontario, to the Pacific Coast, for the company, which subsequently became the Canadian General Electric Company. Following this, Mr. Ross held other positions with this company and with the General Electric Company in United States, subsequently becoming district steam turbine specialist for the General Electric Company at Cleveland. At one time he was district steam turbine specialist in the Cincinnati, Ohio, office of the General Electric Company.

Ernest Charles Joho (A'26) telephone equipment engineer, Bell Telephone Laboratories, Inc., New York, N. Y., died December 7, 1933. He was born at Elizabeth, N. J., in 1894. His technical education was acquired through the Western Electric Company. Following one year with the Weston Electrical Instrument Company, Waverly, N. J., he entered the engineering department of the Western Electric Company at New York, N. Y., in 1913. He remained with this organization and its successor company, the Bell Telephone Laboratories, Inc., until the time of his death. For the Western Electric Company he was at first in the drafting division of the telephone system development department engaged on the design of equipment for semi-mechanical telephone offices and panel machine switching telephone offices. He was then in the engineering division of the telephone systems development department as equipment engineer on panel machine switching systems, and subsequently as resident engineer on trial installations for new type equipment at Paterson, N. J. Upon the organization of the Bell Telephone Laboratories, Inc., in 1925, he became telephone equipment engineer in the telephone systems development department. In 1917 he left the Western Electric Company for a period of military service, being reinstated in 1919. As a sargeant in Company C of the 104th Field Signal Batallion, he took part in engagements at Haute Allschut and Meus-Argonne, where he was gassed and suffered a shrapnel wound.

Maurice Grunfield (A'20) assistant chief electrical draftsman, Brooklyn Edison Company, Inc., Brooklyn, N. Y., died January 8, 1934. He was born in Roumania in 1887. He was a graduate electrical engineer from the University of Lille (France). From 1912 to 1915 he was electrical engineer, estimating and designing power plants with the Roumanian branch of Brown, Boveri and Company, Switzerland. From 1915 to 1917 he was designing draftsman on electric generators and motors for the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. From 1917 to 1919 he was electrical draftsman on power stations and substations for the Interborough Rapid Transit Company, New York, N. Y. From 1919 to 1920 he was electrical draftsman, designing power stations, for Dwight P. Robinson and Company, New York. Subsequently, Mr. Grunfield joined the organization of the Brooklyn Edison Company, Inc.

William Wallace Ker (A'95 and member for life) instructor in physics and electricity at the Hebrew Technical Institute, New York, N. Y., died February 15, 1934. Two days before his death he had been teaching as usual at the institute, where he had served since 1887. Mr. Ker is said to have been one of the first instructors in the United States who established a laboratory course in electricity for boys of high school age. For several years, he was a lecturer on electricity in the public school evening lecture course for adults at New York, talking to a total of more than a million persons. His lectures were always profusely illustrated by practical experiments.

Membership

Recommended for Transfer

The board of examiners, at its meeting held February 28, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Ferris, Livingston P., asst. protection devpmt. engr., Am. Tel. & Tel. Co., New York.
Hansen, Klaus L., cons. engr., Harnischfeger Corp., Milwaukee, Wis.

To Grade of Member

Bosch, Lester L., E.E., Columbia Engg. Corp., Cincinnati, Ohio.
Boura, Felix G., asst. substation design engr., West Penn Pwr. Co., Pittsburgh, Pa.
Brown, Richard E., prof. of E.E., New York Univ., New York.
Esterline, John W., pres., The Esterline-Angus Co. Indianapolis, Ind.
Henderson, S. L., section engr., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Keenan, Henry B., engr., Wairarapa Elec. Pwr. Board, Carterton, New Zealand.

Kent, Paul N., distribution engr., Kansas City Pwr. & Lt. Co., Kansas City, Mo.
Linville, Thomas M., motor and generator engg. dept., Gen. Elec. Co., Schenectady, N. Y.
Lusignan, Joseph T., Jr., chief E.E., Ohio Brass Co., Barberton, Ohio.
Miller, Ralph H., supervisor—technical staff—systems devpmt. dept., Bell Tel. Laba., Inc., New York.
Oesterlein, Wm. J., chief E.E., Harnischfeger Corp., Milwaukee, Wis.
Rankin, Harry C., lab. engr., New England Pwr. Engg. and Serv. Corp. Providence R. I.
Spence, Paxton W., elec. engr. in research, Am. Tel. & Tel. Co., New York.
Tuck, H. P., lecturer in E.E., Univ. of Tasmania, Hobart, Tasmania, Australia.
Welman, Douglas P., director and general mgr., Messrs. Aretz, Ltd., London, Eng.

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before April 30, 1934, or June 30, 1934, if the applicant resides outside of the United States or Canada.

Adams, A. W., 7316 Jones Ave., N. W., Seattle, Wash.
Alvarez, R. J., N. Y. Edison Co., N. Y. City.
Amorosi, G. J., 337 E. 63 St., Shrub Oak, N. Y.
Anderson, B. T., Harnischfeger Corp., Milwaukee, Wis.
Anderson, G. C., Gen. Elec. Co., Schenectady, N. Y.
Anderson, T. R., U.S. Coast & Geodetic Survey, Seattle, Wash.
Anderson, T. V., Bristol Silver Mines Co., Pioche, Nev.
Anderson, W. A., Pub. Serv. Commission of N. H., Manchester, N. H.
Andrews, J. O., Glidden Co., Cleveland, Ohio.
Ashman, K. W., Intl. Business Machines Corp., Endicott, N. Y.
Atkinson, L. G., Jr., Westinghouse Elec. & Mfg. Co., Wilkinsburg, Pa.
Baker, E. G., Aristocrat Mfg. Co. Ltd., Toronto, Ont., Can.
Barber, W. H., Buffalo, Gen. Elec. Co., Buffalo, N. Y.
Bardet, P. E., Interboro Rapid Transit, N. Y. City.
Best, R. A., 497 7 Ave., Troy, N. Y.
Blake, R. W., N. Y. State Elec. & Gas Co., Endicott, N. Y.
Blasen, R. E., 607 New Post Office Bldg., Portland, Ore.
Bonstein, H. L., Jr., 1046 Washington St., Easton, Pa.
Boyle, F. B., Jr., 50 Highview Ave., Melrose, Mass.
Brady, L., 406 South 2 St., Las Vegas, Nev.
Brainin, S., 2022 Lexington Ave., N. Y. City.
Butler, A. B., Indiana Bell Tel. Co., Indianapolis.
Chaponis, R. L., 1 Bloor Ave., Toronto 9, Can.
Chennault, W. S., Western Union Telegraph Co., Sweetwater, Texas.
Clark, P. F., Westinghouse Lamp Co., Bloomfield, N. J.
Coakley, J. J., Central R.R. Co. of N. J., Jersey City.
Cohen, A. B., 211 Washington St., Dorchester, Mass.
Coleman, L. L., Okla. Gas & Elec. Co., Oklahoma City.
Collins, H. McD., 1117 Harvard Rd., Crafton, Pa.
Collins, J. D., Pub. Serv. Elec. & Gas Co., Elizabeth, N. J.
Collins, O. B., 6719 McCune Ave., St. Louis, Mo.
Comins, A. W., RCA Radiotron Co., Harrison, N. J.
Congiosi, R. A., Globar Corp., Niagara Falls, N. Y.
Constant, E. S., Okla. Gas & Elec. Co., Oklahoma City.
Cripps, R. H., Harman-Pacific Co., Los Angeles, Calif.
Cummings, G. A., Westinghouse Elec. & Mfg. Co., E. Springfield, Mass.
Darmer, P. E., 520 21 St., Cairo, Ill.
Dibble, C. H. (Member), Corning Glass Works, Corning, N. Y.
Ding, A. P., U. S. Engineers Corp., Portland, Ore.
Eimert, F. J., Mass. Inst. of Tech., Cambridge.
Eisler, J., Mass. Inst. of Tech., Cambridge.
Emrich, O. S., 1537 Anderson, Manhattan, Kan.
Ensminger, W. W., 1416 North 23 St., Birmingham, Ala.
Erbe, J. R., Box 1088, University, Ala.
Evans, J. P., Pa. Pwr. & Lt. Co., Wilkes-Barre.
Evans, W. M., U. S. Electrical Mfg. Co., Los Angeles, Calif.
Fay, C. C., Harbison-Walker Refractories Co., Clearfield, Pa.
Fantur, C. L., Canfield Oil Co., Cleveland, O.
Feick, D. E., 524 Kahler St., Duquesne, Pa.
Ferguson, F. H., Puget Sound Pwr. Lt. Co., Seattle, Wash.
Fink, G. R., Gen. Elec. Co., Schenectady, N. Y.
Flora, C. M., Delco-Remy Corp., Anderson, Ind.
Fossick, J. F., Memphis Pwr. & Lt. Co., Memphis, Tenn.
Friend, W. J., B. C. Elec. Ry. Co., Ltd., Vancouver, B. C., Can.
Gahn, W., 526 40 St., Union City, N. J.
Gehr, G. A., Los Angeles County Forestry Dept., Los Angeles, Calif.
Geiger, E. L., 411 6th St., Troy, N. Y.
Geiger, E. P., 2910 Poplar St., Phila., Pa.
Geraty, J. R., c/o W. C. Geraty Co., Yonges Island, S. C.
Giani, R. R., 123 Van Sicklen St., Brooklyn, N. Y.
Gregg, N. L., Jr., Box 576, Blacksburg, Va.
Grimes, F. M., 7705 Alaska Ave., N. W., Washington, D. C.
Grist, F. J., Stanolind Pipe Line Co., Ft. Worth, Texas.
Grob, R., 820 E. Wells St., Milwaukee, Wis.
Gross, F. J., Univ. of Wash., Seattle.
Gulles, W. L., Tomlinson Bros., New Haven, Conn.
Hagenbach, L. G., Jr., Gibbs & Hill, N. Y. City.
Hale, W. L., Jenkins Music Co., Kansas City, Mo.
Harris, W. N., Portland Gen. Elec. Co., Portland, Ore.
Harshaw, C. H., 209 Rimwood Ave., Buffalo, N. Y.
Hartmann, A. A., 47 S. Queen St., York, Pa.
Hartnett, F. J., 1152 E. 15 St., Brooklyn, N. Y.
Haynie, W. R., Dept. of Water & Power, City of Los Angeles, Saugus, Calif.
Helgesson, L. A., Pacific Pwr. & Lt. Co., Portland, Ore.
Henderson, W. J., Jr., 5122 Oakland St., Phila., Pa.
Hofford, R. A., 5029 Copley Rd., Phila., Pa.
Hofmann, L. H., N. Y. Quotation Co., N. Y. City.
Holcak, J. C., 700 W. Commercial St., Victoria, Texas.
Hopkins, C., Certain-teed Products Corp., Richmond, Calif.
Howles, R. J., N. Y. Edison Co., N. Y. City.
Husing, R. C., N. Y. Pwr. & Lt. Corp., Troy, N. Y.
Hutchinson, C. E., RCA Victor Co., Camden, N. J.
Jaqua, B. G., 3534 College Ave., Indianapolis, Ind.
Johnson, H. M., Troutdale, Ore.
Johnson, J. L., U.S. Patent Office, Washington, D. C.
Jones, J. L., Univ. of Wis., Madison.
Jones, R. W., Galeton, Pa.
Judy, O. B., 813 E. Wells St., Milwaukee, Wis.
Keto, A. I., Dept. of Pub. Works of Wash., Seattle.
Kilgore, J. R., Spanner Vapor Lamp Co., Inc., N. Y. City.
Killian, P. G., 313 Dodge St., Kaukauna, Wis.
Kirby, T. H., 7538 Luella Ave., Chicago, Ill.
Klein, J. N., 1238 N. 24 St., Milwaukee, Wis.
Lankford, H. B., Pa. Water & Pwr. Co., Baltimore, Md.
Leech, H. H., Intl. Boundary Commission, McAllen, Texas.
Leininger, J. R., Mass. Inst. of Tech., Cambridge.
LePage, W. R., 16 Seeley Ave., Arlington, N. J.
Light, C. L., Southwestern Bell Telephone Co., Oklahoma City, Okla.
Long, H. E. (Member), Conn. Pwr. Co., New City, London.
Lowery, G. A., Ohio Pwr. Co., Canton.
Lucas, P. B., 2124 N. 25 St., Lafayette, Ind.
Luther, H. A., U. S. Coast & Geodetic Survey, Providence, R. I.
Mackie, F. D., Wis. Pub. Serv. Commission, Ashland.
Maddox, J. A. M., 120 31 St., Newport News, Va.
Manning, A. E., Kelvinator Corp., Detroit, Mich.
Manthe, R. H., 307 N. Frances St., Madison, Wis.
Marshall, J. L., 215 Centerville St., Marion, Ala.
Marvin, J. R., Univ. of N. C., Chapel Hill.
Mason, C. E., Ind. Bell Telephone Co., Indianapolis.
Matschull, G. E., 2114 W. Garfield Ave., Milwaukee, Wis.
McBride, E. B., Wirt Co., Phila., Pa.
McClain, D. E., Potlach Forests, Inc., Lewiston, Idaho.
McCollum, T. A., Okla. Gas & Elec. Co., Enid.
McDermott, W. M., Gen. Elec. Co., Milwaukee, Wis.
McFarland, J. L., Radio Station WEXL, Royal Oak, Mich.
McGreer, T. H., Clarno, Ore.
McIntire, R. L., Okla. Gas & Elec. Co., Chandler.
McKinney, L. H., Detroit Edison Co., Ann Arbor, Mich.
McLean, C., Northwestern Elec. Co., & Pacific Power & Lt. Co., Portland, Ore.
Miller, D. H., R. R. No. 3, Newcastle, Ind.
Miller, R. D., 1703 Court Square Bldg., Baltimore, Md.
Miller, W. G., Westinghouse Elec. & Mfg. Co., Wilkinsburg, Pa.
Montero, G., Elec. Dynamic Co., Bayonne, N. J.
Moon, P. H., (Member), Mass. Inst. of Tech., Cambridge.
Moore, C. A., Jr., Williamsburg Pwr. Plant Corp., Brooklyn, N. Y.
Mutchler, R. P., U. S. Geological Survey, Morristown, N. J.
Myrick, S. E., (Member), Home Insurance Co. of N. Y., Jacksonville, Fla.
Nelson, J. E., B. C. W. Camp 69-PE, Mounds, Ill.
Nelson, L. M. (Member), 533 W. Third, Hastings, Neb.
Ott, D. E., Fibreboard Products, Inc., Antioch, Calif.
Pasquariello, A. P., Oneglia & Gervasini Inc., Torrington, Conn.
Pavlo, A. L., 340½ E. Houston St., N. Y. City
Payne, A. V., Newark College of Engg., Newark, N. J.
Pearson, H., 243 77th St., Brooklyn, N. Y.
Perley, A. L., 53 E. 95 St., N. Y. City.
Pibl, P. W., Box 15, Westford Rd., Chelmsford, Mass.
Pierce, G. O., 532 Orange Grove Ave., So. Pasadena, Calif.
Posey, J. (Member), 1755 Baltimore Trust Bldg., Baltimore, Md.
Power, W. R., Jr., Appalachian Elec. Pwr. Co., Charleston, W. Va.
Preston, C. R. (Member), Fla. Pwr. & Lt. Co., Miami, Fla.
Preston, L. W., 514 Jones St., Norton, Kan.
Puchy, C. G., 3549 W. 52 St., Cleveland, O.
Quay, I. R., Postal Telegraph-Cable Co., Chicago, Ill.
Quimby, C. W., Box 443, Morris Plains, N. J.
Raleigh, W. J., 1008 N. 6 St., Mankato, Minn.
Raymond, H. E., Southwestern Bell Telephone Co., Kansas City, Mo.
Rogers, H. M., U.S. Coast & Geodetic Survey, Dillon, S. C.
Roseborough, J. A., Continental Can. Co., of Calif., Oakland.
Rucinski, J. J., 766 Newbury St., Springfield, Mass.
Russell, J. B., Columbia Univ., N. Y. City.
Saltmarsh, W. C., Millard St., Suncook, N. H.
Sargent, H. I., Interstate Construction Co., Portland, Ore.
Scarff, M., 612 7 Ave., Devils Lake, N. D.
Schneider, H. C., 2405 Tratman Ave., N. Y. City.
Schreiber, H. F., 565 Park Ave., N. Y. City.
Schum, L., Grays Harbor Corp., San Francisco, Calif.
Schwab, W. G., P. R. Mallory & Co., Inc., Indianapolis, Ind.
Schwennesen, D. O. E., Chicago Water Works, Chicago, Ill.
Scott, C. B., Spencer-Fentriss Co., Oklahoma City, Okla.
Sepmeyer, L. W., 1530 Rodney Drive, Los Angeles, Calif.
Sheppard, H. H., Eldridge R. Johnson Foundation for Medical Physics, Phila., Pa.
Slade, W. E., Swift & Co., Chicago, Ill.
Smith, C. McR., Jr., 206 E. S St., Greenville, N. C.
Smith, S. G., National Tube Co., Ellwood City, Pa.
Speer, D. S., McCann & Co., Pittsburgh, Pa.
Spelman, I. L., United Elec. Lt. & Pwr. Co., N. Y. City.
Spence, A. R., 937 E. 22 St., Brooklyn, N. Y.
Squibb, W. P., U. S. Dept. of Agriculture, Vancouver, Wash.
Stamm, R. W., 325 Walnut St., Pottstown, Pa.
Starrett, E. E., 18 Overhill Rd., Providence, R. I.
Steltzriede, C. W., Barmard Rd., R.F.D. 7, Saginaw, Mich.
Stitt, J. C., Gen. Elec. Co., Cleveland, Ohio.
Stokan, R. S., 1012 E. Third, Anaconda, Mont.
Sullivan, W. L., Mass. Inst. of Tech., Cambridge.
Sussman, P. S., 954 Jennings St., N. Y. City.
Swift, G., Univ. of Pa., Phila.
Tallman, F. H., Cooper Union Inst. of Tech., N. Y. City.
Teter, R. K., 1059 New York Ave., Brooklyn, N. Y.
Thadewaldt, A. O., Miss. Valley Pub. Serv. Co., La Cross, Wis.
Thomas, H. L., Jr., Pa. R. R., Camden, N. J.
Torkelson, T., 1728 Broadway Ave., Everett Wash.
Treadway, W. I. H., 787 N. Marshall St., Milwaukee, Wis.
Tucker, E. O., Jr., Metropolitan Water Dist. of So. Calif., Banning, Calif.
Tucker, W. H., W. W. & C. F. Tucker, Inc., Hartford, Conn.
Vasso, J. W., Am. Brass, Torrington, Conn.
Virostek, J. S., Lower Main St., E. Douglas, Mass.
Voiz, A. C., Mission, Texas.
Walker, F. C., Bureau of Reclamation, Fairfield, Mont.
Weinberg, R. A., 2008 15 St., Troy, N. Y.
Whipp, D. M., 1232 E. Stanley Ave., Glendale, Calif.
Welsh, F. H., Jr., Intl. Business Machine Corp., Endicott, N. Y.
Werts, E. W., C. A. Dunham Co., Marshalltown, Iowa.
Wilkerson, S. C., Aluminum Co. of Am., Calderwood, Tenn.
Williams, G. K., Station WESG, Cornell Univ., Ithaca, N. Y.
Withers, E. J., Shell Petroleum Co., E. Chicago, Ind.
Wolfe, H. C., Wilmington, N. Y.
Wolff, A. E., Cities Ice Cream Co., Aurora, Ill.
Wong, H. Y. L., 771 Broadway, West New York, N. J.
Wood, R. B., Natl. Aniline & Chem. Co., Buffalo, N. Y.
Woodward, J. S., Gen. Elec. Co., Schenectady N. Y.
Wopat, J. D., 4121 No. Kingshighway Blvd., St. Louis, Mo.
Yorton, S. C., 39 Third St., Camden, N. Y.
Young, J. D., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Young, N. P., Okla. Gas & Elec. Co., Oklahoma City.
Ziev, M., Easton Car & Constr. Co., Easton, Pa.
205 Domestic

Foreign

Ambor, C. J., Cia Carboniferá y de Fundicion Schwager Coronel, Chile, S. A.
Austin, D. B., c/o Hong Kong & Shanghai Banking Corp., Shanghai, China.
Bogdanoff, A. K., Teploelectro Project, (T. E. P.) Moscow, U. S. S. R.
Christoff, E. C., 92 Tsar Samouil, Sofia, Bulgaria.
Fukasawa, S., 944 5 Chome, Inetsuka-Machi, Oji-ku, Tokio City, Japan.
Lan, H. A., China Motor Bus Co., Ltd., Hong Kong, China.
Logan, A., Corporation of Aylesbury Electricity Dept., Aylesbury, Buckinghamshire, Eng.
Nagano, F. M., Hawaiian Elec. Co., Honolulu, T. H.
Pillai, P. R., Indian Inst. of Science, Bangalore, India.
Raman, R. V., M/s S. T. Sons & Co., Trinchinopoly, South India.
Ramaswamy, B. S., Indian Inst. of Science, Bangalore, India.
Wadthekar, S. V., Arrah Elec. Supply Co., Ltd., Arrah (Bihar & Orrissa), India.

12 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Bonell, R. K., 45 Clinton St., Newark, N. J.
Darcy, Harris B., 305 M. & M. Bldg., Houston, Texas.
Dean, George H., Corris, Oid Shoreham Road, Shoreham-by-Sea, Eng.
Garvey, Fred A., 4144 Cottage Grove, Chicago, Ill.
Gentilini, Celso, 1512 Wood St., Wilkinsburg, Pa.
Griffith, Geo. M., R. no. 1, Tucker, Ga.
How, John H., 42 Wai Oi Road East, Canton, China.
Mathisen, Karsten V., 912 Noyes St., Evanston, Ill.
Nemkowski, B., 104–25 115th St., Richmond Hill, N. Y.
Sparks, Losey D., 1507 Sherwin Ave., Chicago, Ill.
Tompkins, H. K. V., 1060 Subway Terminal Bldg., Los Angeles, Calif.
Whittemore, J. D., 126 State St., Albany, N. Y.

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, during January are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface or text of the book in question.

HILFSBUCH für EINKAUF und ABNAHME METALLISCHER WERKSTOFFE. By R. Pohl. Berlin, VDI-Verlag, 1933. 142 p., illus., 8x6 in., cloth, 8 rm. Describes the properties of commercial metals and alloys which affect their suitability for various uses, and indicates the best methods of testing and of writing specifications for purchase. The work is intended as a reference book for the purchaser, especially the small buyer.

PHYSICS of ELECTRON TUBES. By L. R. Koller. N. Y. & Lond., McGraw-Hill Book Co., 1934. 205 p., illus., 9x6 in., cloth, $3.00. The fundamental phenomena involved in the operation of electron tubes are explained in this work, which discusses what takes place within the tube rather than circuits that contain them, or their applications. The book is based upon lectures at the Massachusetts Institute of Technology and is intended for engineers and students of physics.

MANUAL of STRUCTURAL DESIGN. By J. Singleton. Topeka, Kansas, H. M. Ives & Sons, 1933. 196 p., illus., 10x7 in., lea., $4.50. Aims to provide, in one volume, all the information required to solve ordinary problems relating both to structural steel and reinforced concrete. It is intended for the practical engineer, conversant with the theory of structural design.

POWER SUPPLY ECONOMICS. By J. D. Justin and W. O. Mervine. N. Y., John Wiley & Sons, 1934. 276 p., illus., 9x6 in., cloth, $3.50. Discusses load predictions, the internal economies of steam-electric and hydroelectric plants and the cost of power from each, peak-load plants, oil-engine plants, purchased power and similar topics; setting forth the general economic principles which govern the selection of the best solution.

SYMPOSIUM on CAST IRON, held at Joint Meeting of the Am. Foundrymen's Assn. and the Am. Soc. for Testing Materials. Phila., Am. Soc. for Testing Materials, 1933. 164 p., illus., 9x6 in., paper, $1.00; cloth, $1.25. The purpose of this symposium is to provide concise, authoritative information upon the composition, metallurgy, properties and uses of the many grades of cast iron now available. Sections are devoted to the metallurgy, properties, classification and specifications, heat treatment and welding of cast iron, as well as one to factors in casting design which are important.

TABLES of INTEGRALS and OTHER MATHEMATICAL DATA. By H. B. Dwight. N. Y., Macmillan Co., 1934. 222 p., illus., 9x6 in., cloth, $1.50. A useful collection of derivatives and integrals of the more important functions, accompanied by a selection of tables of numerical values and provided with a bibliography. The book is clearly printed and of convenient size, and adapted to the needs of college students.

TASCHENBUCH für FERNMELDETECHNIKER. By H. W. Goetsch. 5 ed. Munich & Berlin, R. Oldenbourg, 1933. 600 p., illus., 8x5 in., cloth, 14.50 rm. Especially designed as a reference book for telegraph and telephone engineers, in addition to telegraphic and telephonic communication over wires, it also discusses other electrical methods of signaling used in railway work, mining, clock circuits, telemetering, etc. Revised and enlarged.

TECHNISCHE AKUSTIK, Pt. 1 (Handbuch der Experimentalphysik, Band 17, Pt. 2). By E. Waetzmann and others; ed. by W. Wien and F. Harms. Leipzig, Akademische Verlagsgesellschaft, 1934. 538 p., illus., 10x7 in., cloth, 44 rm. The first of 2 volumes upon applied acoustics, intended to give a comprehensive review of the field. This volume contains chapters on the underlying mechanical and electrical concepts, on acoustic measurement, the microphone, telephone, and loud speaker, on the propagation of sound in free media and on architectural acoustics.

TECHNISCHE AKUSTIK, Pt. 2. (Handbuch der Experimentalphysik, Band 17, Pt. 3). By E. Waetzmann and others; ed. by W. Wien and F. Harms. Leipzig, Akademische Verlagsgesellschaft, 1934. 434 p., illus., 10x7 in., cloth, 36 rm. The prevention of noise and vibration, medical acoustics, musical instruments, sound transmission by radio, the phonograph and phonautograph, and the talking film are discussed in the present instalment of this treatise.

Die TECHNOLOGIE des EDELSTAHLES, Aufbau, Verwendung, Herstellung, Behandlung, Prüfung und Fehler des Edelstahles. By A. Kropf. Halle (Saale), Wilhelm Knapp, 1934. 264 p., illus., 9x6 in., paper, 12.80 rm. The characteristics of the various alloy steels are described and methods of manufacturing, working, and heat treating are discussed. Methods of testing are given, with the standard specifications of England, Germany, Switzerland, and the United States. One chapter is devoted to flaws and their origins. Special attention is given to practical questions.

Die WIRTSCHAFTLICHE AUSGESTALTUNG STÄDTISCHER DREHSTROMNETZE. By W. v. Mangoldt. Berlin, Julius Springer, 1934. 76 p., illus., 10x7 in., paper, 5.50 rm. A discussion of the engineering and economic factors of the design of the a c distribution systems. Methods are given for determining the cable cross section, the most favorable transmission voltage and the number and sizes of the transformer stations in the system. A critical comparison of the most popular systems of distribution is included and the conditions to which each is best suited are explained.

AMERICAN SOCIETY for TESTING MATERIALS. PROCEEDINGS, 36th Annual Meeting, Chicago, Ill., June 26–30, 1933. V. 33, Pts. 1 & 2. Phila., A.S.T.M., 1933. Pt. 1, 1092 p.; Pt. 2, 804 p., illus., 9x6 in., paper, $5.50. Contains the reports of the various committees, new and revised tentative standards, tentative revisions of current standards, and the technical papers presented at the meeting. These include a lecture by Dr. H. J. Gough, a symposium on cast iron, and numerous papers on the testing of metals, cement, concrete, and other materials.

APPLIED GEOPHYSICS in the SEARCH for MINERALS. By A. S. Eve and D. A. Keys. 2 ed. Cambridge, Eng., Univ. Press; N. Y., Macmillan Co., 1933. 296 p., illus., 9x6 in., cloth, $4.25. Supplies a readable account of the theory and practice of the various methods of geophysical prospecting, with some critical appraisal of them, based upon field experience. The new edition has been revised and brought up to date. A bibliography is included.

BILDWORT ENGLISCH, Technische Sprachhefte, Heft 6: CABLE and WIRELESS COMMUNICATION. Berlin, V.D.I.-Verlag, 1933. 33 p., diagrs., 8x6 in., paper, 1.50 rm. The sixth pamphlet of this series provides a practical course in the terminology of telegraph and telephone engineering for the foreign engineer who wishes to read English technical works. The usual technical words are explained by drawings. An English-German glossary is included.

CHEMICAL ENGINEERS' HANDBOOK (Chemical Engineering Series). Ed. by J. H. Perry and W. S. Calcott. N. Y. and Lond. McGraw-Hill Book Co., 1934. 2609 p., illus., 7x5 in., lea., $9.00. A convenient, practical reference book for chemical engineers, as well as plant executives, mechanical engineers, and others engaged in manufacturing. The field covered includes not only chemical engineering but also the important related fields. Special attention is given to cost data.

CONJUGATE FUNCTIONS for ENGINEERS, a Simple Exposition of the Schwarz-Christoffel Transformation Applied to the Solution of Problems Involving Two-Dimensional Fields of Force and Flux. By M. Walker. Lond., Humphrey Milford; N. Y., Oxford Univ. Press, 1933. 116 p., illus., 10x6 in., cloth, $4.75. A simple exposition of the Schwarz-Christoffel transformation, intended for engineers who have had elementary courses in hydrodynamics and aerodynamics, electrostatics and electromagnetism. The subject is presented from the point of view of the engineer, rather than the mathematician, and developed through a number of typical practical examples.

COST and PRODUCTION HANDBOOK. Edit. by L. P. Alford. N. Y., Ronald Press Co., 1934. 1544 p., illus., 8x5 in., lea., $7.50. A reference work for industrial managers, which endeavors to provide, in one volume, all the information usually needed in the administration and operation of industrial concerns. Budgeting, factory organization, production planning and control, purchasing, storekeeping, job standardization, rate setting, incentive plans, buildings and machinery, costs, cost accounting, depreciation, labor, and other topics are treated.

DEPRECIATION, a Review of Legal and Accounting Problems by the Staff of the Public Service Commission of Wisconsin. Submitted to the Nat. Assn. of R. R. and Utilities Commissioners at its 45th annual convention in Cincinnati, Ohio, October 11, 1933. N. Y., State Law Reporting Co., 1933. 196 p., illus, 9x6 in., paper, $1.50; cloth, $1.85. This report, prepared at the request of the National Association of Railroad and Utilities Commissioners, presents the view of the Wisconsin Public Service Commission as to the depreciation policy which should ultimately be adopted, and discusses some of the outstanding problems and legal principles that confront commissions.

HAUSHALT - KÄLTEMASCHINEN und KLEINGEWERBLICHE KÜHLANLAGEN. By R. Plank and J. Kuprianoff. 2 ed. Berlin, J. Springer, 1934. 182 p., illus., 10x6 in., cloth, 13.20 rm. The development of mechanical refrigerators for domestic and shop use is described comprehensively, with full attention to American, as well as European practice. Details are given of the construction and method of working of the compressors, condensers and other components of most of the systems of commercial importance.

Engineering Societies Library

29 West 39th Street, New York, N.Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

Meter Devices Co. Expands.—Due to the rapid growth of its business, the Meter Devices Co. has found it necessary to move into a new factory and offices at 1001 Prospect Ave., S.W., Canton, Ohio. In addition to meter test switches and test blocks, the company also produces a complete line of meter accessories and devices.

New Indicating Cutout.—The L. S. Brach Mfg. Corp., Newark, N. J., has announced a new line of porcelain plug and cartridge cutouts which have neon lamp indicators built in permanently, and known as Fuse-O-Lite indicating cutouts. When a fuse fails, a neon lamp glows, indicating the position of the blown fuse; inserting a new fuse puts out the light.

New Fuses.—The Jefferson Electric Co., Bellwood, Ill., has developed a new line of super-lag fuses, incorporating a design principle that prevents failure of the fuse until the current overload has continued for a sufficient space of time to be dangerous. These renewable fuses are made in all standard ratings, both knife-blade and ferrule types.

New Heavy Duty Receptacle.—The Delta-Star Electric Co., Chicago, has developed a new, heavy duty, multi-contact receptacle for use in connection with metal-clad switchgear and control equipment. The receptacle can be bolted flat against an opening in metal housings enclosing the control wiring, thus giving a direct connection with minimum space requirements. It is made in 3, 4, 5, 6, or 7 poles and all except the three pole are polarized.

Wolverine Tube Co. Appoints Agents.—The J. T. Hill Sales Company, Los Angeles, has been appointed by the Wolverine Tube Co., Detroit, as agent for the Wolverine line of electrical soldering lugs, consisting of standard and automotive types of every size, single and double splicing sleeves for overhead work and split-tinned sleeves for underground work. W. H. Beaven, Birmingham, has been appointed to represent the company in a tier of southern states.

Special Flashlight.—A new flashlight case designed especially for heavy service and work around transmission lines, bus bars or other electrical circuits has been introduced by the Bond Electrical Corp., Jersey City, N. J. Known as the Bond "Voltpruf," the flashlight is heavily insulated for protection against high voltages. The heavy ribbed fiber case is designed to withstand severe service. The new flashlight is available in both focusing spotlight and spreadlight types.

Trade Literature

Mica.—Bulletin, 24 pp. Describes "Micabond," a bonded mica insulating material. It is supplied in punched and formed parts, sheets, tubes, etc. Continental-Diamond Fibre Co., Newark, Del.

Brewery Equipment.—Bulletin 149-A, 16 pp. Describes equipment for the power, electrical, pumping, and other requirements of the brewing industry. Allis-Chalmers Mfg. Co., Milwaukee.

Shafting.—Booklet, 16 pp. Describes production and characteristics of cold finished and other types of shafting. Union Drawn Steel Co., Massillon, O.

Converters.—Bulletin 509-A, 4 pp. Describes construction, operation and uses of various types of frequency converters. Bulletin 502-B describes inverted rotary converters. The Louis Allis Co., Milwaukee.

Illumination.—Bulletin SP-1989, 32 pp. Outstanding developments in illumination are illustrated, including flood lighting, bridge and street lighting, industrial and aviation field lighting, etc. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Cable Installation.—Bulletin, 12 pp., "Installing General Cable Trenchlay." Covers the recommended methods for the handling and protection of all types of low-voltage, trenchlay (non-metallic sheathed) cables. General Cable Corp., 420 Lexington Ave., New York.

Mining Locomotives.—Bulletin D.M.F. 5550, 4 pp. Describes Baldwin Westinghouse mining locomotives. Bulletin D.M.F. 5544 describes Baldwin Westinghouse permissible storage battery locomotives. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Bakelite.—Bulletin, 48 pp., "Bakelite Molded." Describes Bakelite molding materials and their innumerable uses, including electrical and allied applications, and outlines the molding process and necessary equipment. Profusely illustrated. Bakelite Corp., Bound Brook, N. J.

Electrical Equipment for Railroads.—Catalog 1966, 60 pp. This catalog on electrical equipment for railroad shops and maintenance of way describes apparatus such as arc welding equipment, heat treating and melting apparatus, motors, controls, lighting, battery charging, etc. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Time Switches.—Bulletin. Describes a new series of special, self-starting, synchronous time switches in 7 different models, providing a special time control for operating temperature regulators, oil burner controls, neon signs, traffic controls, stoker, draft and machinery controls. The latest addition to the extensive line of Paragon time controls has been developed to meet the demand for a small, compact and simplified time switch at a very moderate price. Paragon Electric Co., Old Colony Bldg., Chicago.

Supervisory Control.—Bulletin C. 1983, 10 pp. Describes Westinghouse two-wire visicode and audicode supervisory control, a simplified and sure means of obtaining remote indication of apparatus units and especially applicable for railway, central station, substation and oil and gas pump line operation. Westinghouse Electric & Mfg. Co. East Pittsburgh, Pa.

Motors.—Bulletin 1165, 16 pp. Describes bracket bearing synchronous motors. In addition to the standard line of motors for general requirements, including exciters, control equipment, etc., the bulletin also treats of special construction features, such as anti-friction bearings, enclosed collector rings, splash-proof type, enclosed fan-cooled type, and vertical motors. A discussion is included on the use of the synchronous motor for improvement of power factor with examples applying the graphical method for figuring power factor corrections. Allis-Chalmers Mfg. Co., Milwaukee.

Boiler-Feed Pumps.—Bulletin No. 2078, 6 pp. Describes Cameron Type NT multistage centrifugal pumps for pressures up to 600 pounds. An interesting feature of this pump is the hydraulic balance obtained by placing an equal number of impellers back to back. This results in the elimination of high-pressure stuffing boxes. Of the two stuffing boxes used, one is under second-stage pressure, the other is under suction pressure. The casing is split horizontally, allowing the entire rotor to be removed without disturbing the bearing adjustment, exposing bearings to dirt or moisture, or disconnecting any part of the piping. Ingersoll-Rand Co., 11 Broadway, New York.

New Lightning Arresters.—Improvements in both protective performance and mechanical construction have been incorporated in the new, form D Thyrite, station-type, lightning arresters of the General Electric Co., and the exclusive no-time lag feature has been continued. The impulse breakdown voltage of the 11.5-kv unit is about 40-kv crest. When applying AIEE standard surge current (1500 amp.), the impulse voltage across the arrester unit is limited to only 36-kv crest—little more than two times the crest rating of the arrester, and an improvement of 30 per cent over previous designs. The sealed construction of the series gap protects the gap elements from moisture or atmospheric influences.

The new arrester embodies unit construction, an exclusive Thyrite feature, whereby standard 11.5-kv arrester units are common to, and interchangeable in, arresters of all voltage ratings. Three-point support and bolting between units of the new arrester simplify assembly and avoid mechanical strains on porcelains. Within the unit the series gap is hermetically sealed, metal caps being bottle-cap-crimped over the ends of the porcelain container, with the gaskets permanently locked in their original compressed position, excluding moisture and making the arrester operation independent of atmospheric influence. The interior elements of the new arrester can be put readily into the unit housings of existing arresters, thereby enabling Thyrite arresters now in service to be modernized to incorporate the advanced protective performance of the new arrester and the advantages of the new sealed gap.

Published Monthly by

American Institute of Electrical Engineers

(Founded May 13, 1884)

Electrical Engineering

Registered U. S. Patent Office

May 1934
Volume 53
No. 5

The Official Monthly Journal and Transactions of the A.I.E.E.

J. B. Whitehead, President
H. H. Henline, National Secretary

Publication Committee
E. B. Meyer, Chairman
R. N. Conwell
W. S. Gorsuch
H. H. Henline
H. R. Woodrow

Publication Staff
G. Rose Hemsinger, Editor
C. A. Graef, Advertising Manager

PUBLICATION OFFICE, 20th and Northampton Streets, Easton, Pa.

EDITORIAL AND ADVERTISING OFFICES, 33 West 39th Street, New York, N. Y.

ENTERED at second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918.

SUBSCRIPTION RATES—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii and the Philippine Islands, Central America, South America (except Argentina), Haiti, Spain and Spanish Colonies; $13 to Canada; $14 to all other countries. Single copy $1.50.

CHANGE OF ADDRESS—requests must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered due to incorrect address cannot be replaced without charge. Be sure to specify both old and new addresses and any change in business affiliation.

ADVERTISING COPY—changes must be received by the fifteenth of the month to be effective for the issue of the month succeeding.

STATEMENTS and opinions given in articles appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters.

REPUBLICATION from "Electrical Engineering" of any Institute article or paper (unless otherwise specifically stated) is hereby authorized provided full credit be given.

COPYRIGHT 1934 by the American Institute of Electrical Engineers.

ELECTRICAL ENGINEERING is indexed in Industrial Arts Index and Engineering Index.

Printed in the United States of America. Number of copies this issue—

18,100

This Month—*50th Anniversary Number*

General

The Fiftieth Anniversary of the A.I.E.E. . 643
By J. B. WHITEHEAD

The Institute's First Half Century 645
By CHAS. F. SCOTT

The Institute's Organization 671
By H. P. CHARLESWORTH

Telegraph Men Founders of the A.I.E.E. 675
By DONALD McNICOL

The Work of the Institute in Standardization 676
By A. E. KENNELLY

The Institute and Industrial Standardization 681
By C. E. SKINNER

Early Headquarters of the Institute . . . 685
By GANO DUNN

Some Major Events in the Life of the Institute 686
By COMFORT A. ADAMS

A Century of Progress in 50 Years . . . 689
By E. W. RICE, JR.

The Equation of Electrical Propagation . 691
By M. I. PUPIN

Digging in "The Mines of the Motors" . 695
By FRANK J. SPRAGUE

Alternating Current Versus Direct Current 708
By LEWIS B. STILLWELL

Developments in Electric Power Transmission 712
By HARRIS J. RYAN

Water Power Development 715
By W. S. LEE

Some Reminiscences of Niagara 720
By P. M. LINCOLN

Some Contributions to the Electrical Industry 726
By C. C. CHESNEY

Lighting "A Century of Progress" . . . 731
By W. D'ARCY RYAN

Communication—Past and Present . . . 745
By BANCROFT GHERARDI

Some High Lights of Electrical History . 758
By ELIHU THOMSON

The Evolution of Electrical Engineering . 770
By DUGALD C. JACKSON

The Engineer a Creator of Leisure . . . 777
By WILLIAM McCLELLAN

Research and Engineering 781
By FRANK B. JEWETT

—Turn to next page

Pictorial

A Few High Lights in Electrical Transportation 707

Some Transmission Structures 711

Some Hydroelectric Power Stations and Equipment 716, 717

Some Early Forms of Electric Lamps . 730

"Century of Progress" Illumination . . 733, 735, 737–44

Some Contrasts in Communication Equipment 748, 749, 752

The Family Tree of the Thermionic Tube 753

Some Steam-Electric Generating Stations 754, 755

Generators of Various Periods . . 756, 757

Typical Electric Motors 768

Early Electrical Instruments 769

Some of the Early Transformers From Which Modern Power Systems Grew 779

Some High Lights in the Evolution of Switchgear 780

Some Contrasts in Radio Equipment . . 784, 785

Some Contrasts in Power System Switchboards 839

Biographical

Note—An asterisk (*) before a page number denotes publication of person's picture on that page.

Adams, Comfort A. *803

Adams, Edward D. *818

Anthony, William A. *790

Arnold, Bion J. *795

Bell, Alexander Graham *791

Berresford, Arthur W. *804

Blondel, André E. *812

Brown, Charles E. L. *812

Brush, Charles F. *815

Buck, H. W. *802

Budde, Emil A. *813

Carty, John J. *801

Charlesworth, Harry P. *810

Chesney, C. C. *807

Clarke, Charles L. *823

Conrad, Frank *818

Coolidge, William D. *818

Crocker, Francis B. *793

de Ferranti, S. Z. *813

Dickerson, E. N., Jr. 823

Duncan, Louis *792

Dunn, Gano *799

Edison, Thomas A. *814

Emmet, William LeRoy *816

Faccioli, Guiseppe *819

Farmer, Moses G. *811

Ferguson, Louis A. *798

Field, Allan Bertram *819

Field, Cyrus W. *811

Foch, Ferdinand *814

Foster, William J. *819

Gherardi, Bancroft *807

Gilberd, William *644

Green, Norvin *788

Hamilton, George A. *816

Hazard, Rowland R. 821

Heaviside, Oliver 814

Hellmund, Rudolf E. *819

Henline, H. H. *820

Hering, Carl *794

Hoover, Herbert *815

Houston, Edwin J. *792

Howell, John W. *817

Hutchinson, F. L. *820

Jackson, Dugald C. *799

Jewett, Frank B. *805

Keith, Nathaniel S. *820

Kelvin, Lord (William Thomson) . . . *812

Kennelly, Arthur E. *793

Lamme, Benjamin G. *817

Lee, W. S. *809

Lieb, John W. *796

Lincoln, Paul M. *801

Mailloux, C. O. *800

Marconi, S. Guglielmo *814

Martin, T. Commerford *789

Mershon, Ralph D. *800

Millikan, Robert A. *816

McClellan, William *804

Osgood, Farley *806

Pacinotti, Antonio *813

Phelps, George M. *821

Pope, Franklin L. *788

Pope, R. W. *820

Preece, Sir William *811

Pupin, M. I. *806

Rae, Frank B. *823

Rice, E. W., Jr. *802

Ryan, Harris J. *805

Schuchardt, R. F. *808

Scott, Charles F. *795

Sheldon, Samuel *797

Shibusawa, Motoji *815

von Siemens, E. W. *812

Skinner, C. E. *809

Sfichter, W. I. *821

Smith, Harold B. *808

Sperry, Elmer A. *818

Sprague, Frank J. *791

Stanley, William *817

Steinmetz, Charles P. *794

Stillwell, Lewis B. *798

Stott, Henry G. *797

Swasey, Ambrose *815

Tesla, Nikola *817

Thompson, Silvanus P. *813

Thomson, Elihu *790

Townley, Calvert *803

Westinghouse, George *816

Weston, Edward *789

Wheeler, Schuyler Skaats *796

Whitehead, John B. *810

Miscellaneous

Among Long-Standing Members . . . 825

Groups on Which the Institute Is Represented 826

Chart of Institute Committees 827

Chairmen of the Institute's Committees . 828

Chairmen of the Institute's Sections . . 831

Past and Present Officers of the Institute 834

Women Members of the A.I.E.E. . . 835

Sections and Branches of the Institute . 835

International Engineering Congresses . . 836

The A.I.E.E. in Standardization . . . 837

Engineering Societies Library 837

The Engineering Foundation 837

Origin and Adoption of the Institute's Badge 838

Significant Electrical Developments . . 840

News of Institute and Related Activities 842

Science Makes More Jobs . . . 845

The Institute's 50th Annual Summer Convention 842

Annual Meeting Notice 843

District Meeting at Worcester, May 16–18 844

Membership 848

Officers and Committees (For complete listing see p. 658–91, September 1933 issue of ELECTRICAL ENGINEERING)

The Fiftieth Anniversary of the A.I.E.E.

By J. B. Whitehead, President A.I.E.E. 1933-34

With a glorious record of tradition, accomplishment, and unique service to profession and to society; with no apparent causes for regrets; and with the promise of the future that lies in firmly planted ideals, the Institute may justly take for itself a happy celebration of its anniversary.

IN CELEBRATING the fiftieth anniversary of the founding of the American Institute of Electrical Engineers, it may also be said that we are celebrating also a similar birthday of the electrical art. The period in which the Institute was founded was that in which the applications of electric power were just beginning to expand beyond the fields of the telegraph, the telephone, and other signal systems which, while already highly developed and rapidly growing in public service, nevertheless were strictly limited in character of service, and commonly involved currents and voltages of relatively low values. However, electric lighting by arc and incandescence also was well on its way, and the first New York Edison central station already was a reality. Evidently the time was ripe for the birth of the profession of electrical engineering.

Similar stirrings from similar causes were occurring in other countries. The Société Française des Électriciens has just at this writing celebrated the fiftieth anniversary of its foundation, thus antedating the A.I.E.E. by a few months. The British Institution of Electrical Engineers was not to see its formal foundation until 1888, but in fact it was already existent in the Society of Telegraph Engineers and Electricians. In other countries, similar societies also were the forerunners of the later expanded organizations with wider scopes.

A most interesting account of the conditions in the electrical art in America in 1884 is to be found in a paper by the distinguished English electrical engineer, W. H. Preece, F.R.S., who was one of a delegation of British scientists and engineers attending an electrical congress in Philadelphia, called for ratifying the Paris units of current, electromotive force, and resistance. Others in the delegation were Lord Rayleigh, Sir Oliver Lodge, and Sir William Thompson. Full of appreciation of the hospitality and courtesy extended everywhere in America, Mr. Preece complains of its summer heat, and also of the dearth of electrical papers and discussion at the joint meetings of the conference and the American Association of Arts and Sciences. He mentions as outstanding topics "The Seat of the Electromotive Force in a Voltaic Cell," the announcement of the Hall effect, and Rowland's claim that the Paris standard for the ohm was not accurate. He notes the advanced state of development of the continuous-current constant-potential generator in this country, but states that in visits to many cities, he did not see an alternating current machine, although they were then quite common in England.

Other literature of this time reflects the continuing interest in methods of measurement as related to telegraph and telephone circuits, the first appearance of direct-reading portable measuring instruments for continuous current lighting and power, and the beginnings of the theory of alternating current and auxiliary equipment. Such a narrow field, so few workers, such limitations for experimental development, well may serve for contrast with the wide complexity and extent of the development of the electrical art today, for evidence of how far we have advanced, and for an appreciation of the vital part played by the Institute.

In one respect a fiftieth anniversary has an advantage over the hundredth and others thereafter. Men are still living who are able to survey the entire past history and so, from personal contact and knowledge, are in admirable position to weigh the significance of the different events and personalities that have had an influence on subsequent development and present status. Many present members of the Institute can trace their identification to its first decade, and a few even to its earliest years. The memories of these men contain great stores of historic interest and value. An effort has been made to garner some of these stores in the series of articles of personal reminiscence by past-presidents of the Institute, which is the chief feature of this anniversary issue of ELECTRICAL ENGINEERING. These articles are indeed the chief feature of our celebration in the reminders they give us of the aims and accomplishments of our distinguished members of the past. These personal reminiscences doubtless will revive similar ones in the memories of others. May I suggest to these that they make permanent records of such reminiscences, sending them to the Institute so that they may play their part in completing the history which is in course of preparation.

Anniversaries are commonly the occasion for looking backward, for a balancing of performance against earlier aspirations, and for a refurbishing of ideals for guidance in the future. Such self-examination may leave us in serious or in happy mood according to the degree of excellence of the past record or to the promise for the years to come. It must be admitted, however, that in the celebrations of anniversaries the happy mood usually predominates:

The successes are dwelt upon; the shortcomings are reserved for more private attention. This is as it should be, for inspiration, enthusiasm, and courage for the future spring more readily from a review of past achievement than of vain regrets, if any, for lost opportunities.

As the American Institute of Electrical Engineers approaches its fiftieth anniversary, in my opinion it may give itself over heartily and with free conscience to the happiest type of celebration, for the Institute has remained true to its ideals, has rendered magnificent service, and set its professional standards on the highest plane. Through successive years those entrusted with its guidance have adhered to the vision of the founders that the basic purpose of the Institute is the advancement of the theory and practice of electrical engineering and of the allied arts and sciences. Efforts have been made from time to time to divert the interest of the Institute to commercial, political, and social problems as related to the electrical art, which, from their nature, are not subject to accurate analysis, are invariably controversial in character, and so tend to disrupt the other sounder unity of interest. The present strength of the Institute in my opinion is due largely to the firmness with which it has insisted that its best service and functions are in the support and development of the scientific basis of the electrical art. This is its strength and the basis of its independence. If I were asked to name the 2 grounds upon which the present strength of the Institute exists, I would place first the record of progress as found in its printed pages, and second the power that its meetings and publications have of attracting aspiring young men, and maintaining their allegiance. Throughout its life in my observation, this appeal to young men has been the greatest asset of the Institute. Beyond question this appeal is inherent in the Institute as the inspiration and the forum of scientific effort and progress in the electrical art.

With a glorious record of tradition, accomplishment, and unique service to profession and to society; with no apparent causes for regrets; and with the promise of the future that lies in firmly planted ideals, the Institute may justly take for itself a happy celebration.

Dr. Wm. Gilberd shewing his experiments on electricity to Queen Elizabeth and her court

A painting by Arthur Ackland Hunt, replica of that in the Town Hall of Colchester, England, commemorating the Three Hundredth Anniversary of Dr. Gilberd's death on the 10th of December 1903

Bion J. Arnold, President, Amer.I.E.E.

Presented by the Institution of Electrical Engineers to the American Institute of Electrical Engineers on the occasion of the International Electrical Congress held in St. Louis in September 1904

Robert Kaye Gray, President, I.E.E., London

(This is a reproduction of the painting that hangs in the Board Room at A.I.E.E. headquarters, and of the information engraved on the name plate)

Lady Scudamore and Ladies of the Court — Sir Walter Raleigh — Queen Elizabeth — Sir Francis Drake — (Portrait of Gilberd) William Gilberd, M.D. (1544–1603) — Cecil, Lord Burleigh

The Institute's First Half Century

By Chas. F. Scott

President A.I.E.E. 1902–03

Some highlights in the life of the A.I.E.E., its heritage, and the environment that has shaped its humble beginning and later tremendous growth, are outlined in this article by a past-president whose record of service to the Institute is surpassed by few, if any, other members. Far from being a mere chronological recital of events, this history contains personal reminiscences of many of the Institute's noted personalities and of their struggles and triumphs. Professor Scott says "the perusal of old-time records, the reading of past-presidential contributions of wide variety, personal reminiscing with old-timers and with others have awakened interesting recollections and have given me a new viewpoint and a perspective of various happenings; these now present a significance which one does not recognize when enmeshed in details." Perhaps Professor Scott's contribution will do as much for other members of the Institute.

THE MILESTONES, 1884 and 1934, which mark the first half century of the A.I.E.E., also designate periods in our national history. The early '80's mark recovery from the Civil War and the depression of 1873 and also the beginning of great changes in our industrial, economic, and social life stimulated by the Centennial Exposition in 1876. Electricity, then a novelty, has been so influential in these changes that we call this period "The Age of Electricity." Following the rapid acceleration came unbalance; economic and social progress is not meshing in with technical and industrial advance, and in these early '30's we are pausing for readjustment.

The story of the accelerating second half of a "Century of Progress" and the story of electricity give meaning and significance to the history of the A.I.E.E. What part has the A.I.E.E. had in the development of The Age of Electricity and in bringing about the new social order?

The combined threefold story—related in detailed account of persons and machines, of inventions and applications, of processes and products, of causes and far reaching effects—would be an encyclopedic task. Nor is the present confused situation suitable for the evaluation of influences and results; that must await a perspective view which the future may reveal.

The happenings of the present are fruition of the shift from adherence to traditional thought and action to scientific methods and progressive change initiated by the scientists of former centuries. Slowly accumulating scientific knowledge afforded a basis for the inventions and engineering that produce our present changes. Economic and social diagnoses of present conditions, now appearing in profusion, substantiate the predictions of George S. Morison (presidential address, American Society of Civil Engineers, 1895, and "The New Epoch," 1903) that manufactured power would create far-reaching and continuing changes and its advent was the most important factor in human progress since the invention of written language. He foresaw radical readjustments throughout the whole range of life during coming centuries, and he indicated the potency of electricity in the new order. In the long range view, "The New Deal" is a preliminary readjustment in "The New Epoch."

Our present task, however, is to study the career of a national organization of electrical engineers during the past half century, to discover its contribution to the industry and to general progress, and to note the effects of its environment on its own development as an organization.

Our Heritage and Environment

An institution, like a man, is the product of heredity and environment as well as individual initiative and effort. Our Institute has a notable heritage and a stimulating environment.

A painting in the board of directors' room at Institute headquarters signalizes the shift from mere knowledge of certain magnetic phenomena and the electric properties of amber to their experimental investigation. This painting portrays "Dr. William Gilberd shewing his experiments on electricity to Queen Elizabeth and her court"; a reproduction of it may be found on p. 644, this issue.

A recent book on the beginning of modern science refers to Doctor Gilbert (or Gilberd) as follows:

"First in time among the scientists who were to usher in a new era was Dr. William Gilbert (1540–1603), the learned physician of Queen Elizabeth. His work, *De Magnete Magneticisque Corporibus et de Magnete Tellure Physiologica Nova* (London 1600), was the first book that contained nothing of peripatetic natural philosophy, did not despise observation in deference to authority, but which was based entirely upon experiment and showed great skill in the use of the experimental method in the investigation of new phenomena." ("The Role of Scientific Societies in the Seventeenth Century," Ornstein, Chicago University Press, 1928.)

"De Magnete" came to the Institute in the Wheeler gift of the Latimer Clark library. It is a noble book, in heavy covers with gold embellishments. Concluding the title page is ANNO MDC. The volume is printed in Latin, in large clear type, and is divided into 6 books and 115 chapters on 240 pages of over 300 words each.

Gilbert, our electrical pioneer scientist, was succeeded during the next half century by Galileo, Torricelli, Pascal, Kepler, Harvey, Bacon, Descartes, Guericke, leaders in an "incredible revolution in man's ways of thinking and doing."

Following Gilbert by a century and a half, Benjamin Franklin wrote to a friend in England, about 1750, that on account of unfavorable weather he was temporarily discontinuing his interesting experiments with frictional electricity, expressing chagrin that they had produced nothing "of use to mankind." Franklin also wrote about this time that the application of science to human affairs might some time within a thousand years lead to great changes—possibly in agriculture double results might be produced with half the effort. Past-president Jewett's contribution to this issue indicates how prompt and ample has been the fulfillment of Franklin's prophecy.

From Static Sparks to Dynamos

A half century later Volta (1800) announced a new source of electricity. "Static" electricity with its instantaneous discharge in the lightning flash or in the spark from a Leyden jar was supplemented by the flowing current of a battery. Then many investigators of the new current—Davy, Oersted, Ampere, Faraday, Sturgeon, Ohm, Henry—noted its mechanical, magnetic, chemical, thermal, and luminous effects. Then followed by inventors who produced the commercial telegraph, the telephone, electrotyping, electroplating, gas ignition, fire alarms, and signals; but primitive lamps and motors found the cost of battery current prohibitive.

Then in 1831 came Faraday's fundamental discovery of electromagnetic induction, which lured scientific and ingenious pioneers by the vision of superceding the battery by transmuting mechanical power into electricity. They were legion. Sylvanus P. Thompson's classic "Dynamo Electric Machinery" names about 50 during the decades following 1831 whose attempts at dynamo making found record in print. Out of it all came a menagerie of queer forms. Thompson's treatise in the '80's shows 32 forms of magnetic fields employed in dynamos, only a few of which suggest the circular yoke with radial multipoles, now all but universal. One with 2 armatures and only one field pole for each (not shown by Thompson) mystified the Electrical Conference of '84. In the Dunham Laboratory at Yale University are pioneer machines employing a dozen types of magnetic circuits. Nevertheless they worked, and they ushered in the new era of cheap electric power.

Physical, Intellectual, and Social Environment

All of this development would have been of little avail had there not been contemporary development of the steam engine. Not only were these engines ready for driving dynamos, but men had become power users; the machinery and methods that underlay the industrial revolution were based on power. So the stage was set for more power and better power—unfettered by the rigid limitations as to distance of transmission, control of speed, and divisibility incident to mechanical power.

Likewise in transportation. Here the first great event after the prehistoric invention of the wheel was the locomotive, then completing a half century of service; but the locomotive, like the stationary engine, was not practicable in small units, and there resulted a wide gap between the horse and the big locomotive. Furthermore the horsecar service on city streets, which began about 1860, covered some 4,000 miles in the early '80's. People were ready for something larger and faster and more comfortable.

Likewise in lighting. The oil lamp with its smoking flame, little changed through a dozen centuries, had adopted whale oil, and the whaling industry had been closed by oil from the earth. My father was a college freshman when he first saw a lamp chimney. Coal oil (kerosene) lamps in general use and the open flame of gas in the cities through their excellence and their limitations gave electrical inventors an inspiring vision of what might be.

Electroplating by battery current was the doorway to a great field in electrochemical industry which cheap power could make practicable.

In communication, 40 years of the telegraph since the Morse historic message on May 24, 1844, and telephone service inaugurated by the opening of the first commercial exchange in New Haven,

Conn., January 28, 1878, had made the public keen for the improved facilities that inventors were striving to supply.

The heritage from early scientific workers—the experiments of Faraday and the theories of Maxwell—was reinforced in the '80's by the scientific men of the time. While the organizations of civil and mining and mechanical engineers came largely from men of experience in old time professions, our electrical society, with less of tradition, needed science. The professors of physics were alert; note those taking part in the Electrical Conference in 1884. Of the 12 members of the officially appointed committee 10 were professors; about the same proportion took part in the proceedings, nor are they all mentioned in the accompanying review of the conference. Among others were Prof. Cleveland Abbe of the U.S. Signal Service, Professor John Trowbridge of Harvard University, and my own former professor, T. C. Mendenhall, who signed a report on atmospheric electricity. At the first session of the A.I.E.E. also the professors were quite in evidence, while 5 of the Institute's first officers were designated as professors.

These professors were not merely theorists and talkers—they set about to train men. Electrical engineering curricula did not originate in the established departments of engineering, but in departments of physics. There they remained until, as Professor Jackson points out in his accompanying contribution, he, himself, initiated the electrical engineering department in 1890. The transition at Yale was made when I went there in 1911.

Engineering schools have had a profound influence on the development of the electrical profession and industry. These schools, primarily civil or mining, numbered half a dozen in 1860 and over 4 score in 1880. Engineering graduates were appearing, supplementing the practical men in industry, and they were ready to develop and adopt new methods. Early electrical students may have had the fortunate scientific sponsorship of departments of physics, but they were primarily engineering students rather than physicists. In short, the engineering school, getting under good headway in the early '80's, prepared the man-power for the professional and industrial developments that soon followed.

American Ideals

All these conditions played their part in the realization of the American dream—the ideal of a new and better way of living, a new freedom in religion and government and thought, and also freedom from the struggle and toil that pioneer life imposed. The Declaration of Independence opened the way to one freedom, while the simultaneous appearance of the steam engine made the other possible. A century later the dynamo arrived to make engine power a hundred times more effective in relieving the toil and increasing the opportunities and comforts that have been a vision of the American dream.

The history of America has been largely the history of the pioneer struggling with nature on the advancing western frontier until the frontier reached the Pacific just after the founding of the Institute. Then came new pioneers, applying science through engineering to conquer and control the forces of nature in the advance of civilization.

Again in longer perspective: The coming of Science brought a shift from tradition and the old ways of doing things to the idea of a better way and the effort to find it. The new principle of progress had become ingrained in American thought and life; it dominated the spirit of the engineer who had built canals and railroads and mills and factories. The electrical engineer—obsessed with the idea that through discovery and invention and engineering application he could make electricity of continually greater "use to mankind"—found himself a Progressive in a receptive world of progress.

From the Centennial, 1876, to the Founding of the Institute, 1884

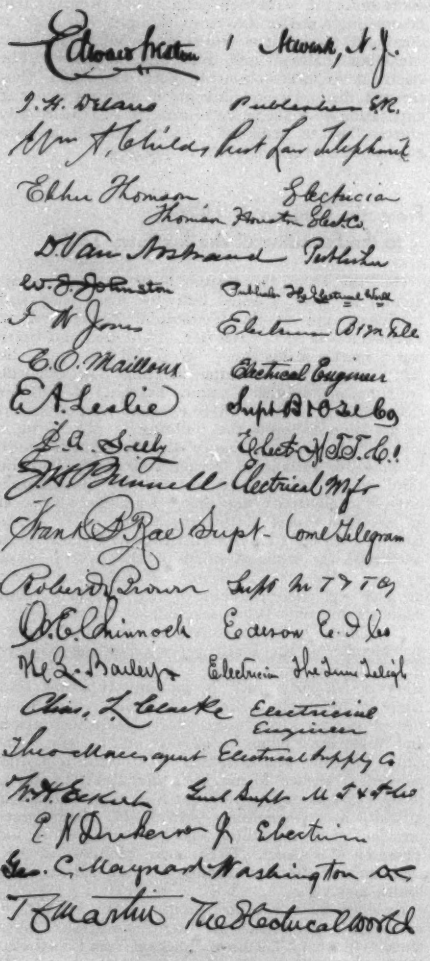
On Prof. Elihu Thompson's 80th birthday anniversary last year, I asked him just what electrical machinery was at the Centennial Exposition in Philadelphia in 1876. His face brightened and there was a sparkle in his eye. "Well, I'll tell you," he said; "there was a Gramme machine that ran one arc lamp, and another Gramme machine wound for electroplating; and a Wallace dynamo that operated an arc lamp on top of the building." (The first, I understand, was from France, the second was made by Professor Anthony of Cornell University, and the third was made in Ansonia, Conn.) Thomson's interest in electricity was aroused and he was soon an electrical expert performing tests. Fifty years later in 1928 the Franklin Institute in Philadelphia celebrated the semicentennial of the first test of dynamo efficiency. Professor Thomson (charter member and past-president of the Institute) had made the test on a Brush machine.

Mr. Charles F. Brush (charter member and Honorary Member of the Institute) outstanding pioneer in arc lighting was present and told a fascinating story of his early work in making dynamos and lamps in his machine shop. He described difficulties of various kinds, particularly with insulation and in getting 2 lamps to operate on the same circuit. Professor Thomson then told of the test and pointed, it seemed to me with affectionate regard, to the exact location of apparatus in the same room in which he was speaking. Mr. E. W. Rice (past-president of the Institute) who had aided Professor Thomson also spoke. These men, pioneers at the beginning of the new industry, were all in fine health and vigor.

By 1884 there were arc lamps in the streets of many cities and towns, representing various "systems"—Brush. Thomson-Houston, and others. Each arc machine supplied its own circuit of, say, 10 or 25 or more lamps connected in series, usually taking 10 amperes.

As the arc light was too intense for general use indoors, the great problem of those days was the "subdivision of the electric light." Edison, intent

on independent switching, like turning gas on and off, developed a fine filament which would take but a small current and thus involve small expense for conducting wires. The largest dynamo at that time suitable for contant voltage would supply only 25 16-candle power lamps. Hence not only lamps but conducting circuits and dynamos had to be developed for the opening of the Pearl Street Station in New York City—great because of incandescent lighting, but even greater as a means of distributing electric power and making energy a common commodity. On September 4, 1932, I heard over the radio the celebration of the 50th anniversary of the opening of the Pearl Street Station, partly from New York and partly from Mr. Ford's Edison Museum at Dearborn, Mich., where the original engineer started one of the original engines and Jumbo dynamos.



Some Well Known Signatures

Among the 21 signatures appearing above are those of 5 living charter members, 3 of whom became officers, and the signatures of 5 other past officers, together with a few of the prominent signers of the original "call" for the organization meeting of May 13, 1884

Electrical Pioneers

Electric cars were being undertaken by Edison, Field, Daft, Van Depoele, Bentley-Knight, Henry, Sprague, and others. It was the day of individualism; the ideal of each was in general a complete self-contained system. There were workers also with storage batteries and with electroplating. In the older groups new telegraph systems were being devised and telephones were extending. There were secrecy and rivalry and competition.

The age-long fascination of electricity intensified as the new dynamo, a source of cheap electric energy, "made it of use to mankind." Edison from telegraphy, Brush from the machine shop, Thomson and Houston, teachers of science, Keith from chemistry, Sperry from his freshman year at Cornell, Sprague from the Naval Academy, Weston from electroplating, Bell, a worker for the deaf, are typical of these pioneers.

Professors of physics took interest in the new developments. Investors and promoters were alert. All of these groups of ingenious, inventive, resourceful yet heterogeneous workers, some concerned with the older "small" currents and others with the new "heavy" currents, had a common bond—electricity.

Engineers Organize; A.I.E.E. Beginnings

In the early '80's there was a shift among engineers from individualism to group organization: witness the Engineers Society of Western Pennsylvania, 1880; The American Society of Mechanical Engineers, 1880; the American Water Works Association, 1881; the New York Electrical Society, 1881; a reorganization forming the Western Society of Engineers, 1882; the Association of Railway Telegraph Superintendents, 1882; the American Street Railway Association, 1882 (later the American Street and Interurban Railway Association); the Civil Engineers Society of Connecticut, 1884; the National Electric Light Association, 1885; the Association of Edison Illuminating Companies, 1885.

Electrical engineers were in condition favoring crystallization, which was precipitated by the announcement of the International Electrical Exhibition, sponsored by the Franklin Institute, to be held in Philadelphia in the fall of 1884. I well remember when Secretary Pope introduced me to

Doctor Keith, a chemist, as the founder of our Institute. He was of medium stature, quiet and pleasant, and his advancing age was apparent. He initiated a call in April 1884 for a meeting of electrical men. The call and the original signatures hang in the Institute parlor. Among the signers were T. A. Edison, and 7 who became presidents: Norvin Green, F. L. Pope, T. C. Martin, Edward Weston, Elihu Thomson, E. J. Houston, and C. O. Mailloux; also George A. Hamilton who was treasurer for 35 years. Following a preliminary meeting April 15, a committee worked out a scheme of organization. On May 13, 1884, the rules proposed were adopted, officers were elected, and the American Institute of Electrical Engineers was formed. The next event was the Philadelphia meeting, September–October, 1884.

The telegraph industry contributed the first president and over half of the vice-presidents and managers on the first council (see article in this issue by Donald McNicol). Those who entered the new electric light and power field were young men. In 1915 I compared the ages of the preceding 12 presidents of several national societies. The average age of the civil engineering presidents was 60, of the mechanicals 57, while that of the electricals was 44. Only 1 of the electricals' presidents was over 47, and only 2 of the other presidents were under 50. My own age at the time of my presidency, 38, was less than any other in these groups. T. C. Martin was less than 38 when he became president.

The A.I.E.E. Prospectus, April 1884

The circular issued in April by Doctor Keith, which received many signatures and initiated the Institute, reveals that the initial ideas of plan and scope were quite broad. The whole 7 paragraphs are well worth perusal. The essentials are these:

"The rapidly growing art of producing and utilizing electricity has no assistance from any American national scientific society."

The American civil, mechanical, and mining engineering societies are prosperous and of advantage to their members.

Foreign visitors to the International Exhibition to be held during the coming autumn should be received by a national electrical society.

It is proposed to follow the model of existing engineering societies whose "members assemble, read, and discuss papers and matters relating to their trades or professions and at the same time enjoy pleasant personal and social intercourse, all of which is conducive to improvement and advancement in ideas, theories, practice, business, and good fellowship."

"Persons who are interested in our electrical scientific educational, manufacturing, telegraphic, telephonic, and like concerns as well as the users of electrical appliances generally, will find it to their advantage, personally and collectively, to establish, work for, and generally aid our proposed society."

"It is proposed to make electrical engineers, electricians, instructors in schools and colleges, inventors, and manufacturers of electrical apparatus, officers of telegraph, telephone, electric light, burglar alarm, district messenger, electric time, and of all companies based upon electrical inventions as well as all who are inclined to support the organization for the common interest, eligible to membership."

Publication of "papers, discussions, and transactions and affiliations with sister societies, a museum, library, original research, protection from unfavorable legislation, settlement of disputed electrical questions, exchange of transactions with other societies, a journal of abstracts of papers read before other societies or published in other journals, etc., etc., are all proposed."

This indicates cosmopolitan eligibility as it includes those who are "inclined to support." The ample list of proposed activities inspires admiration

Some Well Known Signatures

Among the 24 signatures appearing above are those of a living charter member and past officer, the signatures of 12 other past officers, and some of the prominent signers of the original "call" for the organization meeting of May 13, 1884

of the vision of a future that might require a double "etc." While the first paragraph calls for a scientific society, the idea of pure science is considerably diluted in the list of proposed interests.

The early record says the document was signed by "electricians, capitalists, and others connected with electrical enterprises or interested in the advancement of electrical science." Presumably engineers were included under either "electricians," or "others."

Original Rules Adopted May 13, 1884

The propagandic call sold the idea, and the objects and membership are defined more conservatively in the Rules adopted at the organization meeting, the first portion of which is as follows:

"The objects of the American Institute of Electrical Engineers are to promote the Arts and Sciences connected with the production and utilization of electricity, and the welfare of those employed in these industries; by means of meeting for social intercourse, the reading and discussion of professional papers, and the circulation, by means of publications among its members and associates, of the information thus obtained."

"The Institute shall consist of Members, Honorary Members, and Associates. Members and Honorary Members shall be professional electrical engineers and electricians. Associates shall include persons practically and officially engaged in electrical enterprises, and all suitable persons desirous of being connected with the Institute, and duly elected as hereinafter provided. . . ."

State of the Electrical Art in 1884

Three events give snapshot pictures of conditions in the electrical world when the Institute began. They were an Electrical Exhibition held at Philadelphia in September and October 1884; a 6-day Conference of Electricians at the Exhibition during the first month, and the first technical session of the newly formed American Institute of Electrical Engineers during the second month. What was observed at the Exhibition and summaries of the 2 technical meetings throw light on the state of the art and afford interesting views of personalities.

Electrical Exhibition

At the Electrical Exhibition conducted by the Franklin Institute in Philadelphia during September and October 1884, a receptive college student was in charge of an exhibit. What he saw he recorded in the accompanying contribution of Past-President D. C. Jackson. Particularly striking was the attempt of Brush to make his arc light high voltage circuit operate incandescent lamps and appliances in the home. Notes of the Exhibition also are made by past-presidents Sprague and Rice.

The Exposition is summarized in an editorial in *The Electrical World*, October 11, 1884. The fact that N. S. Keith, the founder of the Institute, was associate technical editor, and that he participated in both of the technical meetings held at the Exposition, gives a clue to authorship of the editorial which follows in slightly condensed form.

"The Close of the Exhibition"

". . . It was fortunate that a body like the Franklin Institute should be found ready to plan and carry out an exhibition for this country, and electricity as a science and art owes a debt to the Institute for the prominence that has been given it. . . .

". . . One valuable feature of the Exhibition has been the assemblage within its walls of large numbers of the leading scientific men of this country and Europe, members of the various learned societies. The meetings of the American Association for the Advancement of Science, of the National Conference of Electricians, of the American Institute of Electrical Engineers, of the Telephone Convention and of the Association of Railway Telegraph Superintendents, have been highly important and interesting, and electricians have separated after them feeling that they know a good deal more of each other and of the science to which all are devoting their lives. We esteem it no small thing that on a common platform the best electricians of the two hemispheres have met and exchanged notes and opinions, and have learned to entertain for one another higher feelings of respect and admiration.

"The Franklin Institute, adhering to a time-honored policy, has endeavored to make the exhibition distinctly educational in character. Here again it has succeeded. Even admitting the complaint of a few that the public school pupil scheme was a little overdone, and that exhibitors would have been pleased with the attendance of fewer sweet girl graduates and rivals of Peck's bad boy, the fact remains that thousands of people, young and old, have made their first direct acquaintance with electrical principles and apparatus through the Exhibition, and have acquired a thirst that they will never lose for knowledge on the subject. The great sale of the electrical primers shows how eager the public is to master the science for itself.

"Though the Exhibition did not present to notice many very great novelties, it was a good, representative collection of apparatus and instruments new and old, and will take its place with the Exhibitions of Paris, Vienna, Munich, and London. It has not been without a stimulus to inventors, and no doubt many developments will date back to Philadelphia 1884. An inventor will sometimes work on languidly, trifling, and dallying with an idea that, insignificant as it may seem, is full of potency. Suddenly, as at the Philadelphia Exhibition he realizes that other minds besides his are exploring along the line on which he believed himself to be a solitary traveler; and the mere knowledge that other men see something in the distance, in that direction, too, is one of the sharpest spurs his inventive genius can be prodded with. Moreover, as the inventor looks on the old homely electromagnets of Prof. Henry or on the early telephones of Bell and others, or on Morse's first telegraphic instruments, or on the old Wallace dynamo machines, and then looks around on the 2,500 exhibits representing the electrical inventions and industries of today in which hundreds of millions of dollars are invested, he derives a stimulus of another kind. If fame and the desire to be first at the goal cannot bring him more quickly along the road, there is the inducement of solid wealth.

"The Exhibition closed today, but its effects and results will be experienced through many years."

At the head of the editorial section of the same issue is printed in bold face type:

This paper is printed on a Cottrell press, by a Daft electric motor, at the International Electrical Exposition, Philadelphia.

On the same page is reference to a controversy among certain newspapers as to which should have credit (during the early part of 1884) for the first electric motor-driven presses. Another item, in the issue of November 8, 1884, which is significant because it received neither emphasis nor comment, is titled "Long-Distance Electric Lighting." It is copied from the London *Electrician* and described tests at the Turin Exhibition of a 25-mile transmission by alternate current produced by a "Siemens dynamo machine, of the 30 horse-power type." Gaulard and Gibbs secondary generators were employed in several localities for supplying lamps of various kinds. (The primary coils of the secondary generators or transformers were connected in series.)

Conference of Electricians, September 1884

The National Conference of Electricians held September 8 to 13, 1884 in Philadelphia gives us a snapshot of electrical history in the month preceding the first technical meeting of the A.I.E.E. Papers were read and discussed and recommendations were made.

The National Conference of Electricians was conducted by a scientific commission appointed by the President of the United States. Professor Henry A. Rowland, physicist of John Hopkins University was chairman. Several representatives from England were in attendance. A report of nearly 200 pages was printed as "Ex. Doc. No. 45, 49th Congress, 1st Session" (It is now out of print.) It is included in Volume 1 of "The Executive Documents of the Senate of the United States for the First Session of the Forty Ninth Congress." The report of the conference was printed in current issues of *The Electrical World*.

Professor Rowland gave an interesting historical scientific résumé. In it he signalized Franklin's ability in connecting isolated observations into theory, such as that of positive and negative electricity equal in amount; he invented charge and discharge by cascade; he showed that it was the glass and not the coating of a Leyden jar that contained the charge. Professor Rowland concluded by saying "Let physical laboratories arise...let technical schools also be founded.... It is not telegraph operators but electrical engineers that the future demands."

In his remarks as vice-president of the conference Sir William Thomson (Lord Kelvin, Honorary member of the Institute) stressed the importance of an international system of electrical measurement and the laying out of international standards. He commended the twofold object of the conference—promoting the useful applications of science to the ordinary wants of man and giving character and vigor to the investigator.

The Dynamo Electric Machine

Atmospheric electricity, standards of electrical quantities and of light, and the establishment of a national bureau of physical standards were discussed. Regarding the latter Doctor Keith, initiator of the Institute said: "The time is coming, as Sir William Thomson has so happily suggested, when house to house lighting and utilization of electric energy is to become extensive. Meters have been devised and will be devised to measure this electrical energy, hence the necessity of a bureau of standards to be utilized by the various cities in making a determination of the meters we shall be obliged to use." A committee was appointed to represent the conference before Congress in relation to the establishing of the bureau.

"The Theory of the Dynamo Electric Machine," before the principles of the magnetic circuit were recognized, was an excursion into a fog. Various types of magnets for 2-pole dynamos are shown in half a dozen figures. In the discussion we find this: "Mr. Elihu Thomson: I have been at work on dynamo machines for a long time and my experience teaches me that some of the statements brought forward are not correct." He then specified half a dozen points.

Professor Rowland, who had opened the symposium, introduced the next session thus: "I am very glad to see the matter taken up in this spirit and to have my principles intelligently criticized." The discussion relates very largely to the magnetic field—its form, shape, size, material, and the characteristics of hollow and of concentric cores. One paragraph begins: "Professor Elihu Thomson: I do not agree that those induced currents can be abolished by dividing up the cores." Professor Sylvanus P. Thompson brings up many controversial points. Others participating were Professor Fitzgerald of Dublin, Mr. Keith, Professor George Forbes of London, Professor Anthony of Cornell, and Professor Nipher of St. Louis. The latter in dealing with "The Electric Transmission of Energy" on the following day discussed motor characteristics. If this be included in the discussion of dynamo-electric machines this topic occupies over 25 per cent of the technical record. Here was controversy as to the relations of theory and practice, but much of the discussion seemed to be based on the cut and try method.

Storage Batteries

Regarding "Storage Batteries" Mr. W. H. Preece (head of the British Postal Telegraph, later Sir William Preece, Honorary Member of the Institute) who had been called on somewhat unexpectedly, said "Mr. Edison himself has declared that this question of storage batteries has the most remarkable power of developing man's latent capacity for lying. (Laughter.) I very much agree with Mr. Edison's definition, for I think there has been more lying, more swindling, and more rascality over this question of storage batteries than over any other department of electrical science." So one may note that a half century has produced not only chemical and mechanical but moral development as well.

Mr. Preece said incidentally that secondary batteries (he disliked "storage") furnished electric light in the (British) post office, also in his own house, "where a gas engine works a Gramme dynamo which gives me 42 volts and 52 amperes...when my gardner comes on duty in the morning he lights the gas and charges the battery... I have at my bedside a most charming mellow light, with no smoke, no wick, no heat, by merely turning a tap. I have never had any bother except when the gardner put his foot on the wrong place and the head of the gas engine came down on it and he had to lose 4 toes. Their removal reminds him of the danger of electric lighting. (Laughter.)" Within a few months of this time a student at Ohio State University while starting the new gas engine electric plant lost a toe by similar accident.

The Otto engine ran a 3-light Thomson-Houston arc machine and a 15-light Edison dynamo in the physics laboratory at the university.

Mr. F. J. Sprague remarked "With a gas engine there is difficulty in starting. A person has to put his foot on the flywheel and pull it around before he can get it started. If he simply uses a secondary battery he can light his gas engine and it will start ahead all right." Mr. Preece feeling sympathy for the battery commented "I look upon the employment of a battery for any such purpose as simply barbarous." Little did he foresee that the greatest use of the battery would be for that purpose.

Others discussing batteries included Professor Carhart (of Carhart standard cell fame) Mr. Keith, Professor Thomson, Professor Houston, Lieutenant Jewell, Professor James Dewar of Cambridge, England, Professor Rowland, Mr. Koegh, and Professor Forbes. The discussion covers nearly as many pages as that on dynamo-electric machines.

Telephones and Other Topics

A symposium on "Induction in Telephone Wires, Long Distance Telephoning, and Underground Wires," was opened by Mr. T. D. Lockwood, of the Bell System with some general observations: "Twenty years since, when electricity was a mere branch of physical science—when we referred to the telegraph in its several forms, to electrolysis in its applications to electrotyping and plating, and to the miscellaneous practical operations of gas lighting, burglar and fire alarms, and to electro-therapeutics, we have substantially scanned the electrical field of that day." He reported that "An Essay on Electricity" written in 1792 contained the expression "As electricity is in its infancy, ..."

Mr. Lockwood discusses various items of interest, among them the use of a complete metallic circuit instead of the then commonly used ground return: "It is probable that for such persons as desire to communicate frequently between distant cities loop lines will be built, adapted to form extension of the trunk metallic circuits."

Other subjects discussed were "The Electrical Investigation of the Physical Qualities of Structural Materials" (fatigue) by Captain O. E. Michaelis; "Measurement of Large Currents" by Mr. Keith; "Applications of Electricity to Military and Mining Engineering" by Captain Jewell; and "Lightning Protection" (primarily of buildings) by professors Rowland and Houston.

In concluding the Conference Mr. Alexander Graham Bell moved a vote of thanks "to our distinguished vice-president, Sir William Thomson, and to the other distinguished electricians from abroad" for coming and participating. Mr. Keith announced the formation of the A.I.E.E. and its coming session.

Mr. Preece spoke of the pleasure the visitors had experienced in becoming personally acquainted with their professional friends: "I have noticed a slight tendency to consider criticism as personal and unnecessary, and the debate has at times been a little warm, but personal meetings of this kind entirely eradicate that feeling."

On motion of Professor Simon Newcomb by whom the conference had been opened, it adjourned.

The Institute Papers at the First Session, 1884

"Notes on Phenomena in Incandescent Lamps," by Professor Edwin J. Houston (Illustrated) the first title at the initial technical meeting of the Institute in October 1884 does not sound at all startling, nor do the initial sentences, "I have not prepared a paper, but merely wish to call your attention to a matter I presume you have all seen and puzzled over. Indeed I wish to bring it before the Society for the purpose of having you puzzle over it. I refer to the peculiar high vacuum phenomena observed by Mr. Edison in some of his incandescent lamps." Later Professor Houston remarks: "I believe we shall find the preceding phenomena worth looking into. For my own part I am somewhat inclined to believe that we may possibly have here a new source of electrical excitement." And so our Institute, concerned primarily with the new ways of producing and using electric power, viewed a new puzzle, little dreaming what it might portend. (See p. 654.)

Last September from a meeting of the New York Electrical Society an address by Dr. C. H. Sharp was broadcast on "Edison's radio tube of 1883." The high spots are as follows:

> In investigating the blackening of lamps Mr. Edison introduced a wire between the legs of the lamp filament and brought out a third terminal. He found that if this third wire were connected through a galvanometer to the positive leg of the filament a current flowed between the filament and the wire.
>
> Professor J. A. Fleming next carried out a systematic investigation of the effect; and as a result produced the Fleming valve, the first device purposely made as a radio detector dependent upon electronic action. Doctor Lee DeForest took the next step by introducing the principle of the control of the flight of the electrons by means of an auxiliary electrode, a stroke of genius which elicited admiration of Mr. Edison. Thus the modern radio tube was evolved from the "Edison effect" lamps of 1883.

At the conclusion of Doctor Sharp's address a replica of the original "tube" was employed and demonstrated as part of a receiving set.

Thus the Institute, born under the quickening impulses of the new era of "engineering electricity," presented in the first paragraph of its first paper a puzzling observation—the Edison effect—which through the Fleming valve and DeForest's audion later ushered in another era, that of electronics.

"Underground Wires" and Other Topics

"Underground Wires," the second paper, by W. M. Callender of the Callender Company, stated that such wires were in satisfactory use for telegraph, telephone, and incandescent lighting, but as to arc lighting "the feelings of the light companies toward the underground question is one of great caution and unbelief"—feelings based upon sad experience. Vulcanized bitumen which receives "a peculiar secret treatment" is stated to have proved satisfactory in Callender wire in English use—"a fortunate circumstance as the American public are clamoring for the removal of the unsightly poles which disfigure their streets." Mr. W. H. Preece said that underground wires in England "is a problem that has been solved" and pointed out various differences between conditions in the 2 countries.

"Synchronism" (accomplished by the Delany synchronous-multiplex system of telegraphy) was presented by Professor Houston.

"The Scientific City Street" was described by R. R. Hazard, president, Gramme Co. A frontispiece shows a cross section of Broadway, New York City, with 4 tunnels for trains under the street and spaces under the sidewalks for pipes and wires. Such a scheme was said to be possible since electricity (instead of steam locomotives) is "entirely within the present resources of the art."

"An Experimental Method of Studying the Dynamo Machine" was presented by Professor C. F. Brackett of Princeton. "Its principal feature consists in the use of an exploring coil to determine the relative value of any point of the magnetic field in which the armature revolves."

In another paper, carrying the title "Earthwires; or, the Earth as an Electric Circuit Completer," Thos. D. Lockwood, electrician, American Bell Telephone Company, presents a historical account followed by descriptions of earthing devices. He had been "long impressed with the preëminent importance of the subject."

"Telegraphing without Wires—An Experiment," by S. J. M. Bear, was not our "wireless," but a scheme in which the 2 terminals of the sending circuit (battery and key) were connected respectively to a copper earth-plate and a zinc earth-plate emersed a little way apart on one side of a tub of water, while the relay was connected to a copper earth-plate and a copper plate emersed in a porous cup containing sulphate of copper, near the other side of the tub.

"Chemistry of the Carbon Filament," by Edward P. Thompson, M. E., is a technical paper, but contains this interesting information: "The principal lamps now being largely manufactured and represented at the Exhibition, and in which the filaments differ from one another by distinct chemical reactions which take place in their manufacture, are the Edison, the Swan, the Weston, and the Stanley and Thompson lamps." In the discussion Mr. Keith suggested that several gentlemen connected with various companies say something about their processes but got very little response.

"Depositing-Vats in 'Series'" for electroplating was stated by Mr. H. B. Slater to be simply a descriptive paper presented by request. In discussion of that paper is found: "Mr. Keith: As our honorable guest, Mr. Preece, has said to me, 'This is your hobby,' I may be supposed to say something. I have a paper prepared on this subject embracing the laws which govern it and some remarks as to...the production of pure metals... I have investigated it extensively since 1876." Mr. E. A. Sperry participated in the discussion.

The Patent Office

"The Patent Office: Its Relation to Inventors and Its Needs," is longer and provoked more discussion than other papers, although "it was only upon Saturday last" that it had been requested. It is by Mr. C. J. Kintner, chief examiner of the Class of electricity in the U. S. Patent Office. He depicts the significance of invention, and "how the telegraph, the telephone, the railroad, and thousands of other inventions have increased a thousandfold the field of labor." He outlines the organization and procedure in the Patent Office with its total force of 550. He indicates inadequacy and proposes remedies which inventors and business interests concerned with inventions should bring about. This first request to the new Institute met response in later years through American Engineering Council, which among other things protested against a proposed reduction in patent office salaries that would have dispersed experienced personnel and also aided in a revision of patent office procedures by adding the engineering to the legal viewpoint.

Six months earlier at the Institute's organization meeting, May 13, 1884, a letter from Mr. Kintner was received setting forth the inadequacy of his facilities for meeting the demands. Following are some of the items relative to his electrical division:

"Cases awaiting action, 374; force, 8 assistants and 2 clerks.

"This division embraces electrical appliances pure and simple, and has grown in 4 years so far as to include over 6,000 patents.

"Prior to July 1, 1880, there were less than 2,000 patents which disclosed any electrical appliance or apparatus whatever. Since that time, the rapid advance made in telephony, telegraphy, electric lighting appliances, dynamo machines, etc., has placed the division foremost in the arts....

"The rooms are badly ventilated... In my own room there is no gas and I am obliged to use kerosene oil which vitiates the atmosphere."

What are the present activities of the Patent Office, which recently moved into new quarters, for comparison with those of 50 years ago? A request for such information brought the following reply from the Commissioner of Patents:

Dear Mr. Scott:

In the succeeding paragraphs I am giving you the facts you requested in your letter of February 16, 1934, already acknowledged:

Nine divisions of the Patent Office are devoted exclusively to electrical classes. These are Divisions 16, 26, 37, 42, 48, 51, 54, 60, and 65. An aggregate of 84 examiners is employed in these divisions. The electrical divisions are on the average about 3 months behind current dates. As of January 27, 1934, the number of cases awaiting action was 5,643.

The following classes are directed entirely to inventions in various branches of electricity, but they are not, of course, completely comprehensive in that respect:

Class	No. of Patents
13....Electric Furnaces	1,932
136....Batteries	5,110
171....Electricity, Generation	12,665
172....Electricity, Motive Power	9,367
173....Electricity, Conductors	10,300
174....Electricity, Medical & Surgical	1,397
175....Electricity, General Applications	11,206
176....Electric Lamps	5,452
177....Electric Signaling	8,113
178....Telegraphy	5,487
179....Telephony	15,849
191....Electricity, Transmission to Vehicles	5,731
200....Electricity, Circuit Makers and Breakers	17,941
201....Resistances and Rheostats	2,238
204....Electrochemistry	5,471
219....Electric Heating	8,398
247....Electrical Conduits & Housings	2,709
250....Radiant Energy	6,980
290....Prime Mover Dynamo Plants	1,652
105....Railway Rolling Stock, Electric locomotives	456
Total	138,454

Many other classes, such as Class 246, Railway Switches and Signals, 16,481 patents; Class 161, Time Controlling Mechanism, 1,672 patents; and Class 240, Illumination, 16,533 patents, include a very large percentage of patents having electrical features therein. These classes cannot, however, be regarded as strictly electrical. Through all the classes in the Office the use of electrical devices and mechanisms and processes, in combination with and in the art, machine, or process where they occur, is claimed.

Many of the patents in the various classes date back a century or more. Some of the older of these patents are instanced below:

Class No.	Patent No.	Year	Class No.	Patent No.	Year
13...	96,827	1869	176...	20,255	1858
	236,478	1881		20,706	1858
	263,758	1882	177...	1,622	1840
136...	2,521	1842		4,318	1843
	2,984	1843		4,661	1846
	5,400	1847	178...	1,847	1840
171...	3,191	1843		4,453	1846
	5,485	1848		4,464	1846
	10,175	1853		5,612	1848
172...	132	1837	179...	105,552	1870
	809	1838		174,465	1876
	910	1838		197,387	1877
173...	1,096	1839	191...	24,721	1859
	2,056	1841		183,874	1876
	2,284	1841		252,193	1882
	4,807	1846	200...	7,394	1850
	5,889	1848		14,711	1856
174...	D. Harrington.. July 22,	1833	201...	25,532	1859
	D. Harrington.. Jan. 27,	1834		122,267	1871
	D. Harrington.. Mar. 31,	1835	204...	3,015	1843
	4,167	1845		3,698	1844
	4,176	1845		4,012	1845
175...	3,316	1843	219...	48,584	1865
	5,507	1848		88,006	1869
	7,420	1850		121,765	1871
	7,671	1850	247...	69,947	1867
	8,843	1852		96,641	1869

I trust the foregoing will suffice for your purpose....

CONWAY P. COE
Commissioner

This quantitative expansion and qualitative classification give a revealing picture of the state of electrical development today; more than justifying energetic Kintner's prediction in 1884 that we were then "on the verge of a wave of progress such as was never before known to the civilized world."

A.I.E.E. TRANSACTIONS, VOLUME I

TRANSACTIONS of the American Institute of Electrical Engineers, Volume I, May 1884–October 1884 contains a historical preface relative to organization matters, and a general statement regarding the Philadelphia Meeting, September–October 1884. Rooms at the International Electrical Exposition had been kept open by Mr. Keith, secretary, from September 2 to October 11 which "were visited by a great many members of the Institute and by several foreign electricians. On October 7 and 8 a meeting was held . . . where the papers forming part of this volume were read and discussed. . . . (Owing to ill health, Mr. C. O. Mailloux has not been able to prepare for publication in this volume his paper on 'Exploring the Field of the Dynamo-Electric Machine')." Eleven papers are printed in this volume, including, in addition to those discussed at the Philadelphia meeting, a paper "The Delany Synchronous-Multiplex System of Telegraphy" supplementing Professor Houston's paper on Synchronism."

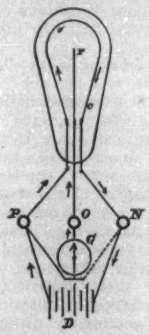
A paper read before the American Institute of Electrical Engineers, at Philadelphia, October, 1884.

NOTES ON PHENOMENA IN INCANDESCENT LAMPS.

BY PROF. EDWIN J. HOUSTON.

Prof. HOUSTON:—I have not prepared a paper, but merely wish to call your attention to a matter which, I suppose, you have all seen and puzzled over. Indeed, I wish to bring it before the society for the purpose of having you puzzle over it. I refer to the peculiar high vacuum phenomena observed by Mr. Edison in some of his incandescent lamps. I have in my hand an Edison incandescent lamp, having the same vacuum as the ordinary incandescent lamp. This one, however, has, in addition to the carbon filament, a platinum plate, or strip, that is thoroughly insulated from the filament, and supported in the manner seen between the two branches of the filament, as shown in Fig. 1.

FIG. 1.



An Edison carbon filament, *c*, *c*, is placed inside an inclosing glass case in the usual manner. A strip of platinum foil, *p*, is supported as shown inside the loop. The binding posts, P and N,

Page 1 of the first technical paper published in volume I of the A.I.E.E. TRANSACTIONS (see p. 652, column 2)

Reading, Discussion, and Publication of Papers, 1884–1900

The reading and discussion of papers and their publication, supplemented by social meetings were the prescribed means by which the Institute was to accomplish its objects. For nearly 2 decades meetings and papers constituted nearly the whole of Institute activities. A new attitude toward electrical problems then was inaugurated which will be considered later.

The Philadelphia meeting was followed by annual meetings in New York. Then "the importance of the various electrical problems which are continually being brought to public notice" led to the holding of

monthly meetings in New York for "the discussion of current topics." The first was held June 8, 1886, preceded by an informal dinner. The subject of discussion was "Incandescent Lighting From Central Stations." These meetings continued (except during the summer months) until 1918. In March 1894 simultaneous monthly meetings were inaugurated in Chicago, the same paper being read and discussed in the 2 cities. General meetings lasting several days were held regularly each year. As "the national character of the Institute showed the desirability of holding meetings in different parts of the country" the general meeting in 1890 was held in Boston, and in subsequent years in various places.

To secure "recognition for the important researches of Americans" the Institute participated in the International Electrical Congress at Paris in 1889.

Apparently the first constructive technical undertaking was the appointment of a committee in 1889 to formulate "a standard wiring table for light and power purposes." The report was discussed during the following year, and was approved and "entered into engineering practice." (See p. 677.)

In 1891 5 delegates attended the Frankfort International Congress and recommended among other things the adoption of the "henry" as "the name for the practical unit of induction." It also invited the congress to meet in Chicago at the coming World's Fair, which was held in 1893. The technical recommendations were not acted on at Frankfort.

The Institute sponsored the International Electrical Congress in 1893, and established headquarters in the Electricity Building. The register recorded 612 visitors. Shortly afterward 117 were added to Institute enrolment which could largely be traced to the headquarters at the fair. A report on the congress, a volume of nearly 500 pages covering the proceedings of both the official and the general chambers, was issued by the Institute.

The Institute's First Decade

The tenth anniversay of the Institute in 1894 was celebrated at the general meeting of 4 days in Philadelphia. President Houston's inaugural address was entitled "Progress of the American Institute of Electrical Engineers." The following is a condensed version:

The Centennial Exposition of 1876 had so :n broadcast the germs of public interest in electricity. From 1876 to 1884 work in the electrical field was of pioneering nature and of independent character. Each investigator trod the path of discovery alone, often unconscious of the existence of fellow investigators. The time had come for "congregation as opposed to segregation." The exhibits at the 1884 Exposition were a revelation to the hitherto independent workers. The National Conference of Electricians brought professors and investigators in the physical laboratories into contact with inventors and actual workers in the commercial electrical field; but the awakening due to exhibitions and conferences should be surpassed by that of an organized society.

The nature of the influence of the Institute may be noted in a review of its 10-year history (1884–94). The work of its members includes invention, commercial applications, and research in many fields. As a body it made valuable contribution to the Chicago Electrical Congress (notably in scientific standardization) in 1893. It has provisionally adopted names for units and struggled with the definition of "inductance." Parallel with the Institute the electrical press has been a p :tent factor. England, France, and Germany, as well as this country, owe much of their electrical progress to their national electrical organizations.

Advantages of membership are cited. "Proud of the progress shown" a plea is made for support of a central, organized body deriving authority from a membership extending over the entire country. (Membership 890; annual income and expense, just over $10,000 each. Standing committees: papers, meetings, and editing; library; finance, building, and permanent quarters; units and standards; membership.)

Underwriters Rules

In 1896 a delegate was appointed to a "National Conference on Standard Electrical Rules." The delegate, Professor F. B. Crocker was made president of the conference. Presumably, this was the first participation of the Institute with other national groups. "Underwriters Rules" were sponsored by many national organizations which finally resulted in the "National Electrical Code." It was my privilege as an unofficial delegate from a manufacturing company to attend this conference. Nearly a decade earlier I had been a wireman at a time when underwriter's wire was a matter of course, when rosettes and switch bases and fuse blocks for bare lead fuses were all made of wood, both for lamp circuits and for 1,100-volt station service. I could appreciate the importance of the conference and the significance of a serious joint effort of underwriters, architects, builders, and engineering societies to secure safety and excellence.

In 1899 the Institute took action on a practical matter by recommending "the grounding of one wire of every low potential consumption circuit."

Standardization

On January 26, 1898, a topical discussion was held on "The Standardizing of Generators, Motors, and Transformers." This was an occasion of peculiar significance. It was the first important practical engineering problem taken up for extended discussion and continued consideration (unless the adoption of the wire table 8 years earlier be an exception). The complexity of the problem, the number participating in the discussion, the distinction of the committee appointed and the excellence of the "Report of the Committee on Standardization," accepted June 28, 1899, all make a splendid record; but that was only the beginning of a new chapter in the story of standards, told elsewhere in this issue by past-presidents Kennelly and Skinner.

The report of the standardization committee differed from a "paper" as it was not passively presented by a member, but was actively undertaken and prepared by a committee. The attitude of the committee was not that of research seeking something new, but rather of the judge, who considers various definitions and methods of test and current practices to decide what is best for adoption. Some years later when I was a member of the committee and we were revising the report, a table of standard voltages was being drafted. We selected from those in use the particular values that seemed to make the

best sequence. But when we reached 66,000 volts objection was raised by Steinmetz to going further because it was beyond current practice. I ventured to suggest that if we recommended certain voltages in the higher range they might be selected, for practice and confusion avoided. The suggestion was accepted. This incident indicates the initial principle of crystallizing current practice rather than seeking something different or new.

The preceding account of early Institute activities is based upon the historical sketch of the origin and work of the Institute by Secretary Pope, which appears in the 1900 Institute Handbook. Prominence is given here to activities other than the presentation of the papers, which are preserved in nearly a score of volumes. There is a development seen in the monthly meetings in New York and in the Chicago meetings, in the itinerancy of general meetings after the first few years, in the participation in international congresses, in the participation by invitation in the preparation of the "National Electrical Code," and in standardization, both in the wiring table and in the Report of 1899.

In Mr. Pope's history I find no mention of other engineering societies or relations with them, except the courtesy through which early meetings were held in the house of the American Society of Civil Engineers and later ones at 12 West 31st Street, New York, in the house of The American Society of Mechanical Engineers.

Steinmetz, President 1901–02

At the 1894 (tenth anniversary) meeting there was a discussion relative to the magnetic field in induction motors. As I recall, it was rather desultory and was dragging a bit. Then a distinct, resonant voice amply loud from a corner of the large room, shielded from my view by a pillar, gave a comprehensive summary statement of the whole subject. Then the phenomena in certain particular cases was stated, including the effect of the third harmonic in 2-phase motors and in 3-phase motors. The treatment was as complete and the language as perfect as if the speaker were reading from an article prepared for the "Encyclopedia Britannica." It was Steinmetz talking extempore. (As my recollection does not tally with the printed record, I assume that it was condensed before publication.) This was my first contact with him, although I knew him by reputation through his law of hysteresis and his great paper on complex quantities presented at Chicago which has become a basic method in alternating current representation and calculation.

In 1901 Steinmetz became president. A picture is impressed on my memory. A waiting group in the secretary's office: Steinmetz enters with an apologetic smile—his train was late. He takes his seat and receives from Secretary Pope items for the afternoon. As he calls names of committees the reports are made. Later, on the "elevated" going uptown from Liberty Street, Steinmetz sits next to Calvin W. Rice, of the meetings committee, who takes notes as the president talks. "Now I think this subject is of sufficient importance to be considered at a future meeting and some of the best men to take part are so and so." The sequel comes a month or 2 later.

After dining together at a restaurant, the attractive feature of the day for an out-of-town member, we assemble at 12 West 31st Street. There are informal social greetings, then Steinmetz opens the meeting with a comprehensive, concise, perspective résumé of the topic of the evening with his characteristic encylcopedic perfection. Several members then read short papers presenting various points of view on an important and live topic. General discussion follows. These meetings augmented interest, attendance, and membership, and gave the Institute new life.

Sections; Technical Committees; Branches

A steering committee asked me to be Steinmetz's successor as president of the Institute. I acquiesced with some misgivings as the alternatives seemed to be to continue if possible on the same level or to slump; but I had not counted on the aid and support that others might give.

Steinmetz as president had developed the New York monthly meetings. What was there left to do? I noted that my associates in Pittsburgh who had not attended the Institute meetings had no real appreciation of what was going on and no particular interest in Institute affairs. What could be done to extend interest geographically—to members in Colorado and California? Possibly some type of discussion by correspondence might be devised.

Shortly afterward Secretary Pope said that I undoubtedly would be elected and he had a suggestion—one long cherished and oft repeated without result. Local meetings were being held in Chicago, why not in many other places also? I said it was a fine idea, a means for doing nationally what had been so successful locally in New York. I asked him to work out a plan and we would put it through.

High Voltage Transmission Committee

I recently wrote to Past-President Mershon saying that I regretted that he was not contributing to this anniversary issue of Electrical Engineering and suggesting that he write about the transmission committee. His reply explained why he did not feel able to comply, and continued as follows:

Miami, Florida, March 6, 1934

My dear Scott:

. . . . But I will tell you my recollection of the genesis of the transmission committee.

You were president-elect of the Institute. You asked various persons for criticisms and suggestions for betterment. I was one of those asked. One of the reasons you asked me was, I think, that I had been criticizing the Institute for some time. On your request I amplified my criticisms and made some suggestions. One suggestion was that of special committees to handle special lines of work.

One of the lines of work I suggested as of pressing importance was high voltage transmission.

On becoming president, you arranged for a high voltage transmission committee. That was the first committee of the kind, and, I think, the only one for some years. You appointed me chairman of the committee. I remember that the manner of appointment was such as to imply, to me, at least, perhaps due to a guilty conscience on my part—"Now, you think you are so smart, let's see what you can do." I accepted the appointment and the challenge. You let me pick my committee members, and that helped a lot.

The meetings of the transmission committee were a success from the start. They were better attended than the other Institute meetings. This was due in large part to the fact that we had real discussions. I deliberately adopted the policy of getting discussions rather than papers. The papers I called "Introduction to Discussion." They were short and to the point and provocative of discussion. A man will often let slip out in discussion what he will not put into a paper. The crowd, even those not especially interested in the particular subject, likes a good knock down and drag out—figuratively speaking—fight and that was what they got at the transmission meetings. So they always came back for more.

One evidence of the success of the transmission committee meetings is that the McGraw-Hill Publishing Company obtained from the Institute the right to publish the introduction to discussion and the discussions thereon in a separate volume which they sold as one of their technical publications. Later on, I think, they put out an additional volume covering the further work of the committee. This was the first time—and so far as I know the only one—that anything of this sort happened.

I picked the best authorities in the Institute to write the introductions to discussion. That meant the busiest men. And no matter how busy a man might be, I never had a refusal to my request. This was due in part to the fact that the introductions were short. They usually dealt with a limited portion of some particular phase of transmission. But it was undoubtedly due in part to the fact that a man who wrote an introduction knew the lines would be laid for a vigorous discussion and a full meeting, which would be advertising of the best sort for the author and his particular line of work.

As to the postscript to your letter, I cannot say. But there is no doubt, I think, that the work of the transmission committee had a large part in the development you mention.

With best regards,

Sincerely,
Ralph D. Mershon

My postscript asked whether he agreed with a member who said that the present technical committees were the direct outgrowth of the transmission committee.

My own recollection of the early conversation is definite, but differs in detail from Mershon's. What I think I said was "What is the function of the Institute, what ought it to do?" He replied "I think that long distance transmission has reached a stage which justifies the appointment of a special committee for its consideration." It flashed through my mind that this was something new; committees did not make such studies. I also recalled that data from transmission companies were about to be collected by P. M. Lincoln who had just come from the Niagara Falls Power Company to the Westinghouse technical staff; but I replied at once, "If such a committee is authorized, will you be chairman?"

Now, I do not recall the criticisms of which he speaks. The probability is that he did make them, he usually did. I knew him pretty well—we roomed together in the Amber Club at Pittsburgh, of which Lewis B. Stillwell and Calvert Townley were pioneer members. So I knew Mershon's ability and pertinacity, and also his fine streak of pessimism which made him so interesting; but I confess I had never suspected the "guilty conscience"—that's a new idea. I note also that he himself may let slip out in a letter "what he will not put in a paper."

He did a fine piece of constructive work with the high voltage transmission committee, of which Lincoln of Westinghouse and Blackwell of General Electric were 2 of the members.

Census Curves and Student Branches

When president-elect, I asked T. C. Martin what the Institute ought to be and to do. He was a past-president, editor of *Electrical World*, and as a special agent of the U.S. Census was just completing the first census report on the electrical industry (1902). He said "I don't know what the electrical industry is going to be in the future, but in the past it has been doubling every 5 years." I was stunned; how could we use twice as much electric power, and so soon! The original Niagara Falls power houses were being completed, the elevated railway in New York was electrified, the subway was soon to start, the public utilities were putting in big generators; but if the curve were to continue up, where were the men to come from to operate the accelerating industry—men competent to meet the exacting and increasing responsibilities of electric service—more men, better men. I had taken it for granted that the Institute was to promote the arts and sciences related to the utilization of electricity by adding to knowledge through papers, by their discussion and publication. Here was a new need—men. Should not the Institute develop men as well as ideas? I had been interested in the training of college graduates for one company. Here was a universal need for better graduates. The future men of the industry were in the colleges being trained in theory. Why should not the Institute give them an insight into the problems and practices of the profession, without waiting for a sudden plunge from theory to practice on graduation? So I asked several of my professor friends; they agreed; Professor Ryan at Cornell wrote (condensed) "Bully idea; we've already started."

And that is the way the Institute entered a new field, as an educational agency in the colleges.

Looking Backward

And now when I see a "mountain peak" curve of billions of kilowatthours, I look for the 1902 column—if happily the curve goes back that far. I find that the 1907 ordinate is actually twice as high as 1902; 1912, 4 times; 1917, 8 times; (then the interval for doubling changes from 5 years to 7 years) 1924, 16 times; 1931, 32 times—that is where the curve would have been if we had plotted ahead in 1929; but after a point about 25 times the 1902 unit was reached in 1929 the curve was depressed by the depression. It receded to approximately its value about 2 years earlier and then began to climb again.

Thus Martin's rate of growth based upon progress in the '90's, when output was less than 4 per cent of recent values, held true for about a quarter century after 1902. When the output doubles every 5 years

the total energy during a 5-year period equals the total during all preceding periods. During the 6 years 1924–29 the electric energy used for promoting prosperity was equal to the total consumption during the preceding 40 years.

This geometric rate leads to other interesting conclusions if it be taken as the general law of unimpeded progress. It is a common sport to quote those of the olden times who comment on past progress. The late John R. Freeman relates that the eminent engineer under whom he began to work in the '60's said that the previous 50 years of his life had witnessed the most marvelous advance in all history (it included the locomotive and the telegraph). He was right; for looking back a half century from any point on our geometric curve of progress, the ratio of increase is the same. But the old engineer did not stop with the retrospective view; he added "and there surely will never be another such 50 years!" He died happy—without knowing his indiscretion in making such a prediction. Our predecessors in the fall of 1884, who commented on the marvelous development of electricity in their past, may have observed the same ratio of advance which thrills us in viewing our own past.

In my reconnaissance of Institute possibilities, other members commented on the value of papers and discussions, and one emphasized a high professional standard among members. My 3 planks in a progressive platform came, however, from the snapshot conversations with Pope, Mershon, and Martin; they were Sections, a technical committee, student Branches—concerned with expansion of organization to augment the old time presentation and discussion of papers, the inauguration of group technical activities, and the launching of an educational program.

"Proposed Developments of the Institute"—1903

The first meeting of the board over which I presided as president was called for 2 o'clock instead of 3 in order that the plans I had been making might be reviewed and discussed; but there was so much talk about the routine reports of committees, which I was unable to accelerate, that 6 o'clock came and a proposition to adjourn. I remonstrated and insisted upon 5 minutes for considering future plans. Happily I had written a single page letter to the board saying that the incoming president proposed certain plans which could be put into effect if certain new committees were appointed; then followed a list of half a dozen with their functions. Some one moved the appointments recommended; the motion was carried and we went to dinner. It seems to be the mob psychology of councils and conferences that more can be accomplished in final minutes than preceding hours. At the evening meeting I read a sort of inaugural address on "Proposed Developments of the Institute" which gave a survey of the Institute and electrical activities in general, and elaborated the objectives for which committees had been authorized.

The transmission committee soon launched a notable career which already has been described.

How Sections and Branches Started

The committee on local organizations among members and among students had as chairman Calvin W. Rice. He undertook to prepare a statement with rules for oganization and procedure; but he didn't have it ready, so I undertook to show him how on the evening before copy for the October announcement had to be ready. Until midnight we simply devised questions without getting answers. What should be the Institute regulations and the local by-laws? What headquarters supervision and what the local authority? Should Institute papers be presented locally or should there be local papers, and what should be their status? Finances—should there be dues? Every situation that we thought of ended in interrogation mark. The student enterprise was even more difficult to precrystallize. One alternative was to take months to make by-laws; the other was to start. So we asked members to get together in various places and start meetings, we asked professors to have student meetings; and they did. Years later the experiences gained were a basis for by-laws. We did not know then what I discovered very recently that 2 pages of fine print rules for local meetings had been established many years earlier, and it was lucky we didn't for active effort to meet varying conditions is better than passive compliance with preconceived and restrictive rules.

Classes of Membership

There was a committee on membership It was not functioning well and I found it wasn't sure about the propriety and dignity of really asking people to join a professional society. I replied "Make the Associate grade inclusive and the Member grade exclusive." The committee succeeded in continuing the upward trend that Steinmetz had given to the membership curve.

Type of membership presents a problem. In the summer of 1902 I asked Stillwell as to Institute policies and activities. He replied that a high professional status of members should be sought. Years later I reminded him of this and said my policy had been to bring in large numbers of young men. In the meantime he had been president and I asked him what he had observed as the effect of the expansive policy. He replied "They'll grow."

There was also a committee of older members commissioned to note whether groups with special interests were in danger of flocking by themselves instead of remaining within the Institute organization. There was a feeling that the Electrochemical Society might have been organized as a group within the Institute had its policies been broader. The committee found nothing to recommend. A few years later the Illuminating Engineering Society organized about the time the tungsten

lamp appeared, and again there was regret that it had not been organized within the Institute. Later the radio engineers organized their own institute. Now it is our habit to form a new organization when a group of enthusiastic specialists want to get together. It is said that some civil engineers resented the separate organization of the mechanical engineers in 1880. The electrical engineers organized 4 years later ignoring the fact that Dewey's "Index" makes electrical engineering a subheading under mechanical. We delight in organizing and in exercising group individualism. Have not the electrochemical and the illumination groups done far better as independents? After all most of the technical content of each is nonelectrical. There are, on the other hand, advantages in general coördination of electrical groups.

Developments Not Then Proposed

I note that the "proposed developments" of September 1902 included (1) larger membership, (2) more papers and discussions, (3) local Sections, (4) student Branches, (5) collection of data, (6) support of Library, (7) permanent quarters for the Institute and (8) coöperation with foreign electrical societies. (I had been abroad during the preceding summer.) Although there is no suggestion of a Union Engineering Building or of coöperation with sister engineering societies, these ideas quickly evolved.

Engineering Societies Building, 1902–07

In October the building committee invited me to a dinner meeting at the apartment of the chairman, Calvin W. Rice. This committee previously had made regular monthly reports, somewhat to the effect, as I recall, that they had about $5,000 and that a certain estate might possibly contribute $10,000 more; but the committee was persistent and undaunted.

The afternoon before I started to New York for the committee dinner I talked matters over with Walter M. McFarland, officer of my company, who was experienced in engineering society affairs—principally mechanical and naval. I asked him whether a large building for the 4 principal societies was not feasible, sketching a plan which showed 4 independent entrances and offices, a common auditorium in the rear and library above. He said it was sensible and should be carried out.

After the dinner it was stated that there were 2 questions, first whether the set of plans showing a $50,000 building should be selected or the one on a $200,000 basis; and second, where to get the money. There was free discussion on the first point; but little was said on the second. Then I suggested a larger building for the 4 societies and cited the John Fritz dinner at the founding of the medal a few months earlier as a joint activity that showed what engineers could do when they acted together. Two societies had buildings, one of which was a reconstructed residence, and the other 2 societies had downtown office building headquarters. They were scattered in location and in activities; but my air castle was greeted with silence. I said more and was then told that the societies simply wouldn't pull together, "theoretically it is all right, but practically it won't work." (Friend Martin told me afterward that he added "unless there is some outstanding inducement.") I said that if it was all right theoretically it was good enough for me to talk about. So the meeting adjourned without choosing plans or finding funds.

A little later I was invited as president of the Institute to speak at the 25th anniversary of the Engineers' Club of Philadelphia on the topic "The Engineer of the Twentieth Century." I anticipated a simple task in assembling some plausible platitudes, but as I began to write the theme developed. I found that the great discovery of the Nineteenth Century was *coöperation*, made possible by the engineer; that he was an essential factor in our new industrial and economic life; that engineers themselves did not coöperate; they had created great wealth, but did not have a home; I pictured them in a fine "Capitol of Engineering," active in individual professions, but joined in a congress of engineers for the public interest.

Friend Eglin told me afterward that the electrical president had been invited on his assurances as there had been a question about putting an unknown youngster on a program where the veterans Haswell (of handbook fame) and John Fritz were honor guests and its opening speaker Rear Admiral Melville followed by others of well-known repute. He held

Looking Ahead in 1902

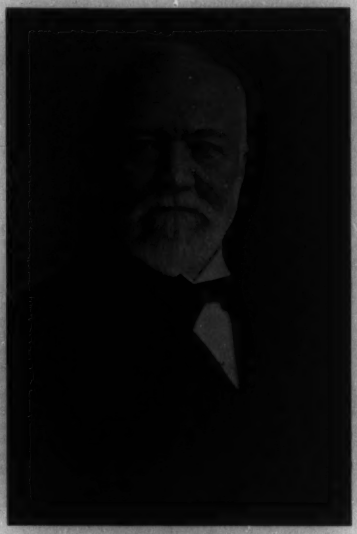
"In the vision of the future may we not discern a reflection of the John Fritz Medal in the larger life of the 20th century engineer? Methinks I see in that reflection the outlines of a magnificent building, the Capitol of American Engineering. Into this home, situated in the metropolis of the nation, are gathered the great engineering societies from their scattered lodgings. Here is a great technical library; here are ample assembly halls and comfortable parlors; here are the headquarters of a score of lesser societies restricted in their scope but affiliated in their work. I see all over the country innumerable local societies and engineering clubs, no longer isolated but joined together into one great combination. I see them affiliated with the national bodies of the several professions—sometimes as local chapters—altogether constituting one great union. There is individual freedom but general coöperation. Representing all the engineering professions and supported by the great union of the national engineering societies, I see an engineering congress giving to engineers a rank consistent with the importance of their work, and increasing the efficiency of the inter-relations among its members. An eminent body, it is powerful in advancing the common interests of engineers, and it represents the engineering profession in its relation to other professions, to pure science, to education, to legislation, to public improvements, and to the general welfare."

From "The Engineer of the Twentieth Century" by Chas. F. Scott, published in A.I.E.E. Trans., v. 20, 1902, p. 305.

his breath when my imagination took flight in regions of the palpably impossible, if not absurd. The real value of the event, however, was that my earlier suggestion had become a definite ideal.

Carnegie Underwrites Engineering Building

Two months later came the annual dinner of the Institute. Under the chairmanship of Martin it was to be a library dinner. Mr. Carnegie, donor of libraries, who had made a contribution to our library was sought as guest of honor. He declined; again he declined; and again; but the seventh invitation was availing. No wonder that he dubbed Martin "the irrepressible." It was a pleasant dinner; the guest was in happy mood. Martin, toastmaster, was at his best—he hoped that there might be more in store for the library. I, too, had some bait; I spoke of engineers and coöperation and a building as a means of coöperation, and I thanked our guest, patron of libraries, for what he had already done for us; I planned no embarrassment, but pictured pleasant possibilities. In response the "Iron Master" chatted about many things and extolled cooperation as a great principle in which America led Europe. The full record is in the Transactions.



Andrew Carnegie

The next morning Mr. Rice, coplanner with Martin, known of the Carnegie household and escort of Mrs. Carnegie to the dinner, telephoned me that Mr. Carnegie wanted us to meet him at his home at 5 o'clock. We were there. Presently he said he was interested in what had been said about a building the evening before, and wanted to know our plans. We said we had none—there was nothing on which to base them. As we sat together on the big sofa, he between us, he said he thought that we 3 Pittsburghers might talk it over together. (Rice then lived in the "Smoky City"); and so we did. Fortunately my colleague knew much more than I about the societies and their resources and Mr. Carnegie's attitudes. At the end of the hour he bid us counsel quietly with a few others and come back when our plans were worked out, and he politely intimated twice more that we had better not come again until we had the plans.

That occurred on Tuesday afternoon. On the following Saturday on returning from golf he found a group of engineers in his library, among them old friends such as John Fritz and Charles Kirchhoff. After friendly greetings he said: "Why, gentlemen, this is very pleasant, but I didn't expect you until you had your plans." "We have them" was the reply—they were on a single typewritten sheet. I recall only the last line "$1,200,000." There was discussion and explanation and then a lull. Presently, he asked "What is to prevent closing this up now?" There being no objection he went to his writing desk and with the ease with which he might have penned a letter of introduction he wrote and read to us with evident pleasure our $1,000,000 valentine (it was February 14, 1903). When he came to the words "Say, one million dollars" his eye twinkled and he moved his hand up and down adding "more or less."

Building Plans Developed

Things moved fairly smoothly. Committees developed building plans and legal procedure by which several societies could own and operate a building. On one occasion when I arrived in New York, however, I was warned that the "union building" idea was not progressing well as the secret ary of the American Institute of Mining Engineers, as well as one of our own members, were not in line. I had never met Secretary Raymond, but found him in an office building down on John Street, where his own desk and that of an assistant together with several rooms containing the Institute library constituted the headquarters. He said he understood there was to be an amalgamation of libraries in the proposed building and explained how in a simple way his own competent librarian was making their own library useful to their scattered members. When I explained that the whole library arrangement would be left for determination as the several societies might desire he was quite satisfied and expressed much interest in the common building plan. He was a fine man, fascinating in conversation, and profoundly devoted to the upbuilding of the mining institute, of which he had been secretary since 1884. In the lobby of the Engineering Societies Building is a life sized bas-relief presented by his friends bearing the inscription "Rossiter Worthington Raymond, Engineer, Editor, Leader, A Founder of the American Institute of Mining and Metallurgical Engineers."

On inquiry I found that our own disaffected member was Mr. J. J. Carty, leading and influential, chairman of the Institute finance committee while I was president. I had known him well, but never so intimately as when we talked about the building. He foresaw a great future for electrical engineering; he was devoted to the Institute; his ideal was a great electrical building. When I said that such a plan would have to start *de novo*, as I was sure that Mr. Carnegie would not switch from the coöperative idea to a building for a single society, he said "all right then, we'll go ahead."

The following winter the American Society of Civil Engineers voted not to join in accepting the gift. We feared that the gift, inspired by the idea of coöperation, was lost; but we fortified ourselves and went again to 91st Street and 5th Avenue. The facts were stated. With evident disappointment equal to our own he said "Then we can't go ahead, can we?" Then we presented letters from many smaller engineering and scientific societies asking for quarters in the proposed building. "Then they can take the place of the 'civils' and we can go ahead." His smile returned. On March 14, 1904, he wrote a new letter addressed to 3 societies and the Engineers' Club increasing the gift to $1,500,000; building plans had developed that called for that amount.

Carnegie's gift to the engineering societies

Three years later, in April 1907, the Engineering Societies Building having been built "within the appropriation" was dedicated in the presence of Mr. Carnegie. About the same time the adjoining new Engineers' Club was opened. The mining and mechanical and electrical societies occupied their respective floors, other groups additional floors and the 3 libraries were placed together on the 13th floor. From this eminence one could see both rivers; looking south the first high building was the Waldorf-Astoria Hotel of about 14 floors (where is now the Empire State Building) while to the north the only high standing edifice was the *Times* Tower.

There were 3 libraries. Just as confluent rivers of different color may flow together for miles unmixed, so these libraries occupied their separate alcoves and were presided over by their original individual librarians for several years. Then came the joint engineering library, administered for widespread usefulness. This is an excellent example of the practical and psychological difficulties as well as the advantages of their shift from individual to common action.

There was serious question in the minds of some whether the 3 younger and more democratic societies could carry through the building enterprise, paying for the land and meeting operating expense, and on the other hand create a professional standard appropriate to the profession; but they did. Rice and Martin, his successor, as chairmen of the building fund committee raised the nearly $200,000 which was the A.I.E.E. allotment for purchase of the land and the Engineering Societies Building soon came to be recognized as engineering headquarters, often by receiving foreign visitors. In joint American activities the civil engineers often participated.

Fortunately the principle proposed by an early member of the joint building committee had been followed and no action had been taken that would prevent or embarrass the entrance of the American Society of Civil Engineers should they subsequently decide to join the "Founder Societies." Finally, in 1917, they removed from their comfortable house on 57th Street and came to 39th Street, contributing for and taking quarters in additional stories built for them above the Library.

The story of the "Union Engineering Building" as it was termed in a pamphlet in May 1903, had an early chapter as well as the final one related in the preceding paragraphs. The ever alert Martin, who was assistant secretary during the Institute's first year reported a building for scientific and artistic societies as an important need. Later there was a specific and impelling reason why the building committee of 1901 was so persistent, a reason I did not know until the union project was well along. Mr. Dunn in his contribution to this issue describes how Dr. S. S. Wheeler purchased in England the Latimer Clark library of electrical books and presented it to the Institute in 1901. I understood that this was a small collection of very old and rare books. In fact, however, it included practically all electrical books up to the early years of the Institute. Two

large volumes were necessary to catalogue it, the cost of which was covered by Mr. Carnegie's early contribution of nearly $7,000. (Mr. Carnegie matched Dr. Wheeler's investment in the Latimer Clark library.) For this the Institute did Mr. Carnegie honor at the Library Dinner, although the catalogue itself was not completed until years later. In the deed of gift of the Latimer Clark library to the Institute there was a condition that the Institute should provide a fireproof building for it within a certain period. That was the reason why Martin and Rice and Weaver were so tenacious in their quest for a building. The project of an electrical society building had been earlier presented to Mr. Carnegie, as related by Mr. Dunn, but it was on too small a scale to interest him. However, the idea of a building "for you all," which would bring together the various technical societies adjacent to the social Engineers' Club, did meet with his sanction.

Years afterward one who had been closely associated with Mr. Carnegie personally and in the handling of his benefactions said, "That was the most successful of Mr. Carnegie's gifts."

Relations With Other Engineering Societies

The Engineering Societies Building had a significance larger than simply society headquarters and library. Mr. Ambrose Swasey in 1914 consulted with some members of the engineering societies to determine the type of trusteeship that might be established to administer a fund for engineering he purposed to establish. When he asked my views I related an incident that had occurred about 10 years earlier. I was with Charles Wallace Hunt, past-president A.S.M.E., and member of our building committee. We were in his library on the heights of Staten Island. It was evening; leaning back in his chair this idealist and engineer of vision prophesied: "I foresee that the charter which we are now securing which enables the trustees not only to hold and administer the building, but also to receive and administer funds for the advancement of engineering will in the future be found very useful." Thus the agency that the foresight of his longtime friend had provided was adopted by Mr. Swasey in establishing Engineering Foundation for research and "for the advancement in any other manner of the profession of engineering and for the good of mankind." Benjamin Franklin was chagrined that his electrical experiments seemed of "no use to mankind." Swasey established a fund for engineering and "the good of mankind." Standard screw threads and copper wire sizes, bigger and better turbines and generators, were but means to an end. The Institute enrolled a new ideal when its representations with those of the other societies accepted the administration of the Swasey gift to engineering for service.

Engineering Foundation came as a new opportunity; the next chapter in coöperation was brought by necessity—necessity for a single engineering voice of authority. The nation in war needed engineering counsel which separate societies with particular interests could not give. So as an emergency measure Engineering Council was formed with representatives from the principal engineering societies. It functioned well.

After the war it was seen that the common agency of the societies might well be extended in its scope. In the summer of 1919 a conference committee was appointed, the A.I.E.E. members being Calvert Townley, L. T. Robinson, and C. F. Scott. There were 3-day sessions and 2-day sessions and many intermediate meetings of subcommittees in shaping ideals, objectives, functions, and procedure. An incident will interest friends of Townley, who was then our president. On reading the record of the first 3-day session (which I was unable to attend) I discovered a recurring sequence. After a topic received about 8 pages of discussion Townley would move a resolution, which was passed. A new topic then received its 8 pages of discussion when again Townley's name reappeared followed by a resolution which was passed—and the cycle was repeated; again and again he stopped, he listened, he moved.

American Engineering Council

In June there was a preliminary conference of many engineering societies to receive the report and in November 1920 American Engineering Council (at first called Federated American Engineering Societies) was organized by the national mining, mechanical, and electrical engineering societies (the civil engineering society not participating until about 10 years later) and other national and local societies. The following sentences from the constitution indicate the high idealism as to the function of the engineer in our modern life:

> Engineering is the science of controlling the forces and of utilizing the materials of nature for the benefit of man, and the art of organizing and of directing human activities in connection therewith.
>
> As service to others is the expression of the highest motive to which men respond and as duty to contribute to the public welfare demands the best efforts men can put forth, Now, Therefore, the engineering and allied technical societies of the United States of America, through the formation of American Engineering Council realize a long cherished ideal—a comprehensive organization dedicated to the service of the community, state, and nation.
>
> The object of this organization shall be to further the public welfare wherever technical and engineering knowledge and experience are involved, and to consider and act upon matters of common concern to the engineering and allied technical professions.

Herbert Hoover, president of the new adventure in engineering, told the administrative committee that the higher standards of living that our industrial age was affording were counteracted by serious maladjustments—accidents, uncertainty of employment, difficulties between worker and employer. He said the engineer was particularly fitted to undertake the problem of readjustment and proposed that the first task of the new organization be the ascertaining of the facts as to industrial maladjustments. Six months later came the report "Waste in Industry." One thing it showed was the gain possible through simplification and standardization. Mr. Hoover had become familiar with the industrial situation

during the investigation and was then able, as U.S. Secretary of Commerce, to secure simplification and standardization by coöperation of various industrial groups which effected national economies aggregating hundreds of millions of dollars. The Council pioneered a new field, and has a record of fine achievement. The organization has not had the support anticipated, particularly by local societies. Two cents a week in dues seems to counteract the idealism of the average engineer for public service.

In the recent development of the Institute the large number of coöperating relationships during the past decade is notable. Mr. Charlesworth in his history of our organization says we are represented on 27 different bodies; in addition more than half of our Sections are in direct coöperation with local engineering societies.

A.I.E.E. and Education

An organization with which we have very much in common interest (though until quite recently not formal relationship) is the Society for Promotion of Engineering Education, which last year celebrated its 40th anniversary. Many members are common to the educational and to the electrical groups, and the mutual interest of the profession and those who train for it is obvious. Professor D. C. Jackson's account of electrical engineering education in this issue deals with the schools and their significance to the profession.

It happens that the Education society has had 2 electrical professors as president and each initiated an investigation of engineering education. Professor Jackson, pioneer in various educational enterprises, in 1907 (a few months after the dedication of Engineering Societies Building) secured the appointment of a joint committee representing the principal engineering and the education societies whose efforts with Carnegie aid culminated in the report of Dr. C. R. Mann in 1918. Later, in 1923, the proposals of the writer who was then S.P.E.E. president, led to a study of engineering education with Carnegie and other support (including that of the engineering societies and Engineering Foundation), supervised by a board of investigation and coördination of which Professor Jackson has been one of the leading members and the writer was chairman. The director of investigation was Dr. W. E. Wickenden, an electrical educator and A.I.E.E. member. Three years of fact-gathering, to which members of the Institute made a notable contribution, were followed by 12 sessions of the summer school for engineering teachers during 7 seasons, completing the cycle of principal subjects in the engineering curriculum in 1933. The director, after 2 trips to Europe, made a compre-

Engineering Societies' Library as seen from the main entrance (1928)

What Can Be Done

1. Act jointly—pool your interest with sister societies and colleges.

2. Take active measures to guide American youth in its consideration of careers.

3. Create a joint accrediting agency for colleges of engineering.

4. Reëxamine and, if practicable, codify your rules of admission to membership.

5. Through student branches educate students in the history, traditions, ethics, and social functions of the engineering profession.

6. Create joint sanctions for the award of professional degrees, and relate them to terms of admission to professional grades of membership.

7. Take a large share in directing the after-college education of young engineers.

8. Certificate the educational and professional attainments of engineers within the profession.

9. Take measures to create other credentials of educational attainment in addition to college degrees.

10. Do your part, through joint agencies, to promote the corporate welfare of engineering education.

From "What the National Engineering Societies Can Do for Engineering Education" by W. E. Wickenden, published in *Mechanical Engineering*, v. 50, No. 2, 1928, p. 119.

hensive report which indicates the close relationship between engineering schools and professional engineering in the principal European countries and in the United States. There was a supplemental study of noncollegiate technical institutes.

The board of investigation has advocated a larger participation in education by the professional engineering societies. That happily seems about to be realized.

"E. C. P. D."

The latest coöperative venture, Engineers Council for Professional Development (E.C.P.D.) is at least indirectly, a result of Doctor Wickenden's repeated exposition of the responsibilities of the professional societies in the educational field. The new group is composed of the national societies of civil, mining, mechanical, and electrical engineers, the American Institute of Chemical Engineers, the Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners (concerned with licensing). Like the Student Branch movement, its principal function is to deal with men, aiding them in preparation for the profession. It is more comprehensive, including precollege guidance and postscholastic development of the engineering graduate in preparation for certification into the profession by his society.

After the foregoing was written I received a letter from Calvin W. Rice whose name appears many times in the early story of library and building and local organizations. He has succeeded in converting electrical enthusiasm into mechanical action; he is now secretary of the American Society of Mechanical Engineers. He writes, April 2, 1934, "It may be of interest to you to see how in '27, 7 years ago, our good friend Wickenden [W. E. Wickenden, now president, Case School of Applied Science] enumerated (in the box) items nearly every one of which are now adopted in the E.C.P.D." The "box" accompanies his lecture on "What the National Societies Can Do for Engineering Education," at the annual meeting of the Society, December 1927, printed in *Mechanical Engineering* (v. 50, No. 2, 1928, p. 119) and republished herewith.

If we class as education the acquiring of knowledge by our members through the reading and discussion of papers and through publications, we agree with an enthusiastic educator who proclaims that the Institute is actually a great educational institution.

Trend in Topics of Institute Papers

That Institute papers have directly aided in solving the problems that have confronted electrical engineers from time to time, is a general understanding in which I have shared. A study of early conditions reveals that this is not always true.

During the first decade of the Institute the acute problem was to make apparatus that would work. Witness the miscellaneous shapes of cut-and-try field magnets of machines. When I entered the Westinghouse factory in 1888 the 2 kw transformer ("40-light" in the nomenclature of the day, *i. e.*, 40 50-watt carbon lamps of 16-candle power) was the largest made. Experimental larger sizes had shown excessive voltage drop and temperature. The largest alternator ("designed for 130 kw and good for 120 kw") had reached the limits of its mechanical design as its armature conductors were laid on a cylindrical core and were (for a while) held in place by band wires which were inadequate for the tangential jerk caused by short circuit or the temperature augmented by eddy currents in the conductors moving through the active field. Then came toothed armatures (one big T-shaped tooth per field pole); then the slotted type. There were many street railway systems in those days each with its own peculiar motor until Lamme's historic No. 3 motor (cylindrical, enclosed, 4 field poles, 4 field coils, slotted armature, machine wound coils, 2 brush arms) became (1892) the prototype of modern motors. There was like struggle for meters and switches and controllers that would operate and keep operating; but the fundamental thing was the machine. A typical larger railway power house had a 500-hp engine belted to a jack shaft with 4 or 5 big pulleys driving 100 kw generators—the largest then available. At the World's Fair in 1893 were 12 duplicate "1000-hp" alternators.

Dynamo and Motor Pioneers Neglected

What guidance did the Institute give to the dynamo and motor pioneers? Under the classification

"dynamos" during the first 5 years are 2 papers; one on a method of testing by Professor Brackett and one on "The Relation between the Cross Section of the Iron in the Armature and Field of a Gramme Dynamo" by Prof. D. C. Jackson. During the next 3 years 2 papers have to do with design, one on compound winding by Louis Bell (Johns Hopkins University, Ph.D.), and one "On the Relation of the Air Gap and the Shape of the Poles to the Performance of Dynamo Electric Machinery" by Prof. H. J. Ryan. During this period the only papers under the classification "motors" which suggest design are "Electric Motor Regulation" by Prof. F. B. Crocker (note the preponderance of professors) and the paper of Dr. S. S. Wheeler (both past-presidents and associated in the Crocker-Wheeler Company) on "The Practical Requirements of Small Motors." Doctor Wheeler says small motors have not been constructed on "the same principles as those of an efficient dynamo machine" of large size. One-tenth horsepower motors were presented; they had a field of "simple horseshoe shape" and showed a departure from ordinary proportions as the Gramme armature was shorter and of larger diameter. Motors of this type were wound for 20-amp and for 10-amp constant current and also for 110-volt constant potential circuits.

Where were other designers with their perplexities and their experiences? Possibly instead of broadcasting their ideas in Institute papers they were preserving them in patent specifications. They were too busy. Note the following paragraph in the discussion of "Distribution of Electricity by Secondary Generators" March 15, 1887:

> "Professor Elihu Thomson: This is the first opportunity I have had of meeting the members of the Institute, and I am very glad that I came down. On former occasions I have been entirely too busy and preengaged to make it convenient to leave the place where we carry on most of our operations."

He then describes his experiment on the reversibility of the Rhumkorff coil (as related in his accompanying contribution to this anniversary issue) and adds that the heavy induced current welded the 2 ends of the wire so that they "actually stuck firmly together. It was with difficulty that I separated them. . . . My recent experiments in welding by electricity are really the outgrowth, as I see it, of that little experiment of the Leyden jar discharge sent through the Rhumkorff coil."

I was surprised to find how little specific technical information is found in the early Institute papers. They were largely descriptive. The nearest approximation to a formula in volumes I to IV of the TRANSACTIONS is in a chemical determination of the carbon resulting from a combination of acid and sugar in the "Chemistry of the Carbon Filament."

STANLEY'S PAPER ON ALTERNATING CURRENTS

There was one paper to which I owe much. Financial reverses in 1887 caused the Baltimore and Ohio Railroad to discontinue the technological school for apprentices in its Mount Clare shops where I was teaching while doing part time graduate work at Johns Hopkins University in mathematics, chemistry, and physics. I visited my old student friend Henry Humphrey who was trying to make incandescent lamps penetrate the darkness of the Hoosac Tunnel. He showed me a little shack at the east portal. "This is the Westinghouse system and the dynamo makes alternating current" he explained; both were new to me. "That is a converter, it has a coil of many turns receiving high voltage and another of few turns giving low voltage." "Why," I replied "that is a Rhumkorff coil backwards."

The only job I could find (after presenting letters from Humphrey in New York) was in Philadelphia. I was so unpromising but persistent a prospect that I was offered a trial opportunity for a week without pay and they would "not charge me for the instruction." I got a job as wireman on the installation of an alternating current lighting plant in the Baldwin Locomotive works. The converter (now called transformer) was a mystery, but I found very helpful my recollection of "self-induction" from the fundamentals of electricity I learned from Professor Mendenhall at Ohio State University during the Spring of 1884 when the Institute was being founded. Also I found useful my personal acquaintance with sine waves gained in making Lissajou curves with a "compound" pendulum in the physics laboratory and also with one I purchased from C. F. Marvin (until recently head of the U. S. Weather Bureau) which he had made in the mechanical laboratory.

I was well prepared by fundamentals and curiosity for a paper (an A.I.E.E. paper I learned afterward) on "Alternating Currents" by William Stanley which I found in *The Electrical World*. The odds and ends of my knowledge and experience fitted into Stanley's simple and clear account—it was rational, satisfying, inspiring. I pictured an author of such erudition as a mature and dignified scientist, such as were pictured with long beards. What was my astonishment a year later when he brought a new machine to Pittsburgh for test (I was wireman for him) to find him young, agile, nervous, enthusiastic, affable and likable. He showed an interest in his young helper which ripened into life long friendship. I surmise that Stanley's paper meant to many others what it meant to me.

But to return to early Institute papers, I find them largely informational and descriptive; there are but few too technical to be understood by the average member. Now and then comes one of outstanding character such as: "A New System of Alternate Current Motors and Transformers" by Nikola Tesla (TRANS., v. 5, 1888, p. 308–24); "On the Law of Hysteresis" by C. P. Steinmetz (v. 9, 1892, p. 3–51 and 621–724); and "Impedance" by A. E. Kennelly (v. 10, 1893, p. 175–212).

CLASSIFICATION BY TOPICS; EARLY AND RECENT

In the 1900 Handbook the prior Institute papers, 1884–99, are listed under topics which are rearranged in an accompanying table in order of the number of papers included in each (a few papers are listed under more than one heading; *e. g.*, "induction motor" is included under both "motors" and "alternating current practice").

Papers published during the past 5 years that fall under the original topics are listed in the second column of the Table. Over 25 per cent of the topics are credited with no recent papers; among these topics, however, "storage batteries" and "primary batteries" have been discussed as auxiliaries in telephone and telegraph offices, also in papers on the "3-power locomotive"; "polyphase systems" is the title of no recent paper, although over 75 per cent of the 660 papers actually relate to this system, so that instead of 0 one might advocate placing 495 under this topic.

Under several topics the number of papers has increased from 2 to 6 times, *viz.*, "motors," "protection from lightning," "insulation," "power transmission," "telephony," and "welding and annealing." While only 2 papers in the last 5 years appear under the topic of "meters," if those discussing metering systems (such as "telemetering," listed as a new topic) and those treating parts of metering systems (such as "instrument transformers") were counted here, the number would be much larger. In the same way the 25 papers appearing under "power transmission" would be greatly increased if those treating "interconnected systems" and "stability," as well as those dealing with "insulation of power cables" were included under this topic. Many of the 49 recent papers classified under the old topic "alternating current practice" might appear more appropriately under a new heading, "engineering and operating practice."

The first period included 15 years; the second, 5 years; "power transmission" averaged only 1 paper in 3 years in the early period and 5 per year in the later period. Incidentally, the first (1892) and the last (1898) of the early papers on "power transmission" were by Chas. F. Scott.

In the lower portion of the table of A.I.E.E. papers are listed the additional topics necessary for including recent papers, indicating what is new or radically modified. This list is significant. Possibly it should be increased by transfer of some papers now in the first table; for example, recent papers classed under "traction" and referring to "steam railway electrification" might be considered as dealing with radical modifications. Many of the "miscellaneous and theory" papers deal with the theory of unlisted topics. The tables, however, are not presented for microscopic dissection, but for indicating general trends.

A.I.E.E. Papers—1884–99 and 1929–33

Topics in 1884–99 List	Early 1884–99	Recent 1929–33
Alternating current practice	52	49
Miscellaneous and theory	52	90
Traction	30	33
Dynamos	28	33
Motors	21	42
Incandescent lighting	19	5
Units and standards	15	7
Measuring instruments, indicators, etc.	14	22
Protection from lightning, etc.	13	41
Arc lighting	12	0
Telegraphy	11	9
International Electrical Congress of 1893	10	0
Magnetism	10	3
Storage batteries	10	0
Photometry	9	0
Central stations	8	11
Insulation	7	49
Prime movers	7	4
Meters	6	2
Electrolysis	5	4
Mining	5	1
Patents	5	0
Power transmission	5	25
Telephony	5	35
Subterranean work	5	8
Automobiles	4	0
Aluminum	3	1
Polyphase systems	3	0*
Primary batteries	3	0
Railway train lighting	3	0
Resonance	3	3
Welding and annealing	3	19
Impedance	1	0
Therapeutics	1	1
Mean per year	26	100

Additional Topics in Papers of the Last 5 Years (1929–34) Which Are New or Radically Modified Since 1900

Interconnected power systems and stability	24
A-C distribution networks and relays	15
Automatic control of frequency and voltage regulation	10
Automatic stations, telemetering, and supervisory control	18
Transformers—tap-changing under load and surge-proof	18
Impulse voltage—generation, measurement and testing	11
Mercury arc rectifiers and inverters	12
Relays—high speed distance type	4
Oil circuit breakers—theory, design, and testing	12
Oscillographs—cathode-ray and portable automatic	6
New types of fuses, lightning arresters, protective gaps, arcing horns, switchgear, etc.	13
Inductive coordination between power and telephone plant	4
Radiotelephony and aeronautical communication	19
Elimination of noise and sound analyses	12
Vehicular traffic signals, railway signaling, and automatic train control	11
Synchronous clocks	1
Television—2 way	1
Electronic applications	11
Electrical equipment for smoke abatement	2
Electric shock	2
Network analyzers	1
Applications to oil well drilling	2
Electric furnaces	1
Electric house heating	2
Mean per year (additional topics)	43
Mean per year (all topics)	143

*No papers were on the subject of "Polyphase Systems;" yet over 75 per cent of the papers involve theory and apparatus used in connection with polyphase systems.

Transactions and Other Records; N.E.L.A.

Presumably many early papers were voluntary contributions by authors while others were requested by the committee responsible for providing a program. Later came more definite planning of programs, as in Steinmetz' presidency and in later years when the convention programs are largely sponsored by the technical committees.

It sometimes is assumed that the Institute Transactions present a complete moving picture record of electrical engineering. This is only partly true; the Transactions constitute an invaluable but not a complete record. The electrical press, including the *Electrical World*, the *Electric Journal*, the *General Electric Review*, publications of the Bell Telephone System, "proceedings" of related societies in the fields of electrochemistry, illumination, welding, radio, and education as well as certain papers presented to the A.S.C.E. and A.S.M.E. are needed to complete the record; nor can patent specifications, interferences, and litigation be omitted for they contain much of historic value.

Steinmetz great paper on complex quantities was

presented to the Electrical Congress of 1893. This congress, as well as that of 1904, was sponsored by the A.I.E.E. and the "Proceedings" were printed under our auspices but as independent volumes. It seemed to me in 1904, and I am of the same opinion now, that the proceedings of such congresses might well have appeared as supplemental volumes of our TRANSACTIONS thereby placing there and in our indexes much worthwhile material.

The National Electric Light Association received papers that should have been ours, such as Lamme's classic on the induction motor (1897). The technical committees of that association have done a great piece of work. Engineers of public utilities were given a Herculean task of installing apparatus and providing systems to meet growing demands. Previous rapid growth had been accelerated during the war period and the output during the final war year 1918 is shown on a widely published curve as 34 billion kilowatthours. By 1929 this had increased nearly threefold to 93 billion; nor did this involve mere duplication of equipment. Scientific research and engineering development were producing new apparatus for generation and transmission and control while "super power" and interconnection were imposing new problems in design and operation. Engineers of the utilities were urged to quick action by the endeavor of their managers to meet the public demand for electric power; and the criticism of utility financing and management cannot be attributed to failure of engineers to meet their gigantic problems.

But what of their relations to the Institute? It seemed to me in 1902 that the N.E.L.A. was taking up many technical problems that the A.I.E.E. had been handling; and under the vigorous stimulation of its president, H. L. Doherty, it was doing a real job. Recently Mr. E. C. Stone of the Duquesne Light Company (Pittsburgh, Pa.), for several years chairman of the technical committees of the N.E.L.A., stated the relationship thus:

"Our problems were urgent; as public utility engineers we got together to solve them; we were largely A.I.E.E. members; but when we had something new and outstanding we wanted it to appear as an Institute paper, on account of the prestige and standing of the Institute."

This sentiment, if my observation is correct, is widespread.

Origin of Papers Published in the A.I.E.E. Transactions During the Past 3 Years (1931-33)

Occupational Classification of Authorship	No. Papers	Percentage
Electrical manufacturers	176	40.0
Central stations	60	13.6
Universities	55	12.5
Committees	45	10.2
Communication companies	28	6.4
Railways	12	2.7
Industrial	11	2.5
Consulting engineers	10	2.3
Government	3	
Unattached	2	
Jointly by manufacturers and central stations	15	3.4
Jointly by communication companies and central station	6	.1
Jointly by universities and central stations	3	
Jointly by universities and manufacturers	2	
Jointly by manufacturers and railways	3	
Jointly by competitive manufacturers	4	
Jointly by communication companies and manufacturers	2	
Jointly by consulting engineers and central stations	1	
Total	438	

The Institute Functioning as an Organization

When in December last I accepted a part in writing the history of the Institute it seemed to me that the influence and achievements of its members acting as an organized group in contrast to what they might have accomplished as individuals would be a fruitful line of inquiry.

The trend toward organization has been general. When the Institute was organized, engineering and technical societies were few; now they are legion. Industry and business have been completely revolutionized by consolidations. I have just noted an article in *Cassier's Magazine*, October 1901, on "Some Recent Industrial Consolidations" which lists great combinations or "trusts" in steel, locomotives, agricultural implements, shipbuilding, machinery (Allis-Chalmers Company), tin cans, and watches, also "carpet, packing, egg, and cereal consolidations. . . . Lighting and street railroad companies all over the country . . . oil-field companies, coal companies, and electric power organizations are being amalgamated from the Atlantic to the Pacific. . . . Each week and month add a chapter to the remarkable industrial revolution." A companion article deals with trade combinations in Great Britain and on the Continent.

The economies of large scale physical operation—in large measure the development of engineers who provided power and machinery—forced the small factory, often developed by the individual who became owner, manager, and expert, to shut down or to merge with others.

In electrical manufacturing there were in the '80's many makers of arc lighting equipment and incandescent generators and lamps and railway motors and various electrical equipment and accessories. Consolidations came, notably the General Electric Company in 1892, as described in Professor Thomson's accompanying article, which continued the absorption of other companies, such as those of Sprague and Stanley. The Westinghouse Electric and Manufacturing Company in 1920 was a composite of a score of prior organizations, as shown in Colonel Prout's biography of George Westinghouse.

Research and design shifted from individuals to groups. A generator or a transformer or control equipment is now the product of many experts. Sprague's Richmond car and his early multiple unit train control were probably about $99^{44}/_{100}$ per cent pure Sprague; but the monster Pennsylvania single-phase locomotive is the product of the combined experience and technical acumen of scores of Westinghouse and General Electric experts collaborating in the design of motors and controls, and coöperating with engineers of the Pennsylvania Railroad and the Baldwin Locomotive Works. The scale of activities

has passed the capability of the individual; group action is essential.

Changing Industrial Environment

These snapshots during recent decades picture the changing industrial environment of our Institute. We cannot pause here to indicate the potency of electric power and processes in shaping large scale production nor the significance of the telephone as the high speed tool of modern business. We may consider for a moment, however, the electrical developments that preceded and made possible large scale operation in electric power. As illustration note the Hartford Electric Light Company and its progressive upbuilding under the leadership of its president, A. C. Dunham (donor of the Dunham Electrical Laboratory at Yale University). About 1897 its station supplied arc lighting on 10-amp and on 6.6-amp circuits, incandescent lighting on 3-wire d-c and 1,100-volt a-c circuits, and power on 500-volt d-c circuits. There were 24 belt-driven generators, aggregating a trifle over 1,000 kw supplying their loads by 21 separate and independent circuits which could not be put in parallel.

Then came polyphase alternating current, at first from water power, then (1901) from the pioneer steam turbine in an American central station, Westinghouse-Parsons (Parsons applied for and received his English patent on the turbine in our natal year, 1884), and now from a General Electric mercury boiler and turbine. There is interconnection with surrounding plants, and even Niagara power by intermediate interchange has served Connecticut in an emergency. The key to it all is the polyphase system, announced in Tesla's Institute paper in 1888; demonstrated on a large scale at the Chicago World's Fair in 1893; put into large scale service at Niagara in 1895; and now providing practically all of our world-wide electric power service. One day at the World's Fair Dr. Louis Duncan, then president of the A.I.E.E., said "Scott, some of us want to discuss power transmission at the electrical congress tomorrow afternoon. Can't you describe the Westinghouse polyphase exhibit?" My account appears in the "Proceedings" of the congress published by the Institute. Several years later in presenting a paper "Niagara Power" to the Engineers' Club in Philadelphia I used a diagram showing the varieties of a-c and d-c services at fixed and varying and adjustable voltages that were being supplied locally and at Buffalo from a single set of bus bars. Mr. E. D. Adams reproduced the diagram in his book "Niagara Power"—very commonplace now, but in the middle '90's a revolution that made large scale electric power possible and enabled electricity to become an active agency in large scale coöperation.

The Institute itself, rejoicing in the membership of 279 reported by the national secretary at the end of the first year (although Secretary Pope reports a "total paying membership" of 98 as of May 17, 1887, 322 in 1888, and 742 in 1893; Trans., v. 10, 1893, p. 536) and holding annual meetings at which 11 papers were presented in 1884, 5 in 1885, and 6 in 1886, has grown in membership and activities to the organization it is today. The story of this development is interestingly related in the accompanying article by Past-President Charlesworth. One is impressed by the Institute's territorial expansion—61 Sections and 113 Student Branches; by its score of technical committees; by the 30 or more representations in 27 other engineering and scientific groups; and by the considerable but overloaded operating staff.

Standardization; Kennelly and Skinner

Some of the activities which are essentially those of a group and not possible by independent individuals merit special comment. Standardization is an outstanding professional activity. The contributions by past-presidents Kennelly and Skinner show an amazing development. The Institute was entering its sixth year when it took the first step by recommending the name "henry" for the unit of induction. A few other recommendations as to nomenclature and scientific units and the adoption of a standard wiring table (in which the fixing of the Matthiessen value of copper resistance was a crucial point) was nearly all until the "committee on standardization" came in 1898. It dealt with engineering and technology, and continually expanded its scope. Then about 1920 the work was extended to production and manufacture and later the American Standards Association evolved largely under A.I.E.E. leadership. All this provides scientific, technical, and industrial foundation upon which to build.

These contributions of past-presidents Kennelly and Skinner provoke personal reminiscence. Reading between the lines Kennelly's contribution is autobiographical. It portrays his clarity of thinking and expression; his aptitude and interest in scientific nomenclature, the language that enables engineers to understand one another; his continued interest since his chairmanship of the Institute's initial committee on units and standards. I really came to know him when I was a member of the standards committee and he was secretary of that committee. One incident impressed me greatly—the facility with which he instantly condensed my rambling paragraph into this: "Note. The following definitions and classifications are intended to be practically descriptive and not scientifically rigid." About the same time, some 30 years ago, I was a member of another committee of which Skinner was secretary; it was a works committee on purchasing department specifications at the Westinghouse company; it included representatives of purchasing, engineering, testing, and manufacturing departments of the company. The problem was to prepare specifications acceptable to all departments and to prospective bidders for wire, sheet iron, tool steel, shafts, insulating materials, and what not. The secretary was the focal point for objections from all concerned and it was his function to draft and redraft specifications until they were practical and adequate and received approval. In this he acquired technical and diplomatic experience which stood him in good stead in the battles royal of national groups later on.

Technical Problems

Group attack on technical problems is a powerful agency. The power transmission committee brought together at the Niagara Falls convention in 1903 over 60 interested members who represented, as I noted at the time, practically every transmission company from Montreal to Los Angeles, including cities with underground cables; and there were experts from manufacturing companies, from laboratories, and from colleges. The method of discussion is described by Past-President Mershon. This forum of operating men and designers and experts through successive years laid the basis for the transmission networks that cover the country.

The Institute committees provide a technical meeting place of engineers of commercial competitors. In one instance engineers of manufacturing and operating companies held conferences that finally culminated in tests on 4 large turbine generator units after installation for determination of safe temperature limits. Similarly investigations are under way directed to the standardization of test methods and performance limits to establish the surge voltage strength of transformers.

Again, the comprehensive and inclusive problem of insulation coördination between the various parts of a transmission system is under consideration by several of our committees.

Complex problems require coördinated handling. In early power transmission by constant current at variable voltage (practically the only method considered in Kapp's "Electrical Transmission of Energy," 1888) and by alternating current as the synchronous motor at Telluride in 1891, the transmission wires connected one generator to one motor. Individual machines were connected together in the simplest ways. However, modern interconnected transmission and distribution systems are not simple assemblages of independent units; the characteristics of each of the circuits must be coördinated with the whole to secure operating tranquility. Hence, designers of the various elements and operating engineers, not of one but of many systems, must plan together. Mr. Fortescue points out that the presentation of symmetrical coördinates and of system stabilization to the Institute secured a wide audience of the many concerned. Furthermore, a new idea (usually commended by one's associates) receives a stimulating diagnosis when it encounters the queries of commercial rivals who aim to bring out the weak points or omissions. Improvement is likely to follow, by the originator or his rivals.

A.I.E.E. a Voluntary Organization

As problems become comprehensive and involved, the Institute therefore provides a forum, where designers and operators, irrespective of race, color, or conditions of servitude can meet on common ground, and where quality is the predominating criterion.

The Institute is a voluntary organization; it cannot compel its members nor has it authority to enforce its recommendations or its standards. It depends on the freely given service of its members and on the prestige of its standing as a professional body. I note a sort of reverential regard by our members for something intangible—not for committees or boards or individuals, but for "The Institute"; and its members jealously guard its reputation from commercial or unprofessional taint.

In their Institute activities electrical engineers have learned to work together. Although of diversified interests—technical and commercial—they have coöperated to build their profession and their industry. There have been rivalries and controversies, some quite vigorous, as in several "battles of systems"; but in general in a wholesome spirit of give and take. We have sought to find a better way in a practical spirit of optimistic progress. Our contentions are clarifying and we emerge on a higher plane.

The ability to work together which electrical engineers have attained in the Institute is a quality sorely needed elsewhere. Present forward looking readjustments in industry and business demand a shift from the excesses of ruthless individualism to rational coördination. The threatening difficulty is in getting industry and business to do what engineers have been doing in their Institute work. Possibly the great thing that the Institute has achieved by group action is a demonstration of the methods and results of large scale voluntary coöperation.

Institute Service to Its Members "Social Intercourse"

The acquiring and transmission of knowledge is essential to progress. The great accomplishment of the Institute is the publication of several thousand contributions on 50,000 and more pages of its Transactions which have been distributed to a membership that has increased more than a hundredfold. Papers are scrutinized by experts before acceptance, and are refined and amplified by discussion—a process stimulating to authors and protective to readers. A problem past, present, and probably persisting, is to meet the needs of a varied membership. Our society is not exclusively scientific and professional; it represents an industry; it is made up largely of "associates"; it enrolls students. A technical committee rejoices when a super expert edifies his expert group by symbols or terms that are jargon to the uninitiated. Possibly any one of a majority of our papers is of real significance to 10 per cent or less of our members, which attests value or otherwise according to one's point of view; but our publication policy aims by wide variety to provide for every taste: Note the recently inaugurated series of scientific expositions for younger and general readers, supplementing the educational objectives of Student Branches and the Engineers' Council for Professional Development. If any group feels neglected it may well question whether its own activity is not at low ebb.

I was surprised to note the order in which the

rules adopted May 13, 1884 list the methods by which the new Institute was to accomplish its objectives: it is (1) by social intercourse, (2) by papers. This seems to presage the order of precedence at our annual conventions in which the award of the Mershon Trophy and prizes for golf and tennis arouse greater general interest than awards for best papers. I've been asking myself and others during the past few months, just what really is the outstanding feature of the Institute? I am seeing some things in new perspective. What have I gotten out of the Institute? "Social intercourse" is not limited to banquets and evening clothes, but includes committee meetings and shirt sleeves, golf courses and tennis rackets. It is seeing men, hearing them, meeting them, knowing them, catching their spirit, cherishing their friendships that count. I find that I have met every president except the first and I learned of him quite early, as "Norvin Green, president" was conspicuous on Western Union Telegraph blanks. In a few cases—only 3, Pope, Weston, Houston—the meeting was incidental or brief; with nearly all of the others the association has continued through the years. I met Anthony only a few times, and Bell I think but once; but as it fell to my lot to present to him the John Fritz Medal during the dedication exercises of the Engineering Societies Building it made a deep impression. (I did see him again in 1915 at the public demonstration in our auditorium of the transcontinental telephone, when his original telephone was exhibited and employed by him in talking with San Francisco.) At the dedication in 1907 he was well along in years, but so simple and gentle and kindly and appreciative! As I write these words, they call to mind another great figure. It had been my privilege a few years earlier to visit Lord Kelvin in his home in London. In my memory, Bell and Kelvin are very much alike.

I don't remember what it was that took so much time in our board meetings, but I do remember the men and their ways; and in the fascinating constructive work on the Engineering Societies Building Committee and American Engineering Council it has been a great privilege to work with the leaders in the other societies. Yes, to me "social intercourse" may even take first place, for it has brought me friends and activities that have enriched my life.

Inspiration by Association

President Whitehead finds one of the Institute's best fruits to be "the power which its meetings and publications have of attracting aspiring young men and maintaining their allegiance. This appeal to young men has been the greatest asset and strength of the Institute." Not scientific knowledge, but an appeal "inherent in the Institute."

Past-President Rice speaking of the early years says our "organization formed a nucleus which steadily drew to itself the earnest electrical workers in all parts of the country." What resulted was "the inspiration that comes only from association of people of similar interests and of like minds."

The Institute has been characterized as a great educational institution. The college, too, has its "papers," its lectures, and discussions, its technical laboratories, and is operated with carefully balanced curricula; but what the fortunate student values most in later years is the atmosphere of the place, the methods, the personality, the ideals, the inspiration of his teachers, and the association with fellow students "of similar interests and of like minds." The real things in school, in Institute, in life are intangible, inspirational, spiritual.

Fortunate will be this anniversary occasion if we can show the way we have come and point the way onward in effective service "for the good of mankind" which may inspire our young men to lead on.

Finale

In planning for the fiftieth anniversary of the Institute the committee assigned a particular part to me because of my long personal participation in Institute affairs. I joined the Institute in 1892. I was elected a director in 1895 and have been officer, representative, or committee member continuously since that time. Perhaps Doctor Kennelly alone has a longer record of service.

Possibly I have been unduly responsive to the suggestion that there be ample embellishment by personal reminiscence. The perusal of old time records, the reading of past-presidential contributions of wide variety, personal reminiscing with old timers and with others have awakened interesting recollections and have given me new viewpoints and a perspective of various happenings; these now present a significance which one does not recognize when enmeshed in details.

My romancing excursion into the past is brought to an abrupt close by telegraphic demand of the Editor for copy. I close with a profound sense of inadequacy of my story as a "history" and a feeling that the future may discover that the rôle of the Institute in our changing civilization has a significance we do not realize.

In the fabric of electrical engineering the long scientific threads of the warp are bound together and given pattern and utility by cross threads which are the life achievements of individuals. As the loom keeps weaving through the years new threads of scientific knowledge are added to the old, and new workers contributing woof of finer quality enrich the beauty and enhance the utility of the product.

The Institute's Organization

By H. P. Charlesworth, President A.I.E.E. 1932–33

How the Institute's organization has grown from its early modest beginning to meet the widely diversified needs of a rapidly expanding membership is reviewed briefly in this article. One cannot review the history of the Institute's organization "without being impressed with the flexibility it has shown in adapting itself to changing conditions, and we may be confident that this will continue . . . in the future."

ON THIS the occasion of the fiftieth anniversary of the Institute, it is my privilege to review briefly what has taken place over the years past with respect to its organization. To this end, it will be interesting, I believe, to look back at its early form and consider how it has expanded from a very modest beginning to meet effectively the diversified requirements of the various activities that naturally developed in an institution associated with such a rapidly growing industry.

As Professor Scott tells us in his historical review, the American Institute of Electrical Engineers came into being at a meeting in New York City on May 13, 1884. While the initial membership cannot be stated with exactness, as the early records are incomplete, the first rolls carried the names of many who were destined to be leaders in the electrical arts over a long period of years, including Thomas A. Edison, Alexander Graham Bell, Elihu Thomson, Edwin J. Houston, Edward Weston, Theodore N. Vail, Charles F. Brush, Elmer A. Sperry, and Norvin Green. They were quickly followed into membership in the new organization by other men whose names are associated with outstanding contributions to the early development of the art.

General Organization

Management of the affairs of the Institute was placed in the hands of a council composed originally of a president, 6 vice-presidents, 12 managers, a secretary, and a treasurer. In 1901 the name of this managing body was changed to "board of directors." Its makeup, through successive changes, has been modified slightly so that it now includes 10 vice-presidents, instead of 6, and 2 junior past-presidents. The national secretary acts as secretary of the board without vote. In the interim between meetings of the board, matters requiring attention are passed on by an executive committee of 7 members.

While the term of the national secretary is one year, through repeated election and reappointment, he has been in fact a continuing executive officer of the Institute, and the development of the Institute's activities has been influenced in large measure by the wisdom and vision of the men who have occupied this office. Of the 4 national secretaries who have served the Institute, 2 have covered 47 of the Institute's 50 years.

The first secretary, Dr. Nathaniel S. Keith, under whose leadership the original group that formed the Institute was brought together, served only for the first year. For the next 27 years until his retirement in 1911, it was the Institute's good fortune to have the services of Mr. R. W. Pope, a charter member, in this office. His executive ability and enthusiasm, and his wise, discriminating counsel contributed greatly to the Institute's progress during his period of service from a modest beginning to a large and effective organization. The traditions established by Mr. Pope were capably sustained over the next 20 years by his successor, Mr. F. L. Hutchinson, who brought to the office a rare statesmanship and a detailed knowledge of Institute affairs gained in a long experience as assistant secretary. In the difficult years since Mr. Hutchinson's death in 1932, this office has been filled very ably by Mr. H. H. Henline, who also had long experience as assistant secretary before assuming his present duties.

Growth of the staff working under the national secretary at Institute headquarters is illustrative of the development of the Institute. Starting with only part time of the secretary alone, later supplemented by some stenographic help, the staff grew to a force of 35 men and women at its peak in 1931. In the course of the depression years it has been reduced to 25. The growth of the staff reflects the increase both in the amount and in the variety of services performed. An important division of the present organization is the editorial division which edits and publishes Electrical Engineering and Transactions of the Institute, under the direction of Mr. G. Ross Henninger. Advertising in Electrical Engineering is under the direction of Mr. C. A. Graef. Other important work is represented by the committee secretaries, Mr. H. E. Farrer serving as secretary of the standards committee and the board of examiners and Mr. C. S. Rich serving as secretary of the technical program committee. The business office and general office management work constitutes the largest group and is under the direction of Mr. F. A. Norris. The sustained loyalty of the staff to the ideals of the Institute always has been one of the Institute's great assets.

Geographical Divisions

While from the beginning the Institute was a national organization, technical activities at first centered a good deal about New York City. Except for the first regular technical meeting, which was held in Philadelphia on October 7 and 8, 1884, all of the meetings for the first 5 years were held in New York. After that there were occasional meetings in other cities, Boston (1890 and 1899), Chicago (1892), Philadelphia (1894), Niagara Falls (1895), Eliot, Maine (1897), and Omaha (1898). Minutes of the early meetings show that the officers were increasingly aware of the geographical problems presented by the far-flung distribution of the growing membership. There were repeated discussions dealing with measures for enabling the active participation of distant members in the Institute's affairs and for increasing the usefulness of the Institute to them. Mr. Pope was a constant champion of these distant members. Only a few days after the third anniversary of the Institute, he offered the following suggestion:

"It has come to my notice that there is a field for the establishment of branches of the Institute in some of the larger cities.... The electrical interests in other cities are very large and with a little assistance and advice, perhaps, and by providing in the rules for the establishment of such branches, I think some good may be accomplished in that direction...."

Again in 1893, Mr. Pope called attention to the increasing proportion of the membership residing outside of the vicinity of New York. Shortly afterward a plan was authorized by which, upon petition of 20 members, meetings might be held in any city at the same time as those held in New York, the same papers being read and discussed simultaneously at all meetings. Many meetings of this kind were held in Chicago; but the practice was not generally followed elsewhere until 1902, when independent local meetings and activities became a prominent feature of Institute work.

At that time Mr. Pope discussed this matter with Dr. Charles F. Scott, then president-elect, and he later appointed a committee on local organizations to promote local meetings. As a result, plans were approved for the organization of local groups of members in geographical Sections. Also, at the suggestion of President Scott, groups of engineering students in universities and technical schools were organized into Branches. This establishment of Institute Sections and Branches was a move of fundamental importance in the Institute organization. The members of both Sections and Branches multiplied quickly and, with this, began the really rapid growth in Institute membership.

The importance of this step is illustrated by the fact that there are today 61 Sections and 113 Student Branches. The Sections cover the portions of the United States, Canada, and Mexico that include approximately 85 per cent of the Institute members, who are automatically members of the Sections in which they reside. The expenses of the Sections are borne by the Institute through a remission of a portion of the dues of Section members and by other appropriations. The Sections possess a high degree of autonomy, each having its own by-laws, electing its own officers, and conducting its own meetings.

Student Branches are in each case conducted with the general advice of a counselor appointed by the president of the Institute, and are quite autonomous in character. They provide a means by which, even during his college years, the student may become associated with his profession. The student members receive a subscription to Electrical Engineering and favorable terms of admission to the Institute upon completion of their courses.

The very important part that the Sections and Branches have in the life of the Institute, through frequent meetings for the presentation and discussion of papers, is illustrated by the fact that in the year ending April 30, 1932, they sponsored a total of 1,632 meetings having a total attendance of 160,000. Studies are constantly being made of means to strengthen the Sections and Branches and increase the scope of their already wide activities. This sectional organization has been of inestimable help in providing broader opportunities for the development of engineers through the exchange of experience and through inspiring contacts with eminent members of the profession and in the general development of the electrical arts and of the Institute. Provision is made for a conference of delegates of the Sections and Branches at each summer convention; out of these conferences have come many suggestions of value for carrying on and broadening the activities of the Institute.

Always on the alert to adjust the organization to changing conditions, the board of directors in 1919 appointed a committee on development to consider, among other things, ways and means of increasing the service rendered by the Institute to its members. As a result of the committee's recommendations in order to provide a closer relationship between the Institute and its Sections and Branches, the area of the United States and Canada covered by the Institute was divided into 10 districts and the number of vice-presidents was increased to 10, one for each of the districts. These district organizations keep in very close contact with the Sections and Branches in their areas and form a needed link in the geographical organization of the Institute for the most effective coördination and extension of its activities.

Committee Organization

It is interesting to note that the committee organization which is such an important feature of the Institute's activities began very early in the Institute's history. At the second meeting of the council on June 3, 1884, the following standing committees were appointed:

Dynamo electric machines
Telephones
Telegraph
Arc lamps
Incandescent lamps
Prime motors and transmission of power
Electric railways and signals

Underground and submarine cable work
Electrochemistry and metallurgy
Voltaic batteries, galvanometers, and measurements
Secondary batteries

This list is significant as indicating the scope of the art and its recognized divisions at that time and as representing an early precedent for our present technical committees.

In these first days there was no recognition of specific committees in the rules of the Institute and, generally speaking, these committees like the other early committees were short lived, the committee organization changing from year to year. However, prior to 1900 there had emerged certain committees of a permanent character, including the committee on meetings and papers, committee on membership, and board of examiners. Of interest also among the committees of the early days are the committee on finance, building and permanent quarters, the editing and library committee, the committee on standardization, and the committee on units and standards.

In any association of the character of the Institute, committees of members are sure to carry a very important part of the activities, and it is not surprising that with growth there should have developed as a permanent part of the organization, a large number of committees: specifically, 18 technical committees, each dealing with some branch of the electrical art, and 25 general committees. Beginning with the transmission committee appointed by President Scott in 1902, the technical committees have increased in number and in range of activities to include the discussion and the stimulation of all branches of electrical development. Of the general committees, one group deals with questions involving management, including the executive committee, committee on coördination of Institute activities, board of examiners, finance committee, headquarters committee, the committees on membership, transfers, publications, and technical program. Some of these committees deal with general questions of policy, including the Institute policy committee, committee on legislation affecting the engineering profession, and the committee on code of principles of professional conduct. Other committees deal with relations to other organizations and with the award of medals and prizes. Other important committees are those devoted to the activities of Sections and of Student Branches.

It is naturally out of the question in this brief review to discuss or even to outline the scope of all of these numerous committees. This important phase of the Institute's activities and the way in which the organization has developed and been modified to meet changing conditions is well illustrated by a brief discussion of the form of organization devoted to one of these important matters, namely, standardizing work. The first committee dealing with standardization was appointed in 1889 to prepare a table of standard wire sizes. Subsequent temporary committees from time to time carried out the fundamental work of establishing standards of performance for electrical machinery, leading to the establishment in 1907 of a permanent standards committee to carry on this work. This committee developed rapidly in the scope and importance of its work. Moreover, with the growing interest of other organizations in engineering standards, the Institute took the lead in 1918 in promoting the organization of the American Engineering Standards Committee (now the American Standards Association) to bring about the closer coördination of the standard work of various organizations. The development of the A.S.A. has led to the organization in 1931 of the Electrical Standards Committee, in which the members of the A.S.A. most directly involved in electrical standards closely coöperate, and to whose auspices have been transferred a considerable part of the work formerly done solely under the auspices of the A.I.E.E. standards committee.

Another phase of this activity is the relation of the Institute to international standardization. From the first, the Institute took an important part in international electrical congresses and in 1904 the International Electrical Congress in St. Louis was held under its auspices. An outcome of this congress was the International Electrotechnical Commission, which was represented in this country by a committee of the Institute established in 1907. Subsequently, the membership of this committee was broadened to include representatives of other interested organizations and in 1931 its sponsorship was transferred to American Standards Association.

These variations in organization arrangements illustrate the traditional point of view of the Institute to be ready to take the initiative in undertaking new activities when an evident need develops, yet retaining a flexibility for the modification of these arrangements and closer coöperation with other organizations as this becomes desirable.

Relations With Other Organizations

Realizing that for the broad development of engineering, and to take a proper place in the general activities of the country, it is not sufficient for the electrical engineer to work solely with those of his own group, the coöperation of the Institute with numerous other organizations always has been recognized as desirable. This is illustrated by many other features of the organization, it being represented on 27 engineering, scientific, and research bodies, several of which it aided in founding; through these, it takes part in numerous activities involving a wide range of engineering, scientific, and research projects of public importance. In the American Engineering Council it coöperates with representatives of 20 engineering organizations in the study of public questions that are largely engineering in their nature or are of particular interest to the engineer. With 3 other national engineering societies, the American Society of Mechanical Engineers, the American Society of Mining and Metallurgical Engineers, and the American Society of Civil Engineers, it appoints representatives who together constitute the United Engineering Trustees, Inc., an organization formed for the purpose of holding title to and administering the Engineering Society Building, a number of endowment funds, and other property.

This bringing together under one roof of the largest national engineering societies has been an important factor in stimulating the development of close co-operative relations between them. This joint organization also maintains the Engineering Societies Library, a free public reference library of more than 140,000 volumes, including many rare and valuable books. Through this relationship and also by direct appointment, the Institute participates in the activities of the Engineering Foundation, which was founded in 1914 by Ambrose Swasey "for the furtherance of research in science and in engineering and for the advancement in any other manner of the profession of engineering and for the good of mankind."

Others of the 27 organizations upon which the Institute is represented might be mentioned, such as the National Research Council, the American Association for the Advancement of Science, and the Engineers' Council for Professional Development. However, sufficient has been said, I believe, to illustrate fully the breadth and importance of these relations with other organizations.

As to the Future

Embarking on the second half of the Institute's century of progress we are witnessing a time of rapidly changing conditions affecting both the individual and society as a whole. It is impossible, of course, to predict what further changes in our form of structure may develop as we enter upon the years ahead. However, one cannot review the history of the Institute's organization as we have just done, without being impressed with the flexibility it has shown in adapting itself to changing conditions, and we may be confident that this will continue to characterize the Institute in the future. As social, governmental, and economic conditions continue to change we may be assured that under the continued wise direction of its officers, its board of directors, and those in charge of the various geographical subdivisions and committees, the Institute's organization will be quickly modified and expanded to meet each new demand and to take advantage of each new opportunity for service.

A Group in Attendance at Past-President's Luncheon, Swampscott, Mass., June 28, 1923

Calvert Townley 1919-20 · Dugald C. Jackson 1910-11 · Paul M. Lincoln 1914-15 · Carl Hering 1900-1 · F. L. Hutchinson SECRETARY

E. W. Rice, Jr. 1917-18 · Charles F. Scott 1902-3 · William McClellan 1921-22 · John W. Lieb 1904-5

A. W. Berresford 1920-21 · Harris J. Ryan PRESIDENT ELECT · Charles P. Steinmetz 1901-2 · Frank B. Jewett 1922-23 · Comfort A. Adams 1918-1919

Ralph D. Mershon 1912-13 · T. Commerford Martin 1887-8 · Elihu Thomson 1889-90 · A. E. Kennelly 1898-1900

Telegraph Men Founders of the A.I.E.E.

By Donald McNicol, Fellow A.I.E.E.

Of the 25 men who signed the original organization call, 21 were in the telegraph business, as were also the Institute's first 2 presidents, 2 of the initial vice-presidents, and 4 of the initial managers.

PRIOR TO the formation of the American Institute of Electrical Engineers several electrical societies were operating locally in the large cities. The members of these local groups were engaged in the telegraph business, employed as teachers in colleges, and some were dabblers in electrical experiments.

The need for a national organization developed 6 or 8 months in advance of the opening of the International Electrical Exhibition held in Philadelphia, Pa., in 1884. In the April 15, 1884, issue of *The Operator* (the principal American electrical journal of that time) appeared a "call" for the formation of a national electrical society. One paragraph of the announcement read: "An International Electrical Exhibition is to be held in Philadelphia next autumn, to which many of the famous foreign electrical savants, engineers, and manufacturers will be visitors, and it would be a lasting disgrace to American electricians if no American electrical national society was in existence to receive them with the honors due them from their colaborers in the United States."

The American societies of civil, mechanical, and mining engineers had been in existence for some years, but apparently it required the spur of visitation from abroad to prompt the "electricians" to undertake the formation of a national society, with headquarters in New York.

In the call that was sent out another paragraph read: "It is proposed to make electrical engineers, electricians, instructors in schools and colleges, inventors and manufacturers of electrical apparatus, officers of telegraph, telephone, electric light, burglar alarm, district messenger, electric time and all companies based upon electrical inventions, as well as all who are disposed to support the organization for the common interest, eligible to membership."

The call was issued for a meeting to be held in the rooms of the American Society of Civil Engineers on May 13, 1884. Those who subscribed their names to the invitation were:

F. W. Jones, electrician, Bankers and Merchants Telegraph Co.
George B. Prescott, telegraph electrician.
George A. Hamilton, electrician, Western Union Telegraph Co.
Gerrit Smith, electrician, Western Union Telegraph Co.
E. A. Leslie, superintendent, Baltimore and Ohio Telegraph Co.
Norvin Green, president, Western Union Telegraph Co.
A. W. Dimock, president, Bankers and Merchants Telegraph Co.
W. J. Johnston, publisher, *The Operator*, a telegraph journal.
Stephen D. Field, electrician, Commercial Telegraph Co.
P. B. Delany, electrician, Multiplex Telegraph Co.
G. V. B. Frost, superintendent, American District Telegraph Co.
George B. Scott, superintendent, Gold and Stock Telegraph Co.
C. H. S. Small, assistant supt., Gold and Stock Telegraph Co.
C. L. Buckingham, counsel, Western Union Telegraph Co.
J. H. Bunnell, manufacturer of telegraph instruments.
W. C. Behrens, commissioner of underground wires.
E. A. Calahan, secretary, Standard Multiplex Telegraph Co.
Thomas A. Edison, inventor.
Theodore Mace, agent, Electrical Supply Co.
Thomas R. Taltavall, telegrapher.
L. G. Tillotson, manufacturer of telegraph apparatus.

In addition to these telegraph men there were 4 other signers, namely: P. H. Vander Weyde, president, New York Electrical Society; Rowland R. Hazard, President of the Grammer Electric Company; N. S. Keith, electrical engineer; C. O. Mailloux, electrical engineer.

Prior to the general meeting of May 13, a meeting of the signers of the call was held in the rooms of the A.S.C.E., on April 15, 1884. At this meeting also were present: Joseph P. Davis, vice-president of the Metropolitan Telegraph and Telephone Company; W. A. Hovey, president of the Merchants Electric Light Company, Boston; W. H. Eckert, general superintendent of the Metropolitan Telegraph and Telephone Company; George L. Beetle, Western Electric Company; and T. H. Delano, publisher of *The Electrical Review*.

At the meeting of May 13, a set of rules for the management of the Institute was adopted, which, in principle, are those that still exist. Norvin Green, president of the Western Union Telegraph Company, was elected the first president of the A.I.E.E. N. S. Keith was made secretary, and R. R. Hazard, treasurer. The vice-presidents elected were: A. G. Bell, Charles D. Cross, Thomas A. Edison, George A. Hamilton, Charles H. Haskins, and Frank L. Pope. The Managers elected were: Charles F. Brush, W. H. Eckert, S. D. Field, Elisha Gray, E. J. Houston, C. L. Hillings, F. W. Jones, George B. Prescott, W. W. Smith, W. P. Trowbridge, T. N. Vail, and Edward Weston. Others present at this meeting included Brig.-Gen. C. H. Barney, George S. Bowen, and Isaac Trumbo the latter from San Francisco, Calif.

A year after the Institute was organized Ralph W. Pope, who had been electrician of the Western Union Extension Telegraph, became secretary, continuing in this position until the time Mr. F. L. Hutchinson became secretary.

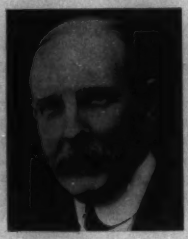
Following 1884, while the electric light, electric railway, telephone, and other electrical industries were growing to maturity, telegraph men continued to exercise influence in shaping the destiny of the Institute. So widely was this recognized that 20 years after the organization of the Institute, at the time Mr. Andrew Carnegie contributed upward of a million dollars toward the construction of the present headquarters building at 33 West 39th Street, New York, he said to Secretary Pope: "Well! the telegraph boys will now have a comfortable place to meet." Mr. Carnegie, himself, was an ex-telegrapher.

The Work of the Institute in Standardization

By A. E. Kennelly, President A.I.E.E. 1898–1900

An historical outline of the standardization activities of the A.I.E.E. is recorded in this article by a past-president who was chairman of the Institute's first standardization committee and who continuously since the appointment of that committee has been actively engaged not only in the standardization work of the Institute, but also in international standardization of electrical units.

THE American Institute of Electrical Engineers has had a remarkable history of standardization activities during the half century that has intervened since its founding in 1884. These activities may be divided into 3 categories: (1) work on units, standard definitions, and nomenclature relating to basic sciences underlying electrical engineering, beginning in 1890; (2) work on similar projects relating to applied science, engineering, and technology, beginning in 1898; and (3) work on projects relating to production and manufacture connected with electrical engineering, beginning in 1920. It is the purpose of this article to offer a brief outline of those activities.



First Recorded Action

The first action of the Institute in relation to standard units occurred on June 17, 1890 (v. 7, p. 89–90[1]) when Prof. F. G. Crocker offered a resolution "that the name of Henry should be given to the practical unit of self-induction." This resolution was adopted and a committee was appointed to report upon the recommended magnitude of the unit. The committee reported January 20, 1891 (v. 8, p. 31) in favor of the magnitude in the practical electromagnetic unit series, *i. e.*, 10^9 c.g.s. magnetic units of inductance, a magnitude already known as the "quadrant," or the "secohm." It is thus interesting to notice that the first standardization recommendation of the Institute was in favor of the name "henry" for the practical unit of inductance.

The Units and Standards (U.&S.) Committee

About the same date (June 1891) the Institute appointed its first standing committee on standardization—the committee on "units and standards." The members of this committee were: A. E. Kennelly, *chairman*, F. B. Crocker, W. E. Geyer, G. A. Hamilton, and G. B. Prescott, Jr.

The U.&S. committee made its first report on June 20, 1891, suggesting that the Institute should recommend to the next International Electrical Congress (Chicago 1893) 4 practical electromagnetic units as follows:

1. A practical unit of magnetomotive force equal to $^1/_{4\pi}$th ampere turn.
2. A practical unit of magnetic flux equal to 10^9 c.g.s. magnetic units
3. A practical unit of flux density equal to 10^9 c.g.s. magnetic units per square centimeter.
4. A practical unit of reluctance, in conformity with units 1 and 2.

It was suggested also that appropriate names should be assigned to these units; but no names were offered. The report was forthwith accepted by the Institute (v. 8, p. 536).

The Institute had also appointed a "standard wiring table committee," to assign the linear resistance of standard-conductivity copper wire of British and American gauges (B.W.G. and A.W.G. or B.&S.) and at standard temperatures (20, 50, and 80 deg C). The personnel was F. B. Crocker, *chairman*, G. Duncan, W. B. Geyer, A. E. Kennelly, G. B. Prescott, E. W. Rice, Jr., M. P. Roberts, H. J. Ryan, W. Stanley, Jr., and S. S. Wheeler. The committee presented a report in 1893 (v. 10, p. 21–5), and prepared a wire table (v. 10, opposite p. 668) part of which is reproduced on the next page.

International Electrical Congress, 1893

A committee also was appointed to prepare a provisional program for the chamber of delegates of the forthcoming International Electrical Congress of Chicago (1893) in regard to units, standards, and nomenclature. Its personnel was: Carl Hering *chairman*, W. A. Anthony, and A. E. Kennelly. The committee reported in January 1893, including the U.&S. committee report of June 1891 referred to previously (v. 10, p. 1–16).

The Chicago congress voted against adopting magnetic units in the practical series, and recommended the retention of the magnetic units in the c.g.s. system, for the present without names. However, the congress adopted the name "henry" for the practical unit of inductance, at the value of 10^9 c.g.s. magnetic units. It also drew up specifications for the practical unit standards under the name of "international electrical units."

In view of the actions of the Chicago congress with respect to magnetic units, the U.&S. committee of the Institute brought in a report November 15, 1893 (v. 11, p. 48–9), recommending the Institute's provisional adoption of the following 4 names for c.g.s. magnetic units; "gilbert" for magnetomotive force, "weber" for flux, "oersted" for reluctance, and "gauss" for flux density. At the first reading, the report was laid on the table; but at a subsequent meeting, on March 21, 1894, the report was re-

1. All bibliographic references refer to A.I.E.E. Transactions.

considered (v. 11, p. 124) and, after discussion, was provisionally adopted (p. 132).

The U. & S. committee also recommended to the Institute that the United States Congress be urged to pass a bill for legislative action on the international series of electrical units adopted by the Chicago electrical congress (May 1894, v. 11, p. 189–90). This resolution was adopted.

In 1894, differences of opinion presented themselves among the members of the Institute as to the meaning of the term "inductance." With a view to securing international agreement on the definition of this term, the U. & S. committee consulted the Institution of Electrical Engineers in London, the Société Française des Electriciens in Paris, and the Elektrotechnischer Verein also the Physikalisch-Technische Reichsanstalt in Berlin. On the basis of the replies received, the U. & S. committee recommended that the Institute should adopt the term "inductance" as meaning a coefficient of induction, with symbol L. The report was adopted May 1894 (v. 11, p. 253–60). The corresponding present definition of the term "reactance" then proposed by Doctor Steinmetz, also was adopted forthwith.

In December 1894, the U. & S. committee reported to the Institute (v. 11, p. 827–9), citing the act of Congress H.R. 6,500, legalizing, in the United States, the international electrical units adopted by the Chicago congress.

Standards of Luminous Intensity

On January 19, 1897 (v. 14, p. 90) the U.&S. committee recommended to the Institute that the amylacetate Hefner-Alteneck lamp should be adopted temporarily as standard of luminous intensity or candlepower, under standard specifications. The committee recommended also that the Lummer-Brodhun photometer screen be adopted for measuring the mean horizontal intensity of incandescent lamps, the lamp being rotated about its vertical axis at a speed of about 2 turns per second. It was recommended further that the mean spherical candlepower of a lamp should be used as far as practicable.

[Supplement to Transactions October 1893.]

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

COPPER WIRE TABLE.

Giving weights, lengths, and resistances of cool, warm, and hot wires, of Matthiessen's standard conductivity, for both A. W. G. (Brown & Sharpe) and B. W. G.

GAUGES To the nearest fourth significant digit.					WEIGHT.			LENGTH.				RESISTANCE.					
A.W.G.	B.W.G.	Diameter.	Area.	Lbs. per foot.	@ 20° C.	@ 50° C.	Lbs. per Ohm. @ 60° C.	Feet per lb.	Feet per Ohm. @ 20° C.	@ 50° C.	@ 60° C.	Ohms per lb. @ 20° C.	@ 50° C.	@ 60° C.	Ohms per foot. @ 20° C.	@ 50° C.	@ 60° C.
0000		0.460	211,600	0.6405	13,990	11,770	10,370	1.561	20,440	18,290	15,540	0.00004576	0.00005135	0.00005635	0.00000219	0.00000245	0.00000269
	0000	0.454	206,000	0.6579	13,490	11,350	10,000	1.519	19,910	17,810	15,130	0.00004696	0.00005272	0.00005788	0.00000225	0.00000252	0.00000277
	000	0.425	180,000	0.5488	9,558	8,037	7,074	1.822	17,000	15,200	12,900	0.00005502	0.00006175	0.00006779	0.00000324	0.00000364	0.00000399

Committee on Standardization

Concurrent A.I.E.E. meetings were held in New York and Chicago (January 26, 1898, v. 15, p. 2–32) devoted to the topical discussion of "The Standardization of Generators, Motors, and Transformers," led by F. B. Crocker in New York, and B. J. Arnold in Chicago. As a result of these discussions, the A.I.E.E. council shortly afterward appointed a "committee on standardization" with the following membership: F. B. Crocker, *chairman*, C. T. Hutchinson, A. E. Kennelly, J. W. Lieb, C. P. Steinmetz, L. B. Stillwell, and E. Thomson. The influence of this committee in electrotechnics and engineering has been so important down to the present day that a brief account of its aims should be given here. The policy of the committee originally planned has remained fairly uniform throughout, as an inspection of its various successive reports will show.

The committee sought to avoid all standardization of sizes or dimensions of electrical machinery. It aimed to define and state in as simple language as practicable, the nature, characteristics, behavior, rating, and methods of testing of electrical machinery and apparatus, particularly with a view to setting up acceptance test standards for electrical industry.

The first report of the standardization committee was adopted by the Institute June 26, 1899 (v. 16, p. 255–68); it also was printed in the A.I.E.E. handbook for 1900, p. 124–36. It included the following subject headings: Efficiency, Rise of Temperature, Insulation, Regulation, Variation and Pulsation, Classification of Voltages, Overloads, etc. There was a considerable demand for the report in the industry from the date of its first appearance, and some 900 copies had been distributed by May 17, 1900 (v. 17). A second report of the standardization committee, revised and enlarged was presented at the A.I.E.E. convention in Great Barrington, Mass., June 20, 1902 (v. 19, 1902, p. 1076–91). After 1902, the successive reports of the committee were reprinted under the title "Standardization Rules of the A.I.E.E." When the A.I.E.E. constitution was amended in May 1907, the standardization committee was established as a standing committee of the Institute, and its name was changed to the "standards committee," which it remains to the present day.

International Electrical Congress at Paris, 1900

The units and standards committee recommended to the Institute May 17, 1900 (v. 17, 1901, p. 309–18) that at the forthcoming Paris congress, names should be advocated for 4 c.g.s. magnetic units provisionally adopted by the Institute in November 1893; also the principle of prefixes for them. The committee also recommended that the question of rationalizing them should be discussed. The committee report was adopted for presentation to the congress.

At the Paris congress, the chamber of delegates limited consideration to 2 c.g.s. unit names only: the "maxwell" and the "gauss." The name "maxwell" was assigned to the c.g.s. unit of magnetic flux, Φ, in accordance with A.I.E.E. recommendation; but there was some misunderstanding as to the unit receiving the name "gauss." The A.I.E.E. delegates believed that it had been adopted for flux density, B, as adopted provisionally by the Institute in 1893, and as advocated by them at Paris. They reported to the Institute in November 1900, that the name "gauss" had been adopted for flux density, B (v. 17, p. 543–7); but the official minutes of the congress, published in 1901, showed that the name "gauss" had been assigned to magnetic field intensity, H. In the English text of the congress preliminary report printed in the A.I.E.E. Transactions (v. 17, p. 552) "gauss" for field density was also ambiguous. This accidental misunderstanding led subsequently to considerable confusion in magnetic literature.

Establishment of the U.S. Bureau of Standards

The Institute endorsed in 1901 (v. 17, p. 615) bills then before the U.S. Congress for establishing a national standardizing bureau at Washington, D. C., "for the construction, custody, and comparison of standards used in scientific and technical work." This bureau, created shortly afterward, came to be known as the National Bureau of Standards, and has exerted a marked influence on science, engineering, and industry. Close connection has been maintained between the Institute's committees and the Bureau of Standards.

International Electrical Congress of St. Louis, 1904

The St. Louis congress was notable in the history of the Institute's work of standardization as being the last electrical congress held in America, and as having taken actions in its chamber of delegates that completely changed the procedure of international electrical congresses since 1904, in reference to electrical units and standards.

The congress met September 12–17, 1904, close to the Exposition buildings. The work was distributed under 8 sections, 2 for theory and 6 for applications. There were 3 volumes of transactions, containing 158 papers. The organization was prepared by the Institute. The president was Prof. E. Thomson; honorary vice-presidents: Ascoli, Crompton, Glazebrook, Gonzales, Gray, Lombardi, Perry, and Poincaré; vice-presidents: Arnold, Carhart, Goldsborough, Scott, and Stratton; general secretary, Kennelly; and treasurer, Weaver.

The chamber of delegates, in which 11 countries were represented, decided that it would not be desirable to undertake international standardization by the St. Louis congress. It unanimously recommended, however, that 2 international commissions should be established: (1) to consist of government representatives charged with the legal maintenance of electrical standards in the various

countries, to deal with such units and standards; and (2) to consist of representatives of various national electrotechnical societies, to deal with the standardization of electrical apparatus and machinery. These recommendations were adopted.

Commission 1 later came into operation as International Conferences on Electrical Units in 1905 at Berlin, and again at London in 1908. The last named was attended by government delegates from 24 countries. Important standardization work was accomplished at these conferences in reference to the maintenance of precise standards of legalized electrical units. In pursuance of this work, an international technical committee from the national laboratories of France, Germany, Great Britain, and the United States, met at Washington in 1910.

In October 1933, the Eighth International Conference of Weights and Measures at Sèvres, adopted a resolution assuming the continuation of the London conference of 1908. In that sense, therefore, commission 1 organized at the St. Louis congress of 1904, may be regarded as maintaining a continued existence.

International Electrotechnical Commission

Commission 2 organized at the St. Louis congress later came into operation as the International Electrotechnical Commission (I.E.C.). It was organized in 1905, under the auspices of Col. R. E. Crompton, who was an honorary vice-president of the St. Louis congress. Mr. C. Lemaistre was appointed its general secretary, with offices at 28 Victoria St., London. The first meeting of the I.E.C. was held at London, for organization, in 1906, when Lord Kelvin was elected the first president.

The I.E.C. is maintained by some 25 countries, each of which has a standing national committee with local officers. The work is divided among 18 technical advisory committees, holding meetings from time to time and reporting their decisions at successive general conventions. There have been 19 of these general conventions to date, in the cities of London (1906, '08, '19, and '24), Brussels (1910 and '20), Cologne (1911 and '13), Turin (1911), Paris (1912, '19, and '23), Zurich (1913), Berlin (1913), Geneva (1922), The Hague (1925), New York (1926), Bellagio (1927), and Copenhagen-Stockholm-Oslo in 1930.

The Institute has taken an active share in the maintenance of the U.S. national committee, and after 1908 kept a standing I.E.C. committee the chairmen of which have been F. B. Crocker, E. Thomson, C. O. Mailloux, A. E. Kennelly, D. C. Jackson, and C. H. Sharp. The international presidents have been Kelvin, Thomson, Budde, Leblanc, Mailloux, Semenza, Feldmann, and Enström. There have been 3 honorary presidents: Mailloux, Crompton, and Semenza. Among the advisory committees are those on the rating of electrical machinery, glossary of terms, units, symbols, voltages, etc.

The U.S. national committee of the I.E.C. includes representatives of the Institute, the American Society of Mechanical Engineers, the American Society for Testing Materials, the Electrical Manufacturers Association, several departments of the U.S. government, and the American Standards Association, the secretary of which, Dr. P. G. Agnew, is also secretary of the U.S. national committee of the I.E.C.

The standardization work of the I.E.C. and of its constituent national committees is basically in electrical engineering; however, owing to the close association of steam engines and hydraulics with electric generation, some I.E.C. technical committees deal with fields of mechanical and civil engineering, such as turbines and ratings of rivets.

Since the Bellagio meeting of 1927, the I.E.C. has taken steps to standardize the names and definitions of the c.g.s. magnetic units. Section B of advisory committee No. 1 for nomenclature on "electric and magnetic magnitudes and units" (E.M.M.U.) has held meetings at Stockholm (1930), London (1931), and Paris (1933) at which certain conventions have been recommended for eliminating ambiguity and confusion in international magnetic literature (I.E.C. Documents R.M. 77, 97, and 105). In this undertaking, the aid of the International Union of Pure and Applied Physics has been invoked, through that union's committee on symbols, units, and nomenclature (S.U.N.) which held a meeting at Paris in July 1932, devoted to the same topics.

At the Turin meeting of the I.E.C. in 1911, unanimous agreement was reached on the standard direction of phase advance in vector diagrams, and on the standard direction of inductive reactance in impedance vector triangles ($R + jX$) (v. 30, 1911, p. 2371).

Since 1911, the I.E.C. has been recognized as granting authorization for holding international electrical congresses. No such congresses have undertaken to establish new electrical units.

International Commission on Illumination (Commission Internationale de l'Eclairage)

This international body was the successor of the Commission Internationale de Photometrie, and has national committees in 15 countries. Its first meeting was at Berlin in 1913. Its central office is at the National Physical Laboratory, Teddington, England. Since 1913, the A.I.E.E. has appointed 3 representatives each year to the U.S. national committee of the I.C.I. The last meeting of the Commission was held at Cambridge, England, in 1931.

The I.C.I. undertakes to establish units, standards, and nomenclature in the science and technology of light and illumination. The president of the U.S. national committee is E. C. Crittenden, at the U.S. Bureau of Standards, and the secretary is G. H. Stickney, at Nela Park, Cleveland, Ohio.

American Standards Association (A.S.A.)

This organization, formerly the American Engineering Standards Committee (A.E.S.C.), has been aptly described as a "national clearing house for industrial standardization." It is composed of a

number of engineering societies, manufacturing associations, and operating or consumers associations. Its main purposes are to simplify and standardize production and construction, with the elimination of overlapping, reduplication, and waste. By establishing standards in sizes, specifications, and tests, it enables marked economies to be effected in manufacture and service. The A.E.S.C. was organized in 1919. In recent years, its name has been changed to the American Standards Association (A.S.A). Since 1920, the Institute annually has appointed representatives on the council of the A.S.A. The headquarters of the A.S.A. are in the Engineering Building, New York, N. Y., and its secretary is Dr. P. G. Agnew.

Scientific and Engineering Symbols and Abbreviations

The Institute took part in standardizing engineering symbols and abbreviations in 1926, under the auspices of the American Standards Association. Other sponsoring bodies were the American Association for the Advancement of Science, the American Society of Civil Engineers, The American Society of Mechanical Engineers, and the Society for the Promotion of Engineering Education. The chairman of the section committee was Dr. J. F. Meyer, and the secretary was Mr. P. S. Millar. Nine subcommittees were formed to cover different departments of the work. The subcommittee on mathematical symbols (project Z10f) had 14 members and Prof. E. V. Huntington was the chairman. This work was approved by the A.S.A. in January 1928. For purposes of amplification and revision the original committee is being continued but with some subdivision and reorganization of both scope and personnel.

Standard Definitions of Electrical Terms

The Institute was made sponsor for a glossary of electrical engineering terms, under the auspices of the A.S.A. in 1928. Some 30 scientific and engineering societies and organizations are represented on the sectional committee, the chairman of which is Prof. A. E. Kennelly, and the secretary, Mr. H. E. Farrer. The committee is divided into 18 subcommittees with the following chairmen: Messrs. H. L. Curtis, C. V. Christie, R. C. Sogge, H. E. Ruggles, H. D. James, J. F. Meyer, C. H. Sanderson, J. H. Davis, E. B. Paxton, F. M. Farmer, C. H. Sharp, G. W. Vinal, W. H. Martin, H. Pratt, M. G. Lloyd, and W. Wilson.

The personnel includes a total of about 120 members; including the experts consulted in the work, a personnel of more than 300 members are engaged. The numerical classification adopted was by group, section, and term numbers, designed to correspond with those proposed by the nomenclature of the International Electrotechnical Commission.

The sectional committee brought in a report which was printed by the Institute in August 1932. This report included more than 3,000 terms. The published report is in process of amendment and amplification prior to being submitted for acceptance by the coöperating organizations and the American Standards Association.

Summary

It has been pointed out that almost from its foundation 50 years ago, the Institute has actively engaged in standardization. It has done this through appointing many of its members to service on committees of standardization, and by expending a very appreciable share of its revenue on the publication of the results. It also has fostered many papers and discussions.

The Institute's standardization work may be divided into 3 categories:

1. Work on units, standards definitions, and nomenclature relating to basic sciences underlying electrical engineering.

2. Work on similar projects relating to applied science, engineering, and technology.

3. Work on projects relating to production and manufacture connected with electrical engineering.

These 3 classes of standardization may briefly be called: (1) basic, (2) technical, and (3) manufacturing standardization. Each is so important to the welfare of engineering, that the question of their relative importance to the Institute becomes insignificant.

1. The Institute's basic standardization, relating mainly to the sciences of physics, chemistry, and mathematics, has been carried on in large measure through the International Electrotechnical Commission (I.E.C.) and the International Commission on Illumination (I.C.I.), such work being mostly of an international character. It also has carried on such work through international electrical congresses, and through special committees of its own and allied societies dealing with basic subjects.

2. The Institute's technical standardization, relating to engineering practice, has been carried on largely through its standards committee, which was appointed in 1898 and is still actively at work. It has dealt principally with standard definitions, behavior, and tests of energy transporting and transforming machinery and apparatus, as used in the various branches of electrical engineering.

3. The Institute's share in manufacturing standardization, relating mainly to economical production, has been conducted principally through the Electrical Standards Committee, an organization representing the entire electrical industry, and the American Standards Association (A.S.A.), an organization representing all industries connected with engineering.

It is interesting to observe that the Institute's basic standardization was first in order of development, going back to 1890. Its technical standardization came next, the standards committee having been appointed in 1898. The participation in manufacturing standardization did not take effect until about 1920. There is every reason to expect that the Institute's future will be as closely associated with standardization along all 3 lines, as has been its past.

The Institute and Industrial Standardization

By C. E. Skinner, President A.I.E.E. 1931–32

The Institute's standardizing committee, which has been in existence for 36 of the Institute's 50 years, was the first official group representing designers, manufacturers, and operators of electrical apparatus in a joint effort to arrive at mutual understandings. These cooperative efforts have been continued until today the Institute holds a major place in the formulation and approval of electrical standards in the United States and has an important rôle to play in international electrical standardization.

DURING the 36 years since its conception, the standards committee of the American Institute of Electrical Engineers has rendered a most signal service to American electrical industry and to the world. Brought into being in a spirit of coöperation, then unusual in industry, it has continued as an agency in bringing all parties at interest together in sincere efforts to arrive at mutually satisfactory understandings. Its goal has ever been to reach the ideal and it has uncompromisingly followed this ideal when fundamental principles were at stake. It has always sought to combine the ideal with the practical in its consideration of those problems which have a commercial bearing and which do not permit an exact solution.

A roster of its members through the years includes many names of men known throughout the world for their contributions to almost every phase of the electrical art. A large percentage of the men who have attained the presidency of the Institute have served as earnest working members. Its rules, promulgated from time to time and changed as became necessary with the developing industry, have exerted a profound influence in shaping and guiding the industry, and this influence has extended into all industrial countries. Its example and accomplishments have influenced standardization in many other fields.

On January 26, 1898, at a New York meeting of the Institute, Dr. Francis B. Crocker, then president, introduced a general discussion on "The Standardizing of Generators, Motors, and Transformers." A very spirited discussion ensued, the general idea of establishing standards being highly commended by all who took part. Those participating in this discussion were: E. W. Rice, Jr., W. A. Mosscrop, Robert T. E. Lozier, A. E. Kennelly, Townsend Wolcott, Cary T. Hutchinson, John W. Lieb, Jr., Gano S. Dunn, H. B. Coho, Frank A. Pattison, F. V. Henshaw, N. M. Hopkins, Charles P. Steinmetz, C. O. Mailloux, and Max Osterberg. Simultaneously a discussion was held in Chicago on the same subject; those participating were: B. J. Arnold, a Mr. Meyer, J. R. Cravath, a Mr. Hickok, George A. Damon, and Prof. W. M. Stine. In addition to the discussions at these 2 meetings, a written discussion was communicated to A.I.E.E. headquarters (and published) by Prof. Charles F. Scott.

As a result of this discussion, the board of directors voted to organize a standardizing committee, and the members of the first committee were appointed on March 23, 1898. There is no more outstanding group of men in the Institute membership than that group. With one exception, each has served the Institute as its president, and all have received world-wide recognition in the electrical field. This first committee consisted of the following:

Francis B. Crocker, *chairman*
Cary T. Hutchinson
Arthur E. Kennelly
Charles P. Steinmetz
Elihu Thompson
John W. Lieb
Lewis B. Stillwell

This first committee wisely confined itself to establishing standards of performance for electrical machinery and apparatus, leaving the manufacturer and the user free to secure that performance by any design and construction found desirable. Definitions and nomenclature were a necessary part of its first report. Fundamental units so far as established were accepted as the basis of measurements. This general policy has been adhered to through the years regardless of the many changes in the personnel of the committee.

Bitter Rivalry in Early Electrical Industry

It should be remembered that at the time of organization of the committee, there was intense and even bitter rivalry in the electrical industry. The battle of the systems was still in progress. Different groups advocated different frequencies for the alternating current field. Transmission voltages were undergoing a constant revision and change. No temperature limits were set, and the method of measuring temperature was not fixed. The method of designating rating varied with the product. No established standard for dielectric tests was in force. Methods of measuring efficiency were in a very nebulous state. There was much confusion in connection with methods of measurement and test. Many honest differences of opinion were being debated with great vigor in the various meetings of the Institute. Commercial rivalry resulted in a multitude of terms and specifications used and issued by

individual groups. Frequently users of electrical equipment had no means of comparing tenders from different manufacturers as these often were couched in terms of the manufacturer's own choosing.

This standardizing committee was, therefore, the first official group representing designers, manufacturers, users, and operators to sit around the table and try to arrive at mutual understandings which would provide a common language, and place all engineers, manufacturers, purchasers, and operators on a common and understandable footing.

The Institute's First Report on Standardization

The first report of the original committee was accepted by the Institute at its meeting in June 1899. This report is a remarkable document, bringing together as it did, authoritative statements agreed to by this eminent body of men and their advisers on the major items which since have become the groundwork of all our electrical standardization. This first report dealt with the following subjects:

1. Efficiency.
   (a) Commutating machines.
   (b) Synchronous machines.
   (c) Synchronous commutating machines.
   (d) Rectifying machines.
   (e) Stationary induction apparatus.
   (f) Rotary induction apparatus.
   (g) Transmission lines.
2. Rise of temperatures.
3. Insulation.
4. Regulation.
5. Variation and pulsation.
6. Rating.
7. Classification of voltages and frequencies.
8. Overload capacities.
9. Appendices.
   (a) Efficiency.
   (b) Apparent efficiencies.
   (c) Power factor and inductance factor.
   (d) Notation.
   (e) Table of sparking distances.

This report was not made mandatory in the electrical industry but was recommended for trial. Manufacturers and users alike welcomed this attempt to end the chaotic conditions that previously had existed. Experience gained in application of the standards and further developments in apparatus and methods, showed the necessity of revision. A committee was appointed which, after consultation with manufacturing and operating engineers, presented the first revised report on standardization rules of the A.I.E.E. in June 1902.

The rapidly growing and changing electrical art made revision of the rules necessary from time to time. A second revision was presented in May 1906 and a third in June 1907. By this time, the very great importance and value of standardization became recognized throughout the whole industry and a standing committee with the title of "standards committee of the A.I.E.E." became effective in the constitution June 1907. The scope and work of the committee necessitated increasing the number of members from time to time until in 1922 there were 37 members divided into a number of subcommittees specializing on various subjects. Up until this time the standards rules, as developed by the standards committee and adopted by the board of directors, were published in a single volume. Nine such volumes have been issued, each with certain revisions and additions as were necessitated by experience and by the changing electrical art.

Because of the increased complexity of the standardization work and its extension into many fields, each requiring revision from time to time, it was decided in June 1922 to change the general plan of operation and to organize working committees, including non-Institute members, to deal with specific subjects. These working committees reported their findings to the main standards committee, which had final jurisdiction over the reports. It was further decided that the standards for each subject should be published separately, in each case the standard so published to be complete in itself. This division of the standards into specific subjects has simplified very greatly the process of keeping them revised and up to date. The work has continued until at present there are more than 40 sections of the standards each in separate pamphlet form. Very recently the plan of grouping those of the same general class has been proposed. As revisions now are less frequent, this would make for economy and convenience.

A.I.E.E. Standards Widely Accepted

Because of their intrinsic worth, the A.I.E.E. rules from the first have been generally accepted by all branches of the American electrical industry as the standards governing the performance, method of test, and application of electrical apparatus and equipment. These results were not achieved, however, without a very great amount of discussion, trial, test, and compromise. The difficult subject of rating was discussed, debated, and even fought over for years. It is difficult to determine the exact limitations of the capability of a machine in any given service, and as similar machines often are required to perform in a multitude of different services, the subject of rating becomes very complicated. Many tests were made and many different opinions were debated in the attempt to arrive at a practical solution and agreement on this difficult question. Again, the temperatures that insulating material of various classes will withstand without serious deterioration is almost impossible to evaluate with any exactness. The final figures adopted are the results of many tests in the laboratory and long experience in the field.

The methods of measuring the actual temperature of an electrical machine present many difficulties. Thousands of man-hours have been spent in tests, measurements, and debates on this subject. Even the apparently simple measurement of temperature by thermometer proved a very difficult subject, and rigid rules were required to enable different observers to obtain reasonably consistent results. Measurement of temperature by change of resistance of windings also presents difficulties; and as the re-

sults give the average temperature only, the actual hottest spots never are found by this method.

These difficulties led the standards committee to seek an accurate method of locating and measuring the maximum temperature reached at any point in the windings, particularly of large and important machines and apparatus. This resulted in the development of internal temperature detectors by embedded resistance coils and thermocouples. Again, much experimental work and many debates were required before exact rules and limitations could be agreed to by the various parties at interest. Overload capacities for various services and the method of measuring such capacities is another phase of standards work that required much attention.

Dielectric tests and methods of making them have taken much time and attention, and have required many changes with experience and the changing designs and requirements from year to year. The measurement of test voltages has been the subject of much experimental work by the best equipped laboratories of both America and Europe. The measurement of efficiency has been one of the most difficult phases of the work, and it is only within recent months that the formulation of a test code on this subject has reached a point where it could be submitted for general approval.

International Standardization

The International Electrotechnical Commission, which is the international standardizing agency in the electrical field, was organized largely through the suggestion of Colonel Crompton of England, following a conference of various "nationals" at the St. Louis Exposition in 1904. For a number of years, the A.I.E.E., and particularly its standards committee, operated as the United States representative of the I.E.C. From time to time delegates were sent by the A.I.E.E. to meetings of the I.E.C. in Europe, with the object of bringing about international electrical standardization. If the work of the standards committee of the A.I.E.E. was beset with many difficulties, to these were added many others when international standardization was attempted. These added international difficulties are due to such things as fundamental developments along different lines in different countries; differences in language, difference in methods of administration, and many others. However, considerable progress has been made through the work of this commission so that there is now at least a common language available for the discussion of electrical matters in the various industrial countries. Special credit should be given to the late Dr. C. O. Mailloux and to Dr. A. E. Kennelly, Institute representatives at many international meetings, who were especially active and effective in the organization and in the shaping of the policies of the I.E.C.

Due to the requirements of the constitution of the I.E.C. and the recognized desirability of bringing all American parties of interest into the international work, the United States Committee of the I.E.C. was enlarged to include the National Electric Light Association and the National Electrical Manufacturers Association; later the work was broadened still further and representatives of the American Society of Mechanical Engineers and the American Society for Testing Materials were added to the United States committee membership. With increased personnel, increased funds, and increased enthusiasm, the work of the I.E.C. has gone forward so that there is now agreement in many important matters in all industrial countries in the electrical standardization field.

American Standards Association

Delegates to European conferences of the I.E.C. in the early days frequently were called upon to state which were the authoritative American standards. This question arose from the fact that other groups, such as the National Electrical Manufacturers Association, had adopted certain standards, sometimes overlapping but usually covering a somewhat different field from those promulgated by the A.I.E.E. These questions emphasized the desirability of establishing an authoritative organization composed of the standard making bodies of the United States which would be empowered to pass upon and to certify those standards which had the adherence of all interested organizations and which, therefore, could be considered as truly American standards. The A.I.E.E. through its standards committee was very glad, therefore, to coöperate with the suggestion that such an authoritative body be formed. This brought into being the American Engineering Standards Committee, later designated as the American Standards Association. The A.E.S.C. was organized by appointed representatives of the 4 national societies of civil, mining, mechanical, and electrical engineers, and the American Society for Testing Materials. The original plan of operation, which has been adhered to consistently, provided that the A.S.A. should be a standards approving body and not a standards making body. Its rules provide for an orderly method of ascertaining whether or not a proposed standard is acceptable to all major parties at interest, and if so, giving it the stamp of approval as an American standard. From time to time additional groups have joined the A.S.A. so that it now consists of 37 member body groups made up of technical and trade associations and Federal Government departments.

The following 2 paragraphs regarding the organization and direction of A.S.A. and its relations with coöperating bodies are found in the American Standards Year Book, 1932–33, p. 8:

"The general direction of A.S.A. affairs is in the hands of a Board of Directors made up of nationally known industrial executives, while the final approval of standards that have been duly submitted by technical committees rests with the Standards Council, composed of representatives of all Member-Bodies of the Association. The details of the Association's work are handled by a staff of trained workers, including engineers who have had practical industrial experience."

"Any organization officially coöperating in A.S.A. work is called a coöperating body as soon as it appoints a representative on a technical committee, or on a committee doing equivalent work. About 475 national organizations are officially coöperating in A.S.A. activi-

ties in this way through 2,700 technical experts appointed as their representatives."

Electrical Standards Committee

After much debate and the consideration of many plans looking to a satisfactory method of coöperation with and adherence to the A.S.A., the A.I.E.E. participated with other electrical groups in the organization of an Electrical Standards Committee (E.S.C.) representative of all American electrical industry. The functions of the E.S.C. as outlined recently by its chairman, Charles Rufus Harte, are as follows:

1. Advisory committee to the standards council (of A.S.A.) for the coördination of standardization work in the electrical field under any recognized procedure of the American Standards Association, with the right to determine questions of sponsorship, scope of projects, and the personnel of sectional committees.

2. Sponsor for projects on behalf of the electrical industry.

3. Sectional committee for the electrical industry, under E.S.C. sponsorship (as provided above). In such cases the formulation of standards may be done by the E.S.C. itself, or by delegation to appropriate working committees at the discretion of the E.S.C.

4. The coördinating medium for American participation in international standardization work within the electrical field.

5. Representative of the electrical industry in the case of projects which involve other industrial as well as the electrical industry, to the extent of determining or recommending a sponsor to act for the qualified and interested groups, or, where the interests of the electrical industry do not warrant sponsorship, to recommend the degree of coöperation desirable in the particular project. The vote of the E.S.C. required on such actions is determined by their relation to actions under the previous classifications.

The E.S.C. is therefore the connecting link between A.S.A. and all groups interested in electrical standardization. The A.I.E.E. still maintains its standards committee which develops or passes upon all new standards of specific interest to the Institute group and is the medium for the revision of standards previously adopted by the Institute. New standards originating either within Institute groups or referred to the Institute through E.S.C. are dealt with by the standards committee. When sponsorship is assigned to the Institute, the standards committee becomes the executive group to carry out the coöperative work required in the formulation of the new standard. Standards formulated within the Institute for which "American Standard" status is desired, are submitted to the E.S.C., which in turn makes its recommendation to the A.S.A. in regard to their status as American standards or tentative standards.

The present arrangement for the initiation, the formulation, and approval of electrical standards has been arrived at only after much debate, consideration of the method of other organizations and evolution from the original self-contained A. I. E. E. standards committee. The present scheme of an electrical standards committee representative of all major interest tying in with the work of specific groups, such as A.I.E.E. standards committee on the one hand, and acting as advisory to A.S.A. seems to be the most flexible and satisfactory arrangements yet evolved in the making of American standards. The Institute holds a major place in the formulation and approval of electrical standards in the United States and has an important rôle to play in future international electrical standardization. It has reason to be proud of its standardization work of the past, and the present cordial coöperative arrangements assure a harmonious and satisfactory part in the electrical standardization of the future.

A Group of Prominent Institute Members in 1897

A picture taken at Schenectady, N. Y., September 24, 1897, during the last visit of Lord Kelvin to the United States. Those in the picture, with year of election to the Institute, are: Albert L. Rohrer (A'87, M'88, member for life); George E. Emmons; Charles P. Steinmetz (A'90, M'91, F'12); Prof. Elihu Thomson (A'84, M'91, F'13, member for life); Lady Kelvin; Lord Kelvin (HM'92); Spencer Trask; Ogden Mills; and George Foster Peabody. Between Professor Thomson and Lady Kelvin is Edwin W. Rice, Jr. (A'87, M'88, F'13, member for life); between Lord and Lady Kelvin is seen Eugene Griffin (A'90); between Mr. Trask and Mr. Mills is seen Dana S. Greene (A'93); behind Professor Thomson and to his right is Jesse R. Lovejoy (A'91, M'24, F'13, member for life); behind Mr. Trask and to his right (third row) is Edward M. Hewlett (A'91, F'17, member for life). Five of these members are living.

(Kelvinator Corp. photo)

Early Headquarters of the Institute

By Gano Dunn, President A.I.E.E. 1911–12

A brief account of the early headquarters and meeting places of the A.I.E.E. is related here by a past-president who was a member of the original committee to solicit Mr. Carnegie's financial support for a new Institute building, and who acted as agent in the purchase of the Latimer Clark Library which was presented to the Institute in 1901 by Past-President Wheeler.

IN 1884 we were born in the house of the American Society of Civil Engineers, then a remodeled dwelling in East 23d Street, New York City. This fact and our use of the paternal mansion for some time afterward undoubtedly established the fundamentally friendly relations that have always subsisted between the electrical engineering and the civil engineering societies.

As our meetings grew larger and because in those days they usually were accompanied by experimental demonstrations in the then new electrical art, we began to use the R. Ogden Doremus Chemical Lecture Theater of the College of the City of New York across the way. It was here, as a student of the City College that I first attended Institute meetings under the presidencies of Norvin Green, Franklin L. Pope, and T. Commerford Martin.

When we outgrew the City College accommodations, we held meetings at sundry other places, some good and some bad, until we were invited by the American Society of Mechanical Engineers to share as guests the accommodations of their then new home at 12 West 31st Street, a remodeled fine old brownstone residence.

The rapid growth of the Institute, with its increasing requirements for meetings, which at times conflicted with the meetings of our generous hosts, put considerable strain upon them and upon us; consequently, a house of our own was felt to be necessary, not only for reasons of physical accommodation, but also for reasons of prestige and society pride.

Lieutenant W. D. Weaver, ex-naval officer, electrical editor, and profound scholar, whose god was a book, quietly agitated the question, which took firm hold of the Institute's leaders in the days when Mr. Andrew Carnegie was beginning his munificent gifts of library buildings throughout the country. Through Weaver, Dr. Schuyler Skaats Wheeler, later to become president of the Institute, learned of the projected executors' sale in London of the Latimer Clark Library, then the second most important electrical and scientific library in the world, which Weaver coveted for the American Institute of Electrical Engineers. Wheeler, for whom I acted as agent in the purchase negotiations, bought this precious library, which otherwise probably would have been dispersed, and presented it in 1901 to the Institute.

In order to stimulate the movement for a house of our own, Doctor Wheeler attached the condition that a suitable building be provided for it within 5 years. Carnegie, to whom this celebrated unhoused library strongly appealed, indicated, through private conferences with Weaver, willingness to receive a committee of the Institute to ask for a building that would suitably accommodate the library, provide for its growth, and at the same time serve as the Institute's home for its meetings and other activities.

Doctor Carl Hering, then president, appointed Dr. John W. Lieb, Mr. Gano Dunn, and himself, a committee to wait on Mr. Carnegie and present the case. In this presentation, the committee included plans for restaurant features, which Carnegie did not approve because he said it made the proposed home of the Institute too much like a club, to which latter type of benevolence he was then opposed.

Mr. Carnegie expressed unusual appreciation of the Institute's plans suitably to house the Latimer Clark Library, and he immediately gave us $7,000 for the preparation and publication of a catalog describing the remarkable books it contained in order that the members of the Institute and libraries throughout the country might know its rich resources. With a twinkle in his eye he asked us to come back to him again with a modification of our plans that would leave out the restaurant facilities.

The rest of the story will be told by others—how on our report of the encouragement we had received, Dr. Charles F. Scott, Mr. Calvin Rice, and Mr. T. Commerford Martin conceived and successfully carried out the idea of asking, and how Mr. Carnegie munificently granted the request for a building that would house not only the Latimer Clark Library, but also the libraries of the American Society of Civil Engineers, the American Institute of Mining and Metallurgical Engineers, the American Society of Mechanical Engineers, and the American Institute of Electrical Engineers, all in one great building that would be a common home for these and other engineering societies, contributing by their jointure, increased respect, authority, and national usefulness to the engineering profession as a whole.

[EDITOR'S NOTE: In Past-President Scott's contribution to this issue may be found an account of the details accompanying the construction of the Engineering Societies' Building. The building was dedicated April 16 and 17, 1907, although a few meetings already had been held in the auditorium.]

Some Major Events in the Life of the Institute

By Comfort A. Adams, President A.I.E.E. 1918–19

Personal reminiscences of some major events in the life of the Institute by a past-president whose active participation in Institute affairs began 30 years ago and who, on the basis of that experience, ventures some criticisms and suggestions.

UNFORTUNATELY, or perhaps fortunately for those who are reading these reminiscences, my memory of the events involved is lacking in detail; in other words, this record will be one of major events without much of the scenery that might add considerably to the interest of the story.

I joined the Institute as an Associate Member just 40 years ago, as a young instructor in engineering. For the first 10 years I took very little part in the affairs of the Institute except to attend an occasional meeting. My earliest memory of any important event was the presentation of my first paper which was entitled "The Heyland Machine as Motor and Generator," in May 1903. This paper was the result of a long summer's work in the laboratory, and apparently it marked the demise of the Heyland machine, at least as far as the United States was concerned. Perhaps the treatment was too thorough. In any case, the study had been a very interesting one and one in which I was so absorbed at the time that I could not appreciate the lack of interest on the major part of the audience. My chief recollection of the discussion was a somewhat caustic remark by President Scott, who was presiding, to the general effect that a college professor was trying to tell all he knew about the subject. In those days papers were less numerous and there were no restrictions as to the time of presentation.*

At the annual convention of 1905 at Asheville, I presented what was probably my best Institute paper, entitled "The Leakage Reactance of Induction Motors With Special Reference to Design." At least this paper attracted more attention and received more recognition on both sides of the Atlantic than any of the others, and I have every reason to believe that it was a substantial contribution to the science of induction motor design. In connection with the discussion of this paper I remember distinctly the criticism of some of the designing engineers to the effect that the methods outlined were all right for a college professor, but too cumbersome for the designing engineer. These criticisms, however, were completely canceled in my own mind by the generous approval of Doctor Steinmetz who said in effect that the designing engineers would have to use more thorough methods of analysis in the near future. From this time on I not only attended most of the annual conventions, but also began to participate actively in Institute affairs.

Although I presented later a considerable number of other papers which were received favorably, they do not stand out quite so vividly in my memory as the earlier ones mentioned. Moreover, the Institute itself began to mean so much more to me than just a place to read and discuss papers, however interesting and valuable that part of the Institute activities may be. I began to feel myself a member of a large family and to count the friendships made during that period among the happiest of my whole career.

Early Standardization Work

In 1910 President Jackson appointed me chairman of the standards committee and this was the beginning of my official participation in Institute affairs. At this point it may be interesting to give a brief account of the background of the standardization work of the Institute, as the standards committee had been in existence only 2 or 3 years. Prior to the initiation of this work, there was no accepted definition of the rating of an electrical machine. A motor was labeled 10 hp or a generator 100 kw, largely at the option of the manufacturer, without any accurate definition of what the rating meant. The result was, for example, that motors labeled 10 hp and made by different manufacturers might differ as much, according to our present ideas of rating, as between 10 hp and 15 hp. In fact a common argument of the salesman was to the effect that his motor would carry a larger overload than that of his competitors. On this account the need for standardization was apparent to many of those concerned, and the standards committee of the Institute was organized in 1907.

For several years after my first connection with this committee, I was either chairman or secretary and my most active memory of real work for the Institute was in connection with that service. I counted it also a great privilege to have been intimately associated in this work with men like Steinmetz, Lamme, Kennelly, Crocker, Scott, Skinner,

*Past-President Scott's version of this is as follows: "The Meeting notice read: 'May 19. Annual meeting. Announcement will be made regarding the proposed union engineering building and formal action by the Institute will probably be taken. It is expected that letters from some of the past-presidents regarding the project will be read.' There were letters from Edison, Kennelly, Hering, Anthony, Sprague, Thomson, and J. G. White. Resolutions were to be passed. It was to be a historic event. The program opened with 3 papers for which cautionary time signals worked properly for Behrend's paper on alternator regulation and Garfield's on alternator compounding; but the time relay on Adams' paper didn't function and the Heyland motor wouldn't stop. The paper was 50 pages in length. The president was more concerned with birth of the building than with the mortuary exercises that 'marked the demise of the Heyland machine.' Professor Adams' present statement indicates the remarkable restraint of the presiding officer in the suppression of his real feelings."

Hobart, Robinson, Burke, Cox, Merrill, Robins, and many others, the neglect to mention whom means no lack of appreciation of their work.

Although it would be very pleasant to tell more of the very interesting and sometimes difficult work done in the early days of standardization, I understand that 2 other past-presidents (Kennelly and Skinner) have been specifically assigned to discuss 2 different phases of this subject.

In 1912 I was elected as a manager of the Institute and from that time on served as a member of the board of directors for 8 years as follows: for 3 years as manager, for 2 years as vice-president, 1 year as president, and 2 years as junior past-president. If my memory for details were better, I could give some very interesting accounts of some of the good fights we had on the board, but suffice to say that I count these as among the most interesting years of my life.

Although I have served on many other committees of the Institute, the one that stands out most prominently, next to the standards committee, is the Edison Medal committee of which I was chairman for several years.

Growth of American Standards Association

Through my connection with the Institute I became connected with a number of joint activities of engineering societies which came into being within the period of my connection with Institute affairs and which now make up a very important part of our service to the profession.

After a few years of work on the standards committee, it became obvious to some of us that, owing to the inevitable overlapping of the standardization work of the several engineering societies, a coördinating body was necessary in this field. As a result of this conviction, and at the invitation of the president of the Institute, a meeting of representatives of the 4 national societies of civil, mining, mechanical, and electrical engineers and of the American Society for Testing Materials was called for January 17, 1917. At this meeting a preliminary plan of organization was presented, largely the work of Mr. H. M. Hobart, and it is interesting to note that with the exception of scope the present organization of the American Standards Association follows very closely the lines of this original plan.

I was chairman of the organization committee and could tell a long story of the struggles involved in its work, including the removal of fear, petty jealousies, and prejudices from the minds of those involved. Suffice to say that it took nearly 3 years to get the approval of the 5 original societies to a plan of organization for the American Engineering Standards Committee, as it originally was called.

I was first chairman of this committee and often compare in my own mind the small beginnings with the present American Standards Association into which it has developed. Also I have often compared the process of evolution of such a relatively small job of coöperation with that larger job of the coöperation of the nations of the world, which cannot go on much longer without a really effective mechanism of coöperation. My work in connection with the organization of this movement was one of the most instructive activities of my whole career, and I could easily expand in my reminiscences thereof, but I understand that past-president Skinner has been assigned specifically to that task.

Joint Engineering Activity in the World War

A very important though transient joint activity was in connection with the great war. The offer of the services of the engineering societies to the government was accepted by President Wilson who appointed as members of the general engineering committee of the advisory commission of the Council of National Defense, 2 representatives of each of the 4 principal national engineering Societies, these representatives being in every case presidents and past-presidents.

This committee started out under the chairmanship of Dr. Hollis R. Godfrey, who had drawn up very comprehensive plans for the mobilization of the industrial and economic life of the United States during the war. Although this plan was marvelous in its comprehensiveness, and would have been wholly satisfactory from Mr. Stalin's point of view, it was altogether too idealistic and comprehensive to be introduced overnight in a country with our traditions.

After considerable discussion we decided to look for some more limited and feasible scheme of serving the government and in June I presented a plan which was the outgrowth of my experience in standardization. At this time Dr. Godfrey resigned as chairman of the committee and I was elected in his place. As space does not permit a description of this plan, I will merely say that it was presented to the Council of National Defense, that parts of it were put into force, and that just before the close of the war General Goethals started to put other provisions of this plan into effect as far as the government end was concerned.

One of the most interesting problems presented to the General Engineering Committee was in connection with the manufacture of anchor chain, the production capacity for which in this country was utterly insufficient for the needs of the Emergency Fleet Corporation. This problem was solved largely through the generosity and coöperation of the General Electric Company by the development of a cast steel anchor chain which was distinctly superior to the old wrought iron hand-forged chain, and which could be produced rapidly in any desired quantity.

Another activity that was the outgrowth of the General Engineering Committee was the application of electric welding to the shipbuilding program. In this connection the Emergency Fleet Corporation requested the organization of a special welding committee with myself as chairman. This committee was in existence a little more than one year; and although it did not exactly revolutionize the welding industry, it saved the government at least a million dollars in the Hog Island program alone and also succeeded in developing an appreciation of research work in welding as well as a spirit of coöperation

throughout the welding industry. This spirit and appreciation have been continued through the medium of the American Welding Society and its research branch, the American Bureau of Welding, both of which were the direct outgrowth of the welding committee of the Emergency Fleet Corporation.

Other Joint Engineering Activities

Another joint activity of the engineering societies is the American Engineering Council which takes care of the nontechnical service engineers can render to the country. Herbert Hoover was the first president of the council and I was a member during its early years.

The joint activities of the engineering societies in the research field are handled in part by the Engineering Foundation and in part by the engineering division of the National Research Council. These 2 organizations are closely allied; in fact, the Engineering Foundation helped materially in the financial support of the engineering division of the Research Council for many years. I was chairman of the engineering division from 1919 to 1921.

The John Fritz Medal Board is made up wholly of past-presidents of the engineering societies. I served as secretary of the board for one year and as president for one year and awarded the medal to Orville Wright.

I have described briefly these joint activities not only because my participation therein resulted directly from my connection with the Institute, but also because they constitute a rapidly increasing portion of the services of the Institute to the engineering profession.

Some Criticisms and Suggestions

If I were asked to criticize the activities of our engineering societies, I certainly would present as my first and major criticism the general messiness of their organization and a serious lack of coöperation resulting often in serious delays in important movements. As a matter of fact, attempts have been made on several occasions during the past 15 or 20 years to reorganize our engineering societies along the lines of the more consistent and rational system employed by our German colleagues.

It is easy, of course, to explain how our present organization grew up in the mushroom fashion, and the coöperative or joint activities mentioned have been designed to reduce the overlapping and confusion of effort in fields where the confusion was so great as to make it absolutely necessary. However, there still remains a considerable number of overlapping activities resulting not only in duplication of effort and inefficiency, but also in a situation that makes it necessary for many engineers to become members of a large number of societies. It would be easy to go into detail on this subject, but this is hardly the place to do more than mention it.

There is one very delicate subject involving not only the affairs of the Institute but of other engineering societies, which I approach with considerable diffidence, namely, the corporation influence in the conduct of the work of these societies. From time to time outsiders and sometimes insiders have criticized the administration of our engineering society affairs on this basis. It just happens that I have probably had as good an opportunity as any to know what these influences have been; and I am glad to put on record here the conviction that although at times there were indications of mild efforts on the part of corporation representatives to modify our constitution and by-laws so as to make corporation influence more easily applied (for example, in the election of officers), these efforts usually failed and left our Institute as free from corporation bias as could possibly be expected under the existing economic order. As a matter of fact, the number of corporation officials or employees who have any tendency toward bias in this connection constitute an absolutely negligible portion of the Institute membership. Moreover, as I am a member of nearly all of the other engineering societies and am fairly intimate with their administration, I feel sure that the same thing can be said for them. On the other hand, there are some so-called professional societies not included in our "Founder" group of which the same statement could not be made with equal force.

Electrical Engineers and Economic Problems

A very common and long-standing criticism of engineers is to the effect that they are too narrow in their interests and do not take sufficient part in the broader public affairs of the nation. This criticism is no longer valid in anything like the degree that it was 20 years ago. I still think, however, that our own Institute perhaps has been peculiarly lacking in this respect, particularly if we are to judge by the contents of our Transactions. These same Transactions present a wonderfully fine record of the scientific and technical development of electrical engineering; but as compared, for example, with the *Proceedings* of the American Society of Mechanical Engineers, they are distinctly lacking in papers or addresses dealing with the broader and even more important economic and social problems.

It is a fact often pointed out that the training of the engineer is such as to develop the habit of sound and unbiased logic. This is particularly true in the case of the electrical engineer whose problems are solved more often by analytical methods of a fairly scientific type than is true of engineers in any other branch. Assuming this to be the case, there is no reason why this same type of unbiased logic should not be applied by the electrical engineer to the solution of the broader problems mentioned.

My presidential address delivered in June 1919 took for its subject "Coöperation"; in the light of recent events it may be of interest to quote one paragraph:

> "I do not propose any revolutionary program, but merely the hastening of the natural evolutionary development by the application of a little perspective and common sense. This does not involve altruism except in so far as a vision reaching somewhat beyond the end of one's nose may be considered altruistic. It is merely a step forward, a step of progress, which may prevent our being forced into some revolutionary stride which is doomed to failure and can mean only destruction and disaster as long as it endures."

A Century of Progress in 50 Years

By E. W. Rice, Jr., President A.I.E.E. 1917–18

Although now celebrating only the fiftieth anniversary of its founding, the Institute "has a record of accomplishment that would have done justice to a life of 100 years."

IT does not seem possible that the Institute is only 50 years old. It has a record of accomplishment that would have done justice to a life of 100 years. So the golden milestone reached this year affords a natural occasion for noting the remarkable growth and the profound progress which have come to pass since the A.I.E.E. was founded.

Fifty years ago the electrical industry was a very young infant, indeed. Yet so lusty was it that the enthusiastic pioneers of the day thought that electricity deserved an exhibition all its own. Philadelphia seemed a fitting place and therefore, under the auspices of the Franklin Institute, founded by Benjamin Franklin, the patron saint of electricity, the first all-electrical exhibition of all time was celebrated there in the year 1884.

Only a few years before, in 1876, at the Centennial Exposition held also in Philadelphia, I saw for the first time an electric light and an electric motor. It was probably the first time in the United States that the electric dynamo was shown in operation to produce light and power. Aside from the electric telegraph, which was an important commercial electrical activity even in 1876, a few dynamos used for electroplating, and batteries for the operation of electric bells, constituted about all there was to be seen of the electrical industry at that time.

A year or so later, Charles F. Brush, in Cleveland, started the manufacture and sale of his arc lighting system. Elihu Thomson, in Philadelphia, invented his famous 3-coil arc dynamo with automatic regulation; and in Menlo Park in 1879, Thomas A. Edison produced the first incandescent lamp and the multiple system of electric generation and distribution. Thus, a few years after 1876 (less than a decade, in fact) saw most of the inventions made upon which the present electric power and light industry has been founded.

The years immediately following were so prolific that at the all-electric exhibition of 1884, which I have mentioned, electric dynamos, lamps, motors, and electric measuring instruments of various kinds, the inventions of Edison, Thomson, Weston, and others, were shown by the many manufacturing companies already formed to introduce such products to the public. This exhibition was well attended by an interested and even enthusiastic public.

Bell's electric speaking telephone, first shown in 1876 at the Centennial Exposition in Philadelphia, by 1884 had been adopted rather extensively in large cities, and had become an important factor in the electrical industry.

The electric trolley was, as yet, commercially unknown in 1884. Van Depoele and Sprague, Bentley and Knight, and other inventors were just making their first tentative experiments in the application of electricity to the propulsion of street cars.

While I was personally acquainted with many of the electrical pioneers, Bell, Edison, Brush, Sprague, Van Depoele, Sperry, Weston, Stanley, and others, it was my particular good fortune to be intimately associated with Elihu Thomson. I was educated under him at the Central High School in Philadelphia, and after graduation in 1880, went from Philadelphia to New Britain, Conn., as his assistant, and in 1883 moved from New Britain to Lynn, Mass. In 1884, the year that witnessed the beginning of the A.I.E.E., we were actively promoting the arc light system of Professor Thomson through the medium of the Thomson-Houston Company. This company sent samples of its products to the Electrical Exhibition in Philadelphia, and I had much to do with the exhibit.

It is of special interest to note that at the same time and place, our newly founded American Institute of Electrical Engineers held one of its first meetings. At the very first session at which papers were read, there was a brief discussion led by the late Prof. Edwin J. Houston, on the "Edison effect," the discovery of which had been announced the previous year. Other subjects, at this and following meetings, dealt with underground wiring, the experimental testing of dynamo machines, the patent protection of electrical inventions, secondary battery plants, and telegraphic and telephonic progress. Such discussions, which became constantly more important and profitable, spurred electrical progress.

It was high time that the Institute was founded, as the scattered "electricians," as we called ourselves in those days, needed the inspiration that comes only from association of people of similar interests and like minds. In those early days the pioneers were so busy with their daily work that little time could be spared to attend meetings. However, even if meetings were sparsely attended, the organization formed a nucleus which steadily drew to itself earnest electrical workers in all parts of the country. It became the recognized meeting place, the forum, the clearing house of electrical ideas, and eventually the authority for such standardization, technical and professional, as was needed in a rapidly expanding art.

I believe that the realization of the value of scientific methods perhaps was greater in the electrical industry than in the older and well established enter-

prises. There was a close connection between the universities and technical schools and the electrical industry, even in its earliest days. The novelty and highly technical nature of our problems led those of us who were in charge to draw upon the colleges and universities for graduates trained in such scientific and technical knowledge as then existed. These new, eager, young men were set to work in the engineering and testing departments, and those of special aptitude were given opportunity to assist in the research necessary to a new industry.

History shows that progress often has been dependent upon the energy and genius of some individual. In the future, advances undoubtedly will come in the same way; but we believe that more frequently the best progress will follow the use of organized research based upon coöperative efforts of many men in universities, industrial organizations, and national institutions.

In all this work the A.I.E.E. has occupied a commanding position. This has been true during the past and will continue to be true in the future. I am glad to testify that my faith in the value of the Institute was definitely increased during the term I was privileged to serve as president. The spirit of coöperation and of broad interchange of fundamental knowledge which it has fostered, has been invaluable. In common with other scientific societies, the Institute has inculcated a spirit of unselfish service to its members and to all mankind.

Science is international; its field is the world; information is freely exchanged; there is no tariff on scientific ideas; progress therefore is based upon the contributions of all workers in every civilized land.

I extend my heartiest felicitations to the Institute on this occasion of its golden jubilee. In common with those others who have served as its president, I wish for the institution a long and useful future. May its contributions to the progress of our profession during the next 50 years, if possible, exceed those it has rendered during the half century that is just closed.

A Group of Those Attending the 15th Annual Meeting, Boston, Mass., 1899

Those in the picture are, left to right, bottom row: (?), A. V. Garrett, S. E. Doane, R. W. Pope, W. L. Puffer, C. P. Steinmetz, Elihu Thomson, and W. J. Hammer. Second row: H. E. Clifford, (?), H. Ward Leonard, W. E. Goldsborough, William Brophy, A. E. Kennelly, and E. A. Sperry. Third row: W. L. Smith, (?), W. S. Aldrich, H. J. Ryan, (?), Joseph Wetzler, and (?). Fourth row: C. M. Bigelow, (?), (?), H. B. Coho, (?), W. D. Weaver, G. F. Sever, (?), Louis Bell, (?), and (?). Top row: (?), and A. L. Clough.

The Equation of Electrical Propagation

By M. I. Pupin, President A.I.E.E., 1925–26

Members of the Institute always have been interested primarily in those parts of electrical science that concern the motion of electricity in conductors. Although Kirchhoff and Maxwell formulated the equations of electrical propagation more than 30 years before the founding of the A.I.E.E., it remained for the period coinciding with the life of the Institute for the full meaning of their theoretical achievements to be demonstrated. It seems particularly appropriate, therefore, that on the Institute's 50th anniversary these achievements should be reviewed by one who has had such a large part in applying them and in extending them to long distance telephonic transmission.

THE Semicentennial celebration of the American Institute of Electrical Engineers is a fitting occasion for a review of the many advances which during the last 50 years have been achieved in the science and in the art of electrical engineering. This art, like every art, is long and it will take many a skilled electrical engineering artist to draw a picture that will display adequately these advances in the electrical engineering art. I am not one of these artists; I am only an amateur of this art. Hence, my brief story will confine itself to a description of one only of the many advances on the purely scientific side of electrical engineering during the lifetime of our Institute. This advance relates to the mathematical theory of electrical transmission for telegraphy and telephony.

I cannot introduce my story better than by mentioning briefly the foundations that Faraday and Maxwell laid to the electrical engineering science. We all understand today the full meaning of the laws that Maxwell, summing up the discoveries of Oersted, Ampère, and Faraday, formulated as follows; call them Maxwell's laws:

"The rate of variation of the magnetic flux through any area is proportional to the electromotive force generated by the varying flux along the boundary curve of that area.

"The rate of variation of the electric flux through any area is proportional to the magnetomotive force generated by the varying flux along the boundary curve of that area.

"Flux and force of the same type are proportional to each other in ideal insulators."

An Important Chapter in Electrical History

To the concepts *electric and magnetic flux* is connected one of the most important chapters in the history of electrical science. These concepts were born in the mind of great Faraday, and they were nursed and made strong by the genius of Faraday's most distinguished pupil, Maxwell. According to these 2 prophets of science, electric and magnetic flux represent the electromagnetic energy of the electromagnetic field. Where these fluxes are, there is electromagnetic energy; and the variation of the fluxes in any part of space means that electromagnetic energy is moving from one part of space to another, along the paths mapped out through space by the fundamental laws just quoted. Maxwell's equation of electromagnetic energy propagation shows the way of these paths; but the full meaning of Maxwell's equation of energy propagation was not revealed to ordinary mortals until Hertz published the results of his classical experiments in 1888. At that time our Institute was only a youngster, barely 4 years old; but since then the education of this youngster has grown almost as rapidly as the fame of Maxwell's electromagnetic theory which predicted the motion of the electromagnetic energy through free space. The electrical engineer has today an incomparably deeper understanding of this motion than he had 50 years ago. The young radio art of today is his best interpreter of Faraday's and Maxwell's speedy energy flux. I shall now examine briefly the background of the electrical theory that preceded Maxwell.

Our Institute is an institute of electrical engineers. Its members always were interested primarily in those parts of the electrical science that concern the motion of electricity in conductors. Their interest in the motion of the electric and magnetic flux through free space and through insulators as predicted by Maxwell's theory is of more recent date, and it was stimulated by the modern achievements of the radio art. It is fitting, therefore, that on the occasion of the semicentennial celebration of our Institute a word or 2 be said concerning the history of the achievements of that part of our science which during the last 50 years succeeded in solving several of the theoretical problems of the motion of electricity in conductors, and thus inaugurated a great advance in the telegraphic industries.

Discoveries of Ohm and Joule

One cannot look back to the earliest days of this history without seeing at the very first glance the illustrious names of Ohm and of Joule. The laws

discovered by them are the earliest disclosures of quantitative relations between electrical forces and electrical motions in conductors. The advancement of the electrical science since the discovery of these 2 laws over 90 years ago suggests a more up-to-date terminology in their statement. It can be shown that a change in the terminology of the electrical theory was inaugurated by Maxwell nearly 80 years ago. The principle of conservation of energy, still unknown in the days of Ohm and Joule, suggest the following more modern form of statement of Joule's law:

"The heat energy generated per unit of time by a constant current between 2 points on a linear conductor is equal to the product of the current into the electrical reaction of the conductor."

The term "electrical reaction" which appears in this statement was not known in Joule's time. The word "reaction" is a familiar term in Newtonian dynamics. Electrical reaction is, of course, a force in the overcoming of which the current generates heat. Joule's law makes this force equal to the product of current and resistance; call it *resistance reaction*. But Ohm's law says that this resistance reaction is equal to the difference of potential between the 2 points on the linear conductor. This potential difference is the moving force, or, employing Newton's terminology, we can call it the electrical action; and then Ohm's law can be stated in the following Newtonian form:

"In a constant current between 2 points on a linear conductor the electrical action is equal to the electrical resistance reaction."

It is a small step, only, from this simple case of electrical motion studied by Ohm and Joule to the general case of any electrical motion in the simple circuit consisting of a linear conductor under the action of any electrical forces. The principle of conservation of energy makes it obvious that:

"In every motion of electricity between 2 points on a linear conductor, the sum of electrical actions is equal to the sum of electrical reactions."

Call this *the generalized form of Ohm's law*. The terminology it employs exhibits clearly the similarity between *electrodynamics* and Newtonian dynamics. This similarity was the guiding light to Maxwell when he started out to interpret Faraday.

Ohm's studies which led him to the formulation of his law of electrical motion were confined to the motion of electricity in a simple circuit consisting of a linear conductor in which a constant electromotive force sustained a constant current. The next step in the growth of our knowledge of the motion of electricity in conductors was the study of this motion in complex circuits of linear conductors. This step was made in 1848 when Kirchhoff published his historical essay on the motion of electricity in a network of linear conductors in which constant electromotive forces were impressed upon the various branches of the network. He deduced the following historical formula:

"In every closed circuit of a network of linear conductors carrying constant electrical currents the algebraical sum of the products of the currents into the respective resistances of the branches of the circuit is equal to the algebraical sum of the electromotive forces impressed upon these branches."

This formula often is called Kirchhoff's law. I prefer to call it Kirchhoff's rule. It is a mathematical deduction from Ohm's law. Kirchhoff was using Ohm's language; if he had employed the concepts and the terminology suggested by the principle of conservation of energy, he probably would have called "the products of the currents into the respective resistances of the branches of the circuit" the resistance reactions of these branches; and then he could have stated his rule as follows:

"In a network of linear conductors carrying constant electrical currents the algebraical sum of the resistance reactions in any closed circuit of the network is equal to the algebraical sum of the electromotive actions impressed upon that circuit."

Kirchhoff's "Rule" Reveals Energy Relations

In this form Kirchhoff's rule is not a mere algebraical formula deduced from Ohm's law; it reveals energy relations which Ohm's law does not reveal, and it shows that even in a complex circuit which is a part of the network of linear conductors Newton's law of equality of action to reaction is applicable. It supplies an additional illustration of the similarity of electro-dynamics to Newtonian dynamics.

When Kirchhoff's rule is stated in the form just given then its generalization is obvious. If according to the generalized form of Ohm's law, which I mentioned before, the motion of electricity between 2 points on a linear conductor makes the sum of electrical actions equal to the sum of electrical reactions, then, applying this equality to every branch of a circuit in a network of linear conductors, the following energy relation easily is deduced:

"In every circuit in a network of linear conductors the sum of electrical actions is equal to the sum of electrical reactions."

This relation I call Newton's third law of motion of electricity in a network of linear conductors. To call it Kirchhoff's law, as often is done, is certainly misleading. When Kirchhoff published his rule in 1848 the energy principle was still a stranger among physicists. Kirchhoff was not aware of its existence and he could not at that time translate his rule into the language of this principle. Ten years later, however, he was much wiser, and in his epoch making essay of 1858 he applied correctly Newton's third law to the motion of electricity in a linear conductor. In this essay on the propagation of electrical signals over a telegraph wire suspended high above the ground, he felt his way cautiously and finally he recognized that the sum of the inductance and resistance reaction in every element of the telegraph wire is equal to the potential difference between the terminals of the element. He gave expression to what I have called the generalized form of Ohm's law. Kirchhoff did not call it the law of equality of action and reaction; but it was that, and it led him to the equation of propagation of electrical signals over a telegraph wire. This is the famous telegrapher's equation which ever since that time was the guide of telephone and telegraph engineers. Maxwell's equation of propagation of the electric and magnetic flux through free space is, and it should be, practically identical in form with Kirchhoff's equa-

tion of propagation of telegraphic signals over a telegraph wire. Each one of them results from the actions and reactions in the tiny volume element of the electromagnetic field and each exhibits a propagation of transverse waves, and both give a velocity of propagation that is practically the same as the velocity of propagation of light.

I always wondered how so brilliant a mind as that of the late Oliver Heaviside could fail to appreciate Kirchhoff's essay of 1858. Maxwell mentioned it in 1865 in his communication to the Royal Society in which he announced his great *electromagnetic theory*. Heaviside does not seem to have seen it until much later, and when he saw it he did not hesitate to speak lightly of it. Perhaps he, at one time a telegraphist by profession, was somewhat disappointed that a German professor who knew very little of the telegrapher's art anticipated him in the discovery of the telegrapher's equation.

Maxwell Reduced Relations in Electromagnetic Field to Newton's Law

In my Steinmetz lecture (*Science*, July 10, 1925) I pointed out how Maxwell, a faithful disciple of the energy doctrine, reduced the dynamical relations in every part of the electromagnetic field to Newton's law of equality of electromagnetic actions and reactions, and I said:

"The possibility of describing electrical phenomena in terms of Newton's concepts and language is one of the greatest achievements of Faraday and Maxwell."

In that lecture I laid particular stress upon the actions and reactions with which Maxwell's genius endowed the tubes of flux in insulators and in free space. In my present sketch I have endeavored to lay particular stress upon the law of equality of actions and reactions which control the motions of electricity in conductors. Kirchhoff's equation of propagation over a conducting wire is the crown of the theory of these motions just as Maxwell's equation of propagation is the crown of his dynamics of the electromagnetic flux. Kirchhoff's equation preceded Maxwell's by a few years, but Maxwell's equation of propagation cannot be considered in any sense as an extension of that of his predecessor. The 2 belong to 2 different worlds of electrical science, and Maxwell's world was the new world which Kirchhoff never entered.

It may be of some historical interest to record here that Kirchhoff himself was not aware of any contacts between his mathematical researches in the science of electricity and Maxwell's electromagnetic theory. The following quotation from my autobiography ("From Immigrant to Inventor," p. 233–34) throws some light upon this point:

"Gustav Robert Kirchhoff, the famous discoverer, formulator, and interpreter of the science of spectrum analysis, and the founder of the theory of radiation, was at that time (the winter term of 1885–86 when I was student at the University of Berlin) professor of mathematical physics at the university. He was considered the leading mathematical physicist of Germany. His contributions to the electrical theory occupied a very high place. The most important of these was undoubtedly his theory of transmission of telegraphic signals over a thin wire conductor stretched on insulated poles, high above the ground. It was a magnificent mathematical analysis of the problem, and it showed for the first time that theoretically the velocity of propagation of these signals along the wire is equal to the velocity of light. The university catalogue announced that he was to deliver a course of lectures on theoretical electricity during the first term of my residence at the university. I attended the course and waited and waited, but waited in vain to hear Kirchhoff's interpretation of Faraday and Maxwell. At the close of the semester the course ended and the electromagnetic theory of Faraday and Maxwell was referred to on 2 pages only, out of 200; and the part so honored was not, even according to my opinion at that time, the essential part of the theory. In this respect the lectures were disappointing, but nevertheless I was most amply rewarded for my pains. I never heard a more elegant mathematical analysis of the old school electrical problems than that which Kirchhoff developed before his admiring classes. That was the last course which he delivered; he died in the following year, and was succeeded by Helmholtz as temporary lecturer on mathematical physics."

In 1888, Max Planck, the discoverer of the quantum theory became Kirchhoff's successor. It was tragic that Kirchhoff's life was not spared a few months longer so as to permit him to witness in 1888 the triumph of his favorite pupil Hertz.

Early Engineers Paid Small Heed to Kirchhoff's and Maxwell's Achievements

Fifty years ago when our American Institute of Electrical Engineers was founded the *electrical theory* was practically in the same condition in which Kirchhoff and Maxwell had left it nearly 30 years earlier; but the electrical art had advanced much during the 3 decades following the publication of their epoch making equations of propagation. The transatlantic cable had been laid, dynamos were supplying electric energy for lighting and power, and the telephone was gaining rapidly its well deserved popularity. The engineers who guided these new electrical arts, however, paid small attention to Kirchhoff's and to Maxwell's theoretical achievements. I am inclined to believe that many charter members of our Institute knew the work of these 2 great scientists by hearsay only. It was reserved for the period coinciding with the life of our Institute to demonstrate the full meaning of Kirchhoff's and of Maxwell's equations of propagation.

The radio art describes more eloquently than any pen can do what Maxwell's electromagnetic theory has done for the transmission of speech and music, and even of living pictures across oceans and continents. Every schoolboy knows today that these messages are carried on the wings of the electrical waves the existence of which Maxwell's theory had prophesied 70 years ago. The birth of this radio art is certainly the greatest event in the electrical engineering world that our Institute has witnessed during its semicentennial existence; but here I must leave the thrilling story of this great achievement of electrical theory to some radio scientist whose pen is wiser and more skilled than mine.

Long Distance Telephonic Transmission

I shall pass now to another art which also may be said to have been born during the lifetime of our Institute. It is the art of the long distance telephonic transmission over conducting wires. Just as the radio art is an offspring of Maxwell's equation of propagation so the beginnings of long distance tele-

phonic transmission can be traced to Kirchhoff's equation of propagation over conducting wires. We all know how difficult it was 50 years ago to operate Bell's beautiful invention over distances longer than a few miles. The difficulty seemed insurmountable whenever an attempt was made to carry out this operation over telephone cables. The so-called practical engineer was helpless. Kirchhoff's equation of propagation was ready to teach him, but he did not understand its language. There was one word in the vocabulary of this language that he refused to learn. That word was "inductance."

The telegraph engineer of those days had a holy horror of the so-called "choak coils" in the telegraph line; the telephone engineer inherited that fear, and hence he paid small attention to the apostles of the inductance doctrine. The foremost among these apostles was the late Oliver Heaviside. The beneficent action of inductance was evident in Kirchhoff's equation of propagation, because it starts from the generalized form of Ohm's law which says, that in every element of the telegraph wire the sum of the inductance and the resistance reaction is equal to the action of the potential difference between the terminals of the element. This potential difference is the driving force that overcomes the conservative inductance reaction and the dissipative resistance reaction; hence, the greater the first in comparison with the second, the less energy will the propelled electrical wave lose in its passage over the transmission wire. On this point Kirchhoff's equation of propagation, interpreted in the light of the energy principle, was explicit. There was no great need of eloquent apostles of the inductance doctrine. Kirchhoff's equation of propagation was just as eloquent as any of the later apostles of this doctrine; but there was a need of a theory that could tell the telephone engineer how to design a telephone conductor having a sufficiently high inductance and a sufficiently low resistance. The telephone cable waited anxiously for such a theory. The late Oliver Heaviside, in spite of his veritable flood of mathematical essays advocating high inductance in long distance telephonic transmission, failed to furnish an equation of propagation over conducting wires which could tell the telephone engineer more than Kirchhoff had told him.

It was recognized generally that a new electrical transmission structure was needed and a new equation of wave propagation over such a structure. The writer of this story was fortunate to invent such a structure, and to discover a mathematical theory of wave propagation over it which gave the telephone engineer a trusty guide in all future designs of telephonic transmission conductors having as high an average inductance as may be desired. This theory was first communicated to our Institute 34 years ago, and the epoch making advancement which it inaugurated in the telephonic art is certainly one of the memorable events in the life of our Institute. The new structure, as well known, is a telephone conductor with inductance coils inserted in it at periodically recurring points, the distance between them obeying a rule prescribed accurately by the equation of propagation over such a structure. This equation of propagation was born during the lifetime of our Institute. Those of Maxwell and Kirchhoff were handed down to it from the days when the electrical theory was still young. Our Institute was fortunate to witness during its semi-centennial existence the rise of splendid electrical industries which trace their origin to these 3 equations of electrical wave propagation.

Courtesy *Bell Telephone Quarterly*

"Pupinized" Conductors

The youngest equation of electrical wave propagation that I just mentioned is the parent of what is called in this country "a loaded conductor." When this title was applied to it in a lecture before the faculty and students of the Massachusetts Institute of Technology, 32 years ago, Dr. Henry Pritchett, who was then president of this institution, objected to the title. It reminded him, he said, of an intoxicated trolley car conductor. The audience supported heartily his objection, but nevertheless the title "loaded conductor" still persists in the Transactions of the American Institute of Electrical Engineers. Scientists outside of the United States prefer to call this new telephonic transmission structure a "pupinized" conductor. The process of building such a structure they call "pupinization" in all civilized countries outside of the country where the inventor lives and where his invention has done more good than in all the other countries of the earth put together. I am told by my European friends that the word "pupinization" is popular in Europe not only because it is a just tribute to the inventor, but also because it *denotes* a new theoretical achievement in electrical science and *connotes* a precious characteristic of the structure which is the offspring of this theory.

The new theoretical achievement is the equation of propagation over nonuniform electrical conductors and the precious characteristic of such a conductor possessing a high average inductance is the toroidal inductance coil inserted in it at periodically recurring points. Without the inductance coils having a negligibly small external magnetic field, the high inductance telephonic transmission structure described would lose most of its technical value. The word "pupinization" by connotation tells this story; the words "inductive loading" do not.

Digging in "The Mines of the Motors"

By Frank J. Sprague, President A.I.E.E. 1892–93

Some personal reminiscences of experiences in the electrical industry are recorded in this article by "the father of electric traction" who has dug in "the mines of the motors" for 3 score years. From his courageous pioneering efforts great systems of electrical transportation have grown. It is entirely fitting that these experiences, which are so interwoven in the history of the electrical engineering profession, be recorded on the occasion of the Institute's 50th anniversary by a past-president whose entrance into the profession antedates the Institute by a decade.

IN A reminiscent survey of the modern industrial revolution I am reminded of the prophetic utterances of a former commissioner of patents, Thomas Ewbank, in his report for 1849, the year of the great California gold rush, from which some brief excerpts are given in the following paragraphs. On the subject of "Electric Motors":

"The belief is a growing one that electricity, in one or more of its manifestations, is ordained to effect the mightiest of revolutions in human affairs. In subtlety and power, in excitability, rapidity and intensity of action there is nothing like it. Its complete subjugation may be held as a climax of conquests in art, the apex to ambition in science—so blessed and boundless, so surpassing all anticipation, are the seeming results that must follow. When, in addition to what it is now performing as a messenger—one swifter than those of the gods, and more reliable than the boasted Ariels of poets—it can be drawn rapidly from its hiding place, and made to propel land and water chariots, animate manufacturing mechanisms, become an agricultural laborer and a household drudge of all work, then we may begin to think the genius of civilization is vaulting rapidly toward the zenith."

After citing the experiments with Jacobi's boat, Davidson's first real locomotive, and various industrial applications—all dependent upon the zinc battery and the electromagnetic type of motor—he continued in somewhat pessimistic fashion:

"But these experiments, interesting as they certainly were, have brought no marked results, nor afforded any high degree of encouragement to proceed. It might be imprudent to assert that electromagnetism can never supersede steam; still, in the present state of electrical science the desideratum is rather to be hoped for than expected. Great, however, will be his glory who in the face of these discouragements succeeds."

And then describing the rush for gold, a peroration to which there would be varying reactions in these days of social unrest and business bewilderment:

"There is no wealth but labor—no enjoyments but which derive from it. But, to those who are ambitious of ennobling themselves and really enriching their country, *placers* inexpressibly more precious than any to be found on the Sacramento are invitingly open. Let them dig in THE MINES OF THE MOTORS, and they will bring to light, active, fruitful, and everlasting sources of true opulence."

A score of years passed before Gramme brought out the first commercial dynamo electric generator, and 3 years later, at the Munich celebration of 1873, its vital characteristic of reversibility of function was demonstrated, this laying the foundation of the entire system of the transmission of power by electricity. A year later marked my transition from the life of a country boy to that of an abbreviated naval career, by way of a competitive appointment to Annapolis, and found me tarrying in New York City on my way there. I cite this date because it is so close to that of an epochal discovery, although a decade before the founding of the Institute, and because of many electrical happenings in that period.

The metropolitan population then totalled about 1,700,000. There were no telephones or electric lights, no trolleys or subways, not even an elevated railway except a short section on Greenwich Street. Automobiles, of course, were unknown, and the Brooklyn Bridge was in the early stages of construction. I little dreamed of a new era that would change the face of civilization, and that the use of electricity for industrial power and for vertical and horizontal transportation would later make me a factor in the city's subsequent enormous growth.

Naval education brought many experiences, and helped to mold my character in a fashion that contributed materially to later activities. With something of a flair for mathematics and naval architecture, and especially a love for physics, the department for which was headed by the late Admiral Sampson, I was well placed among the surviving third of my class.

Early Inventions

Following a visit to the 1876 Centennial Exhibition came the beginning of new interests, and later, impressed by the work of Bell, Gray, and Edison, a new telephone was essayed. Disciplined for first attempts, special apparatus was sought from Edison, but unable to supply it he suggested my stopping at Menlo Park on the way home from graduation in June 1878. By this time the creative urge had taken full possession, and in the following 2 years, including a period of duty on the Asiatic Squadron, while also acting as special correspondent of the Boston *Herald*, I was guilty of nearly 3 score of inventions of varied character; most of these are recorded in a much prized "Midshipman's Note Book,"

mixed with professional notes and cruise records. A duplex telephone, pocket phonograph, time fuse, quadruplex and octoplex telegraph systems, a weird motor, means for transmitting pictures by wire, gyroscopic control of the mercury horizon and torpedo direction, an electric pantograph, a multiple telescope, regulation of incandescent lights, water cooling apparatus, and control by variations of pressure on a submerged carbon disk of a ship's engines, to prevent racing with exposed propellers, are indicative of a variety of activities which were a nuisance to my shipmates. Many of these inventions were really worth while, but neither naval duties nor available money made possible their development then.

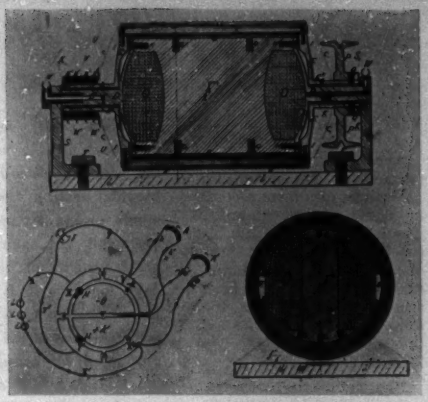
Ordered home for examination in the spring of 1880, a short leave was utilized to experiment at Stevens Institute of Technology (Hoboken, N. J.) with a new type of arc lamp mechanism, and I had the good fortune to meet that famous pioneer, William Wallace of Ansonia, Dr. Henry Draper of New York, and Prof. Moses G. Farmer, then government electrician at the U.S. Torpedo Station, Newport, obtaining from the latter reluctant approval of an attempt to construct a dynamo without a commutator to develop current at a constant potential of 100 volts, a venture that, based upon false premises, soon collapsed.

Detailed for duty to the "Minnesota," a training ship for boys in whose tuition there was little interest, I planned to light the ship electrically by using a dismantled steam pump for motive power, but the loan of a dynamo was refused on the ground of irregular motive power. Soon afterward the ship proceeded to Newport, where in the spring of 1881 I again met Professor Farmer. Here, in the interim of ship duties, the construction of a novel dynamo electric machine was undertaken.

"Inverted" Type of Dynamo and Series-Parallel Control

The characteristics of this machine, involving 2 radical departures, are illustrated in an accompanying diagram. Up to this time all dynamos comprised an external magnetic field assembly, between the poles of which the armature was rotated. In the new machine these relations were reversed, the armature being turned inside out and the coils enclosed by an outside iron shell of iron wire and inwardly projecting ribs, the whole surrounding the field magnet. Built for continuous current and with two armature circuits and commutators, the field magnet was held stationary, while the armature was rotated. This physical relation of external armature and internal field is characteristic of every modern power plant alternator. In all of these the armature, or stator, encloses the field magnet, or rotor, the latter being the moving part.

Another feature was a switch that enabled different combinations of field and armature circuits, and that illustrates the basic principle of all-series-parallel controllers used on d-c railway motors. This was invented independently at the same time by Dr. John Hopkinson of London for control of 2



Inverted type of dynamo electric machine, forerunner of the modern a-c generator; also the series-parallel combination of motor circuits

The latter also was independently proposed for 2 motors by Dr. John Hopkinson of England at the same time (1881). This model was used both as a generator and a motor

motors. Later, this machine was operated as a motor at the shop of Bergmann and Company, and the series-parallel control was used independently for both field and armature circuits on the St. Joseph and Richmond trolley roads in 1887, where it was referred to as an "electromechanical couple." On these equipments both change of field circuits and reversal of movement were effected on a single cylinder, while the armature changes were made by a separate switch. The latter soon was discarded because of the runaway slip of one pair of wheels when starting on a slippery track and high grade with the armatures in series. The combination also was used by Reckenzaun and Condict, and with Thompson's magnetic blow-out was developed by Potter into the widely used street car controller, by which the series-parallel and resistance sequences are effected by movement of a single handle, and the reversal by an independent switch.

Naval life being then in a quiescent stage, assignment was sought as assistant to the officer representing the Navy at the 1881 Paris Electrical Exhibition. This being refused, on the suggestion of the late Captain Howell I procured orders for temporary duty on the U. S. S. "Lancaster," then being fitted out as flagship of the Mediterranean squadron, with privilege of 3 months' leave on arrival. The ship being delayed, I installed a call bell system, the crudities of which may be judged by the character of the materials then available when subjected to sea conditions.

Too late for the Paris Exhibition, I was permitted to attend that to be held at the Crystal Palace, Sydenham, England, and arrived in London early in 1882, with about $20 and the necessity of presenting urgent needs to the U.S. Despatch Agent.

Made a member of the preferred section of the Jury of Awards, I was brought into contact with some of the leading scientists of England and experienced one of the most colorful phases of my life. Among them were: Prof. Fleeming Jenkin of the Edinburgh University; Prof. W. Gryll Adams of the Wheatstone Laboratory of King's College, brother of Charles Adams, who shared with Le Verrier the honor of locating mathematically the position of Neptune; Horace Darwin, son of Charles Darwin the naturalist; and many others. As secretary, I initiated a series of tests of gas engines, dynamos, and electric light; but having overstayed my leave nearly 6 months, with a probable court-martial in sight, I received peremptory orders to report the reasons therefor and to rejoin my ship. On arriving at Villefranche a cable authorized my remaining in London to complete my work, but I stayed aboard ship, and recorded the results in a voluminous hand-illustrated report which, happily, won the commendation of the Navy Department, with publication by the Bureau of Intelligence and praise from English technical journals. I still think it was a pretty good piece of work, and at least I escaped being disciplined. While testing gas engines the indicator diagrams at times showed evidences of advanced explosions, following which a 16-hp Otto engine was run on a forced test for about 10 minutes with the outside ignition cut off and only internal compression firing—a recorded experiment which may be considered the forerunner of the Diesel engine.

Undercontact Overhead Conductor System

During the stay in London in '82, as well as on return in the following spring, an ambition developed to equip the Metropolitan District underground railway electrically. I first planned to use as conductors the running rails and an automatically tensioned midlocated wire, or "working conductor" connected ladder-wise to a main conductor. Later I visioned the freedom of movement of a car between 2 contact planes, these being substituted by the network of running rails, crossovers, and switches, and an overhead conductor following the center lines of all, the circuit of the motors being completed through the wheels and an overhead self-adjusting upward-pressing contact. This is the forerunner of the undercontact trolley and pantograph collectors characteristic of all overhead systems using a single conductor. The undercontact, in a more limited fashion, was proposed also by Van Depoele about 1883, but in a patent interference some years later my evidence of priority abroad was not permitted, such being limited to the date of reëntrance to the United States in May 1883, despite American citizenship and duty. Because, however, of conflicting patent claims and practices, arrangements for mutual use were arranged.

Shortly before this, after passing examination for Ensign I had resigned my commission, with a year's leave, and made an agreement with Edward Johnson to join Mr. Edison as an expert assistant; but before returning home I conducted tests at Manchester on the new Edison-Hopkinson short-cored dynamo, and made a report on the savings possible on the 3-wire system, because of a difference of opinion between the independent inventors, Edison and Hopkinson, the former proving to be right. I arrived home on the day the Brooklyn Bridge opened and promptly reported to my employer, who seemed to think that a salary of $2,500 was per year unduly munificent. With W. S. Andrews I later was sent to Sunbury, Pa., with instructions to complete preparations in 48 hours to start the first overhead 3-wire system. This was put in operation on July 4, and later I was given charge of the electrical part of the first underground 3-wire system at Brockton, Mass.

At this time the sizes of the mains and feeders of the small central stations projected were determined by an actual survey of the lights and the tedious construction of a small model. One day Mr. Edison, in spite of his well-known aversion to mathematics, asked if some one could not "figure it out," and the job fell to me. I soon found that the proportions of mains and feeders adopted were wrong, and, my methods and conclusions being challenged, a layout for the city of Ithaca, N. Y., was selected for a test. I proceeded on the theory that there should be a like maximum drop of potential at the low voltage points of all mains, and that feeder resistances should be inversely proportional to the loads they had to carry. Having demonstrated the soundness of these conclusions, later patented, all determinations for a while were turned over to me and the fortnight's work reduced to about 4 hours.

Both the parent and licensee companies of the Edison system generally were known as "electric light" or "illuminating" companies, thus designating their principal activities. At Brockton I had busied myself developing an electric motor. Convinced that the use of electricity for motive power was as important as, and probably would exceed, that for illumination, I declined to take up the subject as an assistant to my employer and resigned in the spring of '84, just before the Institute was chartered, to form the Sprague Electric Railway and Motor Company. This was at first only a paper organization with a $100,000 capital structure, of which about $1,600 was sold for cash; but I had made a contract with Johnson that he would advance certain monies for corresponding proportionate interests. I was, however, a general factotum for all duties, with a self-assigned annual salary of $2,500.

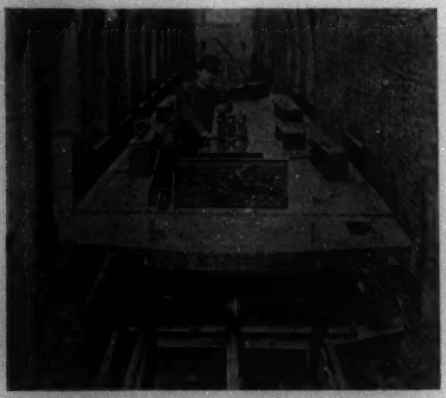
Constant Speed Motor

Our initial industrial motor development was based upon the important fact that on a constant potential circuit the mechanical effects—variations of speed and power output—of a motor could be controlled by inverse variation of the strength of the magnetic field to determine the differential of the line and motor electromotive forces; also, that with 2 magnetizing field coils, one of high resistance across the line for the main field excitation and another of few turns in opposition to it and in series

with the armature, it would be possible with certain proportions to operate a motor at the same speed under varying loads, and even different potential differences, which constant speed might also be varied—this of course a mathematical deduction. In addition, it appeared that by a distorted location of the series coil it would be possible to maintain automatically a fixed nonsparking position of the brushes under varying loads. To insure a strong field in starting, a cut-out or reversing switch was added.

This is the genesis of what was known as the constant speed motor with fixed nonsparking position of the brushes, primarily for use on constant potential circuits; and it was the first motor of this type to be put into commercial service. From the original principle enunciated there naturally followed the idea of regeneration of energy to return electricity to the supply circuit for train braking and elevator operation, the former described in a paper on a proposed equipment for the New York Elevated Railway, read at the Society of Arts in Boston in December 1885.

Production of motors was begun immediately, with exhibition of several types at the Franklin Institute Exhibition in the fall of 1884, these receiving high commendation by English and American



Platform car and truck equipped with 2 "wheelbarrow" 3-point type of suspended motors

Double drive with single reduction adjustable gearing, shunt field control, regeneration, and electric braking. Test made during winter of 1885–86 at the Durant Sugar Refinery, New York City

scientists, including Sir William Preece, Professor Sylvanus Thompson, and Mr. Edison. The holding of the exhibition was the occasion for a meeting of those interested in electrical science and its applications, and at one of them, with a vivid appreciation of the operation of gas engines gained at the Sydenham exhibition, I ventured to propose the use of a storage battery as a starter, a suggestion that met with considerable criticism. Its present day universal use in automobiles is a striking example of the unwisdom of hasty adverse judgments with regard to the possibilities of a new idea.

Commercial introduction of the constant speed motors proceeding rapidly, in May 1885 the Edison Electric Light Company issued a circular to its licensees, in which it urged the use of this motor to add to and even up output, and proclaimed it as the only satisfactory one available. A year later the Sprague company issued the first important industrial electric motor catalogue, detailing the location, and so far as available the history, of nearly 250 machines, and citing nearly 140 industries to which the electric motor could be applied. So was established a new industry which soon became commonplace in its application.

Electric Railway Development

Absorbed in my work I did not join the Institute until May of 1887. Its proceedings for the first 4 years of its existence were compassed in a single volume of Transactions, but besides the application of motors for industrial purposes an active interest had developed in the matter of traction, as indicated by a general plan with colored illustration for a 4-track undergound railway for New York in a paper on "The Scientific Street" by Rowland Hazard in 1884, and 2 papers by T. Commerford Martin, one in December '86 on "Electric Street Cars," and the other in May '87 giving comparative statistics of a dozen and a half installations of varying characteristics made in Europe and the United States, from which this interesting comment may be cited:

> "In Europe, as here, various systems of transmitting the current and of connecting up the motor with the axles and wheels are in use, and as yet no determination as to the best method seems to have been reached."

This uncertainty was emphasized by Reckenzaun's interesting paper at the opening session in the following fall, in which he discussed at length the various motor connecting possibilities, and recorded his surprise at the success of the direct single-gear reduction which was being used on a car equipped for Mr. Wharton of Philadelphia, where we were using a storage battery.

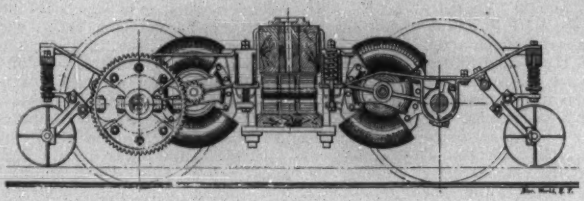
Supplanting those experiments, and others in New York and Boston, there had been a renewal of my interest in the larger problems of electric railways; this immediately centered upon equipment of the New York Elevated, where Daft was carrying on some experiments with a locomotive. The Edison-Field interests had combined, and they had assembled a number of dynamos to provide a 600-volt supply to a third rail on the 34th Street branch of the elevated, on which Stephen Field made a short-lived experiment with an electric locomotive governed by a water rheostat. I had developed what later became universal practice—the 3-point "wheelbarrow" geared suspension—by which the motor was centered on the driving axle at 2 points, so as to maintain parallelism between the armature

shaft and the axle, and was flexibly suspended at the free end to permit free movement. The Field experiments having terminated, Johnson arranged for of the same battery of dynamos to carry out an experiment for which motors, truck, and control apparatus were being prepared. Following a general description of the project made before the Society of Arts in Boston, December 1885, the first demonstration was made on a short track installed between the walls of the Durant Sugar Refinery at East 25th Street, New York City. With only a 150-ft run quick control was essential, with the result that while operating the car for Mr. Jay Gould, one of the owners of the Elevated, an overloaded safety strip blew up in a volcano and ended his interest in electrification.

The success of the test, however, was such that one day Superintendent Chinnock of the Edison Company offered $30,000 for a $^1/_6$ interest, which being refused led him to express the opinion that I was a damn fool, because if successful the remaining interest would be sufficient to insure ample reward, and if not $30,000 was not to be disdained by any inventor.

While preparation for tests on the Elevated proceeded I went to Richmond, Va., for a short rest, but was surprised one Friday afternoon by a wire from Johnson saying that he had promised Cyrus Field to operate a car on the elevated tracks on the following Tuesday. Considering the state of the work my reaction to Johnson's optimism was not flattering; but I hastened back, and despite a strike at the Bergmann shops, where the controller was being built, and with all night work by candlelight, the equipment was assembled in time to present an air of respectability to a gathering of financiers and railway officials on the day appointed. Not a single test had been possible; and considering that it was proposed to handle by distant mechanical means from each end of the car single-brush high-powered motors at 600 volts, with both shunt field and rheostatic control, to regenerate power in slowing down to return energy to the line, and also to use the motor armatures as a final brake, one may imagine the mental attitude with which I faced the gathered throng. Even then I had to wait half an hour to get current on the line.

As arrangements had been made so that either motor could be cut out of circuit, first one was tried and then the other, but without movement. Finally, in sheer desperation both motors were connected, and there followed a perfect series of runs which demonstrated the soundness of the principles employed. Even now I wonder how we escaped complete failure, with burning up of the car and the wooden-cased controller and its German silver resistances. Following the departure of the guests, and while sitting on a tool box resting from the nervous reaction Chinnook offered $25,000 for a $^1/_{12}$ interest, which finally was accepted. As he was not a man of means I asked for whom the purchase had been made, and was told that it was for the president of the Edison Company, who had acted on spiritualistic advice! Later, a like interest was sold on joint account for $26,250, and subsequently the capital structure of what had been a private company was raised to a million dollars, with outside investors interested.



Cross section of truck used in Durant Sugar Refinery test during winter of 1885–86, and from May to December 1896 on the 34th Street branch of the New York Elevated

"Wheelbarrow" 3-point suspension of single-reduction adjustably-geared motors is used, the universally adopted system on most trolley cars and on many locomotives

This equipment was notable in that the 3-point "wheelbarrow" motors were carried on an independent truck, below the car springs, ran with fixed position of tilting brushes for both directions of movement, and had field and rheostatic control of speed, regeneration and braking, as well as the interpole principle of winding for automatic maintenance of fixed brush nonsparking points regardless of load or direction of movement.

Tests continued until December of 1886, but without any special interest on the part of the railroad; and then on the suggestion of an associate I began the building of a 300-hp motor car, to be used as a smoker and to pull trailers. Each truck was to carry a pair of 75-hp duplex motors, adjustably geared to the axles, and with the field magnetic flux carried through the armatures in series, as was later done on the Bachelder locomotives for the New York Central Railroad.

About this time the entrance of Westinghouse into the lighting field with the alternating-current system, reinforced by Stanley's demonstration at Great Barrington and later by Tesla's polyphase motor, had aroused a bitter controversy with Edison, to whom the new system was anathema; and in 1886 I was requested by Johnson to report privately upon the subject. This report urged that the Edison interests, as a supplement to their own system, should actively take up a like development on the ground of economy in long distance transmission; but this recommendation was ignored, and in 1887 the alternating-current system was condemned in the famous "Red Book" as having no value except for lethal purposes.

Finding that headway on the Elevated with any plan was improbable, attention was turned to the

problem of street car operation, in which field a number of pioneers, Van Depoele, Daft, Bentley, Knight, Henry, and others abroad, were actively experimenting or had made limited installations along varied lines. Supplementing an installation with one of the elevated motors at the East Boston Sugar Refinery, individual cars with Julian storage batteries were operated in Philadelphia, New York, and Boston, and then suddenly the opportunity arose to take contracts in the spring of 1887 for equipment of, among others, the Union Passenger Railways in St. Joseph, Mo., and Richmond, Va. At this time, according to Mr. Martin's summary published in the 1887 volume of the A.I.E.E. TRANSACTIONS (p. 183–7) there were about a dozen and a half installations in Europe and the United States, including every conceivable kind of equipment, totalling about 112 cars and locomotives, concerning which I already have quoted his conclusions. He was not, of course, aware of my early suggested plans for equipment of the London underground railways; and the experiments at the Durant Sugar Refinery and on the 34th Street branch of the New York Elevated were of private character.

THE RICHMOND ROAD

The story of this pioneering enterprise, undertaken under extreme conditions and in the face of general predictions of failure, was reviewed at the Kansas City Convention of the National Electric Association in 1890; it has been told so often that only limited reference need be made to it here. Briefly stated, it called for the equipment of 40 cars with 80 motors, more than the aggregate of either European or American established installations, and supplemented by the St. Joseph contract exceeded the total. They were to be operated on an unlaid railroad presenting a combination of curves and grades of unusually difficult character, and the contract included a complete central station. The installation was to be completed in 90 days, with payment of $110,000 "if satisfactory." Our working plans were based on a rough blueprint of a motor and the records of our experimental work. Shortly after the contract was made I was stricken with typhoid fever, and while convalescing took a western trip, leaving the work at St. Joseph in the hands of David Mason, and at Richmond and the New York Shops to Lt. Oscar Crosby and Ensign Dana Greene. On my return in August initial runs were made at St. Joseph, but up to that time I had not been to Richmond; and it was not until the actual conditions there were seen that the critical situation which faced us was realized, one opinion being later summarized during operation in a message to Greene—"This is hell!" With a hard working crew and constant shuttling between Richmond and New York, continued public operation began Feb. 3, 1888, but with an immediate succession of heartbreaking difficulties which, finally overcome, enabled 30 cars, later increased to 40, to be put in operation on May 4, designated by the American Electric Railway Association as National Electric Railway Day.

Among the principal features was a main and working conductor system, with feeders supplied at 450 to 500 volts, paralel-circuit supply, centrally located universal swiveling undercontact trolley, "wheelbarrow" suspension of geared motors, with adjustable double drive and single gear reduction (later changed to double reduction) duplicate double-ended series-paralel control, fixed metal brushes (later replaced by Van Depoele's carbon)

(Above) A trolley car truck equipped with "No. 5 type" 7½-hp motors built in 1887 and used on early Sprague roads in St. Joseph (Mo.), Richmond (Va.) and elsewhere

Double-end single reduction gear drive; adjustable gear at one end; 3-point "wheelbarrow" suspension; fixed brushes; double commutator; sectionalized field windings; series-parallel control. Double reduction gearing soon followed, and then the 15-hp "No. 6" motor

(Left) An early Richmond (Va.) trolley car (1888) illustrating one of the first applications of the universal trolley

Assembly of 22 trolley cars (1888) at the terminal of the Richmond road

These show the centrally located universally swiveled undercontact trolley. The mass starting of this group was one of the factors that determined the abandonment of the projected cable system in Boston, Mass., and the adoption of electricity

A 1,000-hp 60-ton electric locomotive built in 1892–93 after designs by Sprague, Duncan, and Hutchinson, the first heavy duty electric locomotive ever built

The motor armatures were mounted on the axles, and the fields on axle boxes. This locomotive included the first railway application of a pilot controller—the main controller was too big for a man to operate

and lightning arresters. In the very month of the 30-car operation, requiring an average of about 200 hp, prediction was publicly made that 20 cars would require 2,250 hp, and that it would be impossible to operate 30 cars. Later the series method was promoted for use in England, with many high professional endorsements of its possibilities, and the inevitable outcome was referred to as "The Debacle of the Four Professors."

Doctor Holmes' happy references to the trolley in "Over the Teacup" and in his poem on "The Broomstick Train, or the Return of the Witches" are eloquent recognition of the new development. The confidence following the surprise of the native population in Richmond at seeing the heavy grades conquered by an unseen power was later voiced in a circular calling a mass meeting to demand the electrification of a road in New Orleans, La., which was headed: "Lincoln set the slaves free! Sprague has set the mule free! The long haired mule shall no longer adorn our streets."

The Richmond success, although attended by a loss of fully $75,000 dollars, was emphasized in 2 years by Sprague contracts for at least 110 railroads, including the first foreign trolley roads at Florence, Italy, and Halle, Germany, with replacement of several of the experimental equipments in the United States, and marked one of the most remarkable of industrial developments. Meanwhile the Thomson-Houston Company, which had purchased the Van Depoele interests after I declined them, had actively entered the field, and in 1890 was followed by the Westinghouse company. Among the most notable Sprague contracts were the initial one of the West End Railroad at Boston, determined after a critical mass movement demonstration at Richmond for President Whitney, and that for the abolition of cable operation at Minneapolis and St. Paul.

The Institute had meanwhile enlarged its record of TRANSACTIONS, and in catholic fashion continued full records of professional papers presented, so that one on "The Solution of Municipal Rapid Transit," read at the Columbia University meeting, June 19, 1888, was published in full, it and the discussion taking no less than 84 pages. By August 1, 1890, at which time reappeared the impractical suggestion of using 2 rails alone as conductors at 20 volts supplied by motor-generators, 412 companies in the United States alone, over 40 per cent of the total, had adopted the overhead contact electric railway system for the operation of 6,732 cars on 3,000 miles of track.

TELEPHONE TROUBLES

The Richmond installation promptly precipitated legal contests with telephone companies in a score or more of states because of inductive interferences, and particularly cross leakage on the common ground circuits. An early decision against the single trolley with ground return was made by Judge, later President, Taft in the Superior Court at Cincinnati; but this was reversed by the Supreme Court, and thereafter the railroads were entitled to the common heritage. The final result was of the greatest benefit to the telephone industry, because it forced the use of complete balanced metallic circuits, without

which long distance, or even extended successful local, telephony would be impracticable.

A New Deal

The Richmond installation now is acknowledged as the prototype of the modern trolley and the beginning of commercial electric traction. Awake to the new possibilities, the Edison General Electric Company invested $400,000 in the Sprague company, and in 1889 decided to acquire control of it. In the annual report for that year it was stated that of the 200 electric railways that had been generally contracted for, over 90 per cent were built under Sprague patents and that the company had 3,000 motors of all kinds in operation.

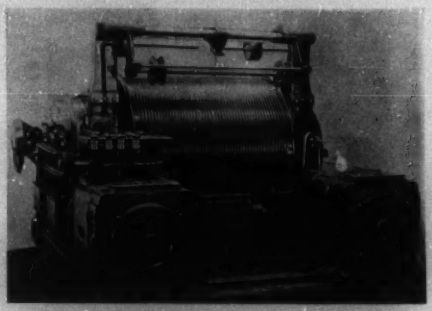
On the consolidation I consented to remain awhile as consulting engineer, but soon found existence of a policy that threatened trolley development and proposed the impossible low potential rail substitute for city operation; realizing this my resignation was tendered in unmistakable terms. It was not until long afterward, however, that there came into my possession an interoffice copy of instructions which announced that, following the purchase of the Sprague company, the system I had developed was to be designated by another name, an act the injustice of which largely has been rectified by time's perspective.

Underground Rapid Transit

The intense activity in the street car electrification naturally had 2 reactions, one the hasty and unwarranted prophecies of the replacement of steam for main line operation, and the other of more immediate importance, its bearing upon the much talked of project for expansion of rapid transit facilities in New York City—to be developed under a newly created board of estimate. Free from immediate commercial responsibilities I turned to this problem with the keenest interest, and having become one of the representatives of the Greathead Shield system of tunneling, in the early part of 1891 I outlined a deep level system at the Electric Club, following this by a comprehensive plan in the *Commercial Advertiser*.

At the May meeting of the Institute I outlined the considerations that should govern the decision with regard to a rapid transit system, citing 3 main features that should be determined in the order indicated, namely, motive power, method of construction, and routes, emphasizing the vital necessity of adopting electric equipment so that there would remain a free choice regarding the other features. Later, in opposition to the Manhattan Elevated Railroad Company's plan to extend its obsolescing system up Broadway, I made (June 13, 1891) a public proposal to install on the Second Avenue line, at a personal risk of $50,000, 2 6-car trains, one to be operated by a locomotive and the other by motors under the cars, at a speed of 40 mph. In my communication to the board of estimate I had stated that if electricity was adopted I was willing to undertake contract for both the steam and electrical equipment for not less than 50 way and express trains. These various manoeuvres were instrumental in preventing any extension of the elevated structure, and compelled serious study of the possibilities of electrical operation.

In my inaugural address as President of the Institute in the following year, on the subject of "Coming Development of Electric Railways," I took occasion to review what had been accomplished in electric traction, and to warn against undue optimism and unwarranted predictions with regard to the prophesied early demise of the steam locomotive.



One of the 49 100- to 150-hp duplex-drive elevator machines built for the Central London Railway, 1897–98

This was by far the largest elevator contract, hydraulic or electric, awarded to that date, and its successful operation was a powerful influence in emphasizing the supremacy of the electric system

New Departure

Following the acquisition of the Sprague company, the late Dr. Louis Duncan, Dr. Cary Hutchinson, and myself became associated, designing and building in 1892–93 for Mr. Henry Villard of the North American Company the first large electric locomotive—one of 60 tons and 1,000 hp, with 4 coupled axles, each to be driven by motors whose armatures were mounted on the axles and the field magnets carried on the axle boxes, with an air-operated main controller actuated by a follow-up master one. Intended for experiments near Chicago, financial reverses ended this scheme; and, after testing, the locomotive, the motors for which were built by the Westinghouse company, was laid up at the Watsessing Works of the Sprague Electric Company and finally dismantled, an unfortunate destruction of a historical machine.

Establishing a private laboratory on West 23d Street, New York City, one of the first experiments undertaken was the construction of an a-c induction furnace, in which the contained metal formed a part of the single turn secondary of a transformer. While

successful theoretically and experimentally, the limited a-c supply available led to abandonment of the work, and with Charles Pratt I took up the development of a screw-driven multiple-sheave electric elevator, essaying through the Sprague Electric Elevator Company the modest task of displacement of the well-established hydraulic system.

Following the erection of one machine at the laboratory, another was installed in the Grand Hotel at 33d Street and Broadway, New York City, and later the idea was sold to George Harding, architect for a building to be erected for the Postal Telegraph Co. at Broadway at Murray St. Here in 1893–94 was installed (and later described in the TRANSACTIONS) the first battery of electric elevators—high speed passenger ones—under a guarantee that if not satisfactory they would be replaced by any selected hydraulic type. The development of this equipment was not without grief, and on one occasion jeopardy to life of practically my entire crew and myself while operating the first car without proper current limit and car safeties.

The entrance of the Sprague company into the field of vertical traction, of course, faced the combined opposition of the established hydraulic companies and the natural conservatism of architects, builders, and owners; but progress was steady and included many types, among those the pushbutton automatic elevator controlled from floor and car, which was the forerunner of the modern signal-controlled elevators.

MULTIPLE-UNIT SYSTEM OF TRAIN CONTROL

The Postal Telegraph building elevator equipment had been notable not only for distant pilot control, with the dead man's switch and the flexible

One of the first practical tests of multiple-unit control, and forerunner of the universal multiple-unit system of train control

Test made during the summer of 1896 at the Sprague shop, Watsessing, N. J., on 4 sidewalk elevator machines equipped with individual controllers, train line, relays, throttle, and master controller, and one with only the "train line"

iron grid rheostats now universally used on heavy work, but also for a testing arrangement which was the forerunner of the invention of the multiple-unit system of electric railway operation. Provision was made such that in addition to individual car control any elevator could be operated from another controller located in the basement. One day, from sheer curiosity, all main pilot controllers were connected in and operated by the "master," with erratic results that for a time quickly ended experiments.

In 1895, my interest in the railway problem being renewed, one day it flashed across my mind that by using the principle demonstrated by the experiment with the Postal elevators I could equip cars individually with power-operated controllers, and combine them into trains of any desired length, regardless of sequence or end relation, and control them from any point by master controllers through an independent jointed train line. No sooner had this idea germinated than it was completely described, with particular reference to use on the elevated railway, preliminary tests were made with a group of sidewalk elevator machines, and 2 offers were made to the elevated railway management to install 6- and 8-car test trains at my own expense, but without any response whatever.

In 1897, however, one of my most difficult years, opportunity arose to put the system into practice. While recovering from a serious fall when installing elevators at the Waldorf Hotel, New York, a trip to London was suggested to seek an elevator contract for the new railway under construction from the Bank to Shepard's Bush. On receipt of specifications, plans rapidly were developed; but shortly before time for sailing a request came inviting me to act as consulting engineer for the South Side Elevated of Chicago, a steam operated road then in the hands of a receiver. Still on crutches and burdened with the work in hand, a new responsibility was unwelcome; but there soon arrived an old friend, Fred Sargent of the firm of Sargent and Lundy, who brought their specifications and a new proposal, and I was asked to make a report, with special reference to their steam plans. Agreeing to give 2 days to its consideration, I saw that 3 companies had made proposals for motor-car and trailer operations, and instantly I saw my opportunity. This was emphasized by the complexity of conclusions that a few weeks before had been presented by John Findlay Wallace, at the February 3, 1897, meeting of the American Society of Civil Engineers, covering several years' study of the "Substitution of Steam as a Motor for Suburban Traffic." Explaining the possibilities of multiple-unit equipment and operation, I won the interest of Sargent, as well as that of William J. Clark, the commercial railway engineer of the General Electric Company, and later of his assistant Frank Shepard.

Delaying sailing, I made a report in a week endorsing the air condenser steam system, about which Sargent knew much more than I did, but condemning the proposed electrical equipment and offering personally to contract for an equipment of the road on the new system. The opposition that developed was of no mean proportion, but although not then in the railroad business, and refusing to give any guarantee other than my own technical experience and a prediction that the bidding companies would seek orders from me for motors, I soon won out. Having to sail for London I left the signing of a contract for nearly $300,000, drawn up with special care by the engineers and officers of the railroad after

First full-train test of 6 cars operated with the Sprague multiple-unit system at Schenectady, N. Y., on July 26, 1897. These were the first section of the 120-car installation on the South Side Elevated of Chicago

my departure, to a young assistant, C. W. McKay, with the handicap of a $100,000 penal bond. This contract called for the equipment of 120 cars with 240 motors, and a 6-car train was to be put into operation by July 15 on a system that existed chiefly in type. I had taken the contract personally, and it was not until my return that arrangements were made to have it taken over by a new company, the Sprague Electric, a combination of the Sprague Electric Elevator and the Interior Conduit and Insulating Companies, the largest stockholder being John W. Mackay.

Meanwhile, to get approval of conservative English engineers and financiers for the largest elevator equipment of any character undertaken up to that time, and an electrical one, on which the success of the underground railroad depended, was a technical and financial problem that taxed the resources of diplomacy; but electricity won, and a contract for nearly half a million dollars was secured on the condition that while the entire work would be proceeded with, we would stand or fall, without recourse, on a test under the direction of the road's engineers, the principal of whom was the late Sir Benjamin Baker, of an advance installation to be made in one of their shafts, which varied from 18 to 30 ft in diameter. I returned to the United States the latter part of June, with the multiple-unit system still on paper except for such preliminary work as could be directed by cable, and with only 3 weeks to prepare for crucial tests. Despite a general strike at our Watsessing shops 2 cars were run on the 16th day of July, and by the 25th, my birthday, a train of 6 cars was ready for demonstration on the tracks of the General Electric Company at Schenectady, N. Y., under an agreement that permitted rejection on adverse decision by either an engineer or officer of the road. The test succeeded, however, and I was able the next day to telegraph to Miss Sarah Farmer, at whose home in Maine the A.I.E.E. was holding its annual convention, word of the success of the new departure on the fiftieth anniversary of her father's experiments at Dover, N. H.

The equipment was progressed rapidly, and by the following spring all steam locomotives were displaced. This project had likewise to go through its birth pains, with heavy losses, but the system installed 37 years ago is still in operation, the multiple-unit system has never been changed in principle or essentials, and it is now universally used where 2 or more motor-equipped units, whether on elevateds or subways, suburban trains or main line locomotive operation, are under a common control.

(Below) First of the multiple-unit controllers to be used in the 1897 tests at Schenectady

This shows a series-parallel standard controller driven by a pilot motor, the reverser, throttle, and relay, but not the train line and master controller

A happily facetious letter from B. E. Sunny on a recent birthday is typical of the almost universal doubt and ridicule with which the new system was greeted, and warrants an excerpt.

" 'He invented the multiple-unit system and applied it to the South Side Elevated in 1898' and thereby hangs a tale.

"I was manager of the General Electric Company in Chicago at that time, and we had had the business of the Elevated Railroad in motors, etc., for some years, and a contract for equipment had been negotiated which contemplated an addition to the old method, the only one known, of a heavily serviced motor car capable of pulling a number of trailers.

"I called on Mr. Hopkins, the general manager, one morning, expecting to receive the signed contract, but found him in rather bad humor. One of the directors had met a fellow in New York with a military title, who had put in an electrically appointed dumb waiter for delivering cocktails to the several floors in a big hotel, which worked perfectly, and he proposed to apply the same scheme to the operation of elevated trains. This seemed to us to be just too funny for anything and we both had a good laugh over it.

"Mr. Hopkins telephoned me the next day that the name of the magician was Lieutenant Frank Sprague, and then it wasn't so funny. Your fame in electric railways was widespread, and you were a terrible man to meet in competition. I saw that fine contract in those days of bad business following the '94 panic slipping away, and it made me feel pretty bad.

"Then you came to Chicago, and the story was that you had no shop; no organization; no installers—just a tooth brush and an idea, but Ye Gods, what an idea! Most men with an idea like that would not have had the presence of mind to carry even a tooth-brush

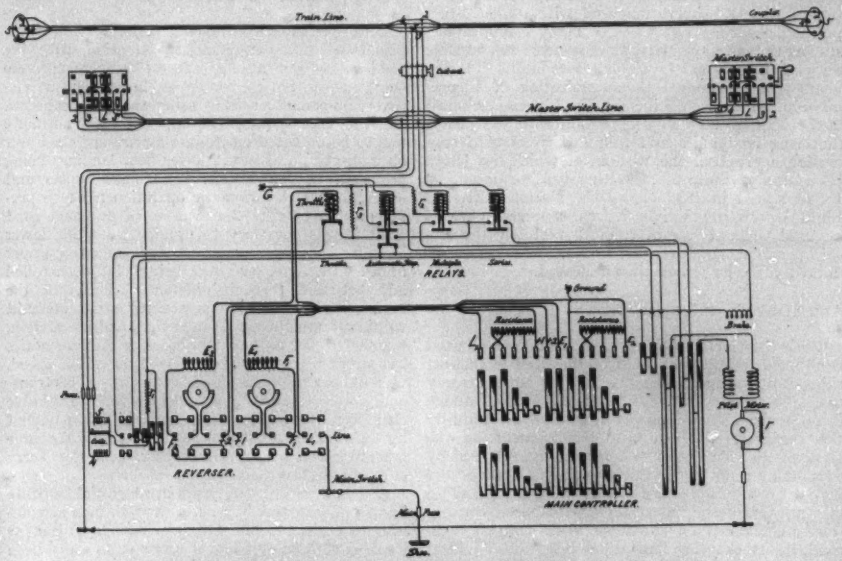
additional! We lost the contract; you won, and it was a great day for railway transportation, for the application of your multiple-control system has been the greatest boon that has come to that most important public service. Indeed, the wonderful results could not have been secured in any other way."

A full description of this equipment appeared in the 1899 volume of the TRANSACTIONS. The success of the system and the commercial undertakings of the large manufacturing companies soon made it essential that control of the Sprague company should be secured, since it was unlikely that a fundamental patent with 246 claims could be broken. This was done in 1902 through the General Electric Company for itself and the Westinghouse and the British Thomson-Houston companies, and after the equipment of a section of one of the French railways, also by the French Thomson-Houston Company, under agreements that by whomsoever used the system should at least carry the Sprague designation, a condition which only partly has been lived up to. The inception of the system and its world-wide adoption and use, however, were emphasized by the unique and gracious testimonial tendered me in recognition of my 75th birthday 27 years after the Institute, at its annual dinner on February 8, 1905, celebrated "The Triumph of Electric Traction."

Before the consolidations referred to were effected, after a million-dollar successful fight to effect the obsolescence of the hydraulic elevator and the supremacy of the electric, which included the building of 584 machines for the equipment of the largest buildings and the Central London Railway, a combination of elevator companies was effected and this part of our business was sold to it. The traction type originally was proposed for a projected memorial to George Morison, to be erected in Chicago, and in 1906 developed by me with use of the equalizing sheave characteristic of street cable systems. It was introduced into commercial practice by the Otis company about the same time.

ELECTRIFICATION OF THE NEW YORK CENTRAL TERMINAL

A grave accident on the New York Central Railroad led to the passing of a law requiring the abandonment of steam as a motive power in the terminal tunnels, and I offered to demonstrate within a year the hauling of a regular train by an electric locomotive. Instead, a Committee for Electrification was formed in 1902, under Vice-President Wilgus, the other members being Superintendent of Motive Power Waite, B. J. Arnold, George Gibbs, and myself. Deciding to extend the equipment beyond the legal requirements, plans promptly were detailed and completed. Final decision was for 600-volt d-c equipment, current being taken from a protected undercontact third rail supplied from substation



Typical circuits of the Sprague multiple-unit system for both car and train assembly

This is an 1897 working diagram and shows the fundamental circuits from which evolved the entire multiple-unit system. A peculiarity of the train line and jumper connections is the arrangement of the speed controlling wires so that they always coupled alike, while the reversing wires are changed on the reversal of cars in train assembly. This was to assure proper direction of train movement relative to truck movement with like movement of the master controller handle in any combination—a fundamental condition for universal assembly

rotary converters, to the transformers of which 3-phase alternating current at 25 cycles was transmitted from 2 main stations equipped with vertical turbines. Gearless locomotives of the Bachelder type were adopted, together with multiple-unit control for them and the suburban cars. In spite of the pressure to adopt other methods, and regardless of the advances that have been made since, no other choice was then practicable, and the performance of the whole equipment, which was initiated in 1905, has fully justified the commission's decision. This was followed a year later by a very extended paper in the A.I.E.E. TRANSACTIONS on trunk line operation.

THE A-C–D-C CONTROVERSY

The adoption of single-phase equipments on some suburban railways, mostly later abandoned for 1,200-volt d-c operation, and on the first section of the New Haven road, was cause for temperamental explosions as to the merits of the different systems, many claims without warrant being vociferously advanced. In this caldron of controversy I found myself deeply involved, sometimes even being charged as the champion of exclusive d-c operation. This was far from the fact, as various papers, discussions and the Institute's records fully demonstrate; but I did offer to assume the responsibility, and urged the advisability, of raising the limits of potential in d-c operation, and without hesitation pointed out the weaknesses of many claims made, stating that a fair comparison of systems was possible only when each was developed to its limit. Twenty years ago I proposed the organization of a commission, which would include the highest technical authorities, to seek in coöperation with the manufacturing companies and railroads a common conclusion a proposal the wisdom of which has lately been amply vindicated. With regard to potentials I had stated in 1890 before the National Electric Light Association that whatever was necessary would be used without fear of results; perfectly successful operation with even d-c equipment is now conducted at the potentials then indicated.

AUXILIARY TRAIN CONTROL

With the electrification of the New York Central completed, ambition turned to the need of making railway operation in general safer by automatically forcing obedience to wayside signals without undue interference with the proper control of the train by the engineer. After a long development on the General Electric tracks at Schenectady, followed by supporting reports, the Sprague Safety Control and Signal Corporation was formed; critical tests of an intermittent inductive system, with speed control, were undertaken on the New York Central Railroad, under exacting limitations determined jointly by representatives of the Interstate Commerce Commission and a committee of the railroads, which I agreed to meet—and then some. On the declaration of the World War this work was partly suspended, and on the formation of the U.S. Naval Consulting Board, in the details of which I was active, the Institute was 1 of 11 societies requested to nominate members, Mr. Lamme and I representing it. Although acting as chairman of the committee on electricity and shipbuilding, my principal activities were in the development of depth charges and delay-action fuses for armor-piercing shells.

Acting under authority of Congress, the Interstate Commerce Commission in 1924 issued orders requiring 49 railroads each to equip a full division with train control, supplementing this by another order 2 years later—all, however, with an unfortunate latitude of construction and requirements. For many reasons I had anticipated that the successful conclusion of the original New York Central tests and a later section trial would be followed by a division installation; but failing this, action was transferred to a number of western railroad divisions, where I agreed to meet any requirements of the commission. There followed a period of successful operation, and then commercial collapse due in part to a change of policy by the Commission and the troubles incident to railroad financing and operation in the recent depression. The period of activity in this field, extending from about 1911 to 1933, was one of great trial and strain, and, considering the commercial results, might have been more advantageously spent in some other direction.

DUPLEX ELEVATORS

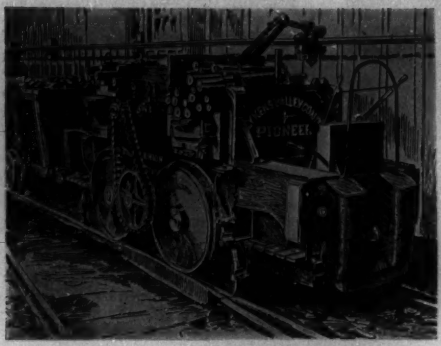
During the latter part of this period vertical transportation again attracted my attention, with the sudden development of a method for safely and freely operating, within proper limits, 2 independent elevators on common rails in a single shaft, to conserve valuable floor space. The upper elevator normally was to be operated on express service and the lower on a shorter local run, 2 lower floor landings being provided. Every elevator has 2 limits, upper and lower, for which automatic operation must be provided. To operate 2 elevators as proposed in 1 shaft it was necessary to provide a floating lower limit for the upper car and a similar floating upper limit for the lower one, these being jointly controlled and actuated through differential action of the main controllers. The first working model was built within a fortnight after conception, and the system, together with a method for actuating the car safeties by excess of acceleration as well as excess speed, was sold to the Westinghouse company. This transaction was attended by a coincidence of remarkable character, the passing of a check in part payment by Vice-President Charles Terry, of exactly the same amount given me by his brother, Professor Terry of Annapolis, over 2 score years earlier.

And now, after many years in which the Institute has signally honored me, still at work in a new development in the difficult days of a new deal, or ideal—and hoping! The 3 score years have been those of a ready acceptance of any challenge in electrical engineering progress, a mental elixir which has made life worth living in the effort to add to human progress and comfort, the zest for which advancing years has not entirely abated.

A Few High Lights in Electrical Transportation

(Above) Electric locomotive built by Moses G. Farmer in 1847, now in the Smithsonian Institute, Washington, D. C. Mr. Farmer used the apparatus when lecturing on electricity
(General Electric photo)

(Below) An electric carriage built in 1893, which weighed 5,100 lb and was capable of attaining a speed of 16 mph
(Holtzer-Cabot photo)



(Above) An electric mine locomotive built about 1888 for the Lykens Valley (Pa.) Coal Company
(General Electric photo)

The achievements in horizontal transportation have been paralleled by equally striking achievements in vertical transportation. At the right is shown one of the elevators recently installed at the Rockefeller Center in New York City; these are the fastest elevators ever built, being capable of a speed of 1,200 ft per minute. The doors of all cars are protected by photoelectric equipment so arranged that an obstruction in the doorway will prevent the door from closing
(Westinghouse photo)

(Above) First electric locomotive built for the Baltimore and Ohio "Belt Line," 1895. The locomotive weighed 96 tons and was equipped with 4 6-pole gearless motors of 360 hp each
(General Electric photo)

(Left) One of the latest 90-mph a-c locomotives built for the Pennsylvania Railroad in 1932–33; it weighs 190 tons and is powered by 3 twin motors with a total continuous rating of 3,750 hp
(General Electric photo)

Alternating Current Versus Direct Current

By Lewis B. Stillwell, President A.I.E.E. 1909–10

An episode of early commercial competition within the electrical industry by a past-president of the Institute who was an "eye witness" to the controversy.

THE preëminent American leader in the development and commercial introduction of the alternating-current system of transmitting and distributing electricity for lighting and power purposes was George Westinghouse of Pittsburgh, Pa., the inventor of the air brake. In 1885 the Gaulard and Gibbs lighting system, invented by the brilliant Frenchman Gaulard, was exhibited at Turin and at the Inventions Exhibition in London. The apparatus employed was crude, but it included the transformer, the key to the problem of electrical transmission.

Mr. Westinghouse promptly secured control of the American patents of Gaulard and Gibbs, incorporated the Westinghouse Electric Company, and began to build up a staff. Before the end of 1886, several central station lighting plants had been sold and the company was in active competition with the Edison Electric Light Company, which for several years had been practically in sole control of the American field of electric lighting by incandescent lamps supplied from central stations.

Edison's brilliant invention of a commercial incandescent lamp had been followed promptly by his feeder and main patent, and by his 3-wire system of distribution. His first central station in Goerck Street, New York City, was a convincing demonstration of the commercial possibilities of the new lighting system, and the pioneer installation in New York had been followed with remarkable promptness by similar plants in a number of other American cities. Adequate financial support had been secured; the Edison Electric Light Company had been organized to manufacture incandescent lamps, central station and distributing apparatus and, in short everything necessary from dynamos to lamps inclusive. Not only had Edison's work been brilliant, but also it had been extraordinarily direct and practical. When Westinghouse acquired the American rights of Gaulard and Gibbs, the Edison Manufacturing Company was a going concern; its activities were extending rapidly and a great commercial success seemed assured.

During the year 1887 a number of alternating-current central lighting stations were installed by the Westinghouse Company in various American cities. The reaction of the Edison Manufacturing Company was prompt and vigorous. The usual methods of commercial competition having failed to stop the invader, unusual defensive measures were adopted.

A bill was introduced in the Senate of the State of Virginia prohibiting the use in that state of any electrical potential exceeding 800 volts; and a committee of 15 Senators was appointed to hold public hearings and report to the Senate.

Howard Levis, Esq., at that time one of the Westinghouse Electric Company's counsel, was instructed to oppose the bill, and I was detailed to coöperate with him.

Learning that Mr. Edison himself was to appear before the committee, President Morton of Stevens Institute of Technology, an eminent authority on engineering matters, was retained for the Westinghouse company, as also was Captain Hugh Garden, counsel of the Sawyer-Mann Electric Company, which had been acquired by Westinghouse interests. Wyndham R. Meredith, Esq., a brilliant young lawyer of Richmond, Va., also was retained.

The day of the hearing arrived. Many residents of Richmond were interested to see and hear Mr. Edison, and the first meeting of the committee was held in the historic hall of the House of Delegates at the capitol. The hall was well filled by a representative gathering of legislators, other public officials, and representative citizens of Richmond, including many ladies.

After the usual formalities, and a statement by the chairman of the committee, Mr. Meredith arose. He began by extending to Mr. Edison a warm welcome to Virginia and in eloquent and most courteous words thanked him for his visit to Richmond. He recalled the fact that "Franklin often had left the laboratories of science for the halls of legislation," and in doing this invariably had been actuated by his deep interest in the public welfare. Mr. Meredith expressed the hope and his personal confidence that in honoring Virginia with a visit, Mr. Edison was actuated by motives no less admirable. It would have been impossible to concentrate the thought of the audience on the question "Why does Mr. Edison come to Richmond?" in a manner more graceful and adroit.

Following the conclusion of Mr. Meredith's able address, which was greeted by the audience with hearty and continued applause, Mr. Edison was called as the first witness in support of the bill. He was questioned by counsel presumably retained by the Edison company and occasionally by members of the committee. His unfortunate deafness made it very difficult for him to hear the questions asked and it was necessary very frequently to repeat them, as a consequence of which his testimony was neither consecutive nor convincing. It was made clear, however, that he favored the bill, and it was evident

that the audience was much interested to see and hear him.

Following Mr. Edison, President Morton was introduced; he made an admirable address which lasted about 20 minutes. Dr. Morton had few, if any, superiors in describing technical matters in popular language, and on this occasion he put forth one of his best efforts. Among other things, Mr. Edison had said in effect that the continuous current was like a river flowing peacefully to the sea, while he compared the alternating current to a torrent rushing violently over a precipice. Dr. Morton courteously suggested that it would be more accurate to compare the continuous current to water flowing in one direction through a pipe, and the alternating current to water moving first in one direction and then in the opposite direction in the same pipe. It would have been difficult for any one in 20 minutes in nontechnical language to make a statement of the question at issue more reasonable and convincing than Dr. Morton's. While it is highly improbable that any large proportion of the audience, or even of the committee, understood what it was all about, the effect apparently was soothing; and when he finished the alternating current system seemed much less dangerous.

Senate Bill No. 238
Virginia Legislature, Session of 1889-1890.

A BILL

For the prevention of anger from electric currents.

Patron—R. Lovenstein.

Referred to the Committee on General Laws.

1. Be it enacted by the General Assembly of Virginia, That
2 it shall be unlawful, on and after the first of April, one thousand
3 eight hundred and ninety, to own, keep, or maintain, in, across,
4 through, or under any public street, highway, or place to which
5 the public commonly has access, any electric circuit, or part
6 thereof, or any substance or thing for the conducting of elec-
7 tricity forming a part of an electric circuit, contrary to the pro-
8 visions of this act.
9 In all electric circuits or parts of circuits as aforesaid,
10 whether such circuits be in whole or in part under or above
11 ground, the electric pressure used shall not exceed the following
12 amounts: The non-pulsating continuous current to a pressure
13 not exceeding eight hundred volts; the pulsating continuous
14 current to a pressure not exceeding five hundred and fifty volts;
2
15 the alternating current to a pressure not exceeding two hundred
16 volts, according to the nature of the current used.

After the passage of this act it shall not be lawful for any individual or corporation, public or private to generate or use, or cause to be used for distribution to the public, directly or by induction, any electric current with sufficient electric pressure to produce ~~death~~ human death accidentally by the direct action of such current.

Thomas A Edison

The first page of the Virginia bill to limit electric potentials in that state to 800 volts (left above); a hand-written note regarding the bill by Mr. Edison (left); and portions of a newspaper account of the hearing from a contemporary paper (right)

THE BILL KILLED.

THE ELECTRIC TALKERS BEFORE THE SENATE COMMITTEE.

THE SPEECHES MADE TO-DAY.

The discussion of the Senate bill to regulate the use of electric currents throughout the State of Virginia attracted a very large number of people to the hall of the House of Delegates in the Capitol last night. Col. Boulware, representing the Edison Electric Light Company, advocated the passage of the bill, presenting Mr. Edison himself as recommending it.

In reply to inquiries Mr. Edison gave a short exposition of his views on the subject, and was followed by Mr. Harold P. Brown, of New York, popularly known as "the electrical executioner" from his connection with the various tests made in New York city to prove that electricity will kill.

Mr. W. R. Meredith, the attorney for the Electric Light and Power Company of this city, stated that the passage of the proposed bill would force his company to abandon its business, and introduced Prof. Morton, of the famous Stevens Institute of Technology, an

***

The audience this morning was not as large as last night, the great attraction, Mr. Edison, not being present. Mr. Brown left for New York last night.

Professor Morton and Mr. R. W. Pope, secretary of the American Institute of Electrical Engineers, spent the afternoon with Mr. M. B. Leonard, the superintendent of telegraph of the Chesapeake and Ohio railway, in visiting the power stations of the Electric railway and the Electric Light and Power Company, which, it is stated, would be obliged to go out of business if this bill becomes a law.

RECOMMENDED THAT IT DO NOT PASS.

The Senate Committee on General Laws to-day reported Senate bill for the prevention of danger from electric currents, with a recommendation that it do not pass. The committee thought it was a matter for municipal authorities.

The committee then called Captain Garden to the stand. The Captain was a cultured and delightful southern gentleman of the best type. At the battle of Gettysburg he had commanded a South Carolina battery, and had left a large proportion of his men on the field. After the Civil War he had settled at Warrenton, Va. His testimony was given in an address which was followed with close interest by his audience. It was eloquent, if somewhat flowery, and he had not spoken long when I noted several of the Senators whispering to each other and looking at him intently. They were recognizing him as Captain Garden of Warrenton, and it was evident that they listened with sympathetic interest and with pride.

Before Captain Garden's testimony was concluded, Mr. Levis and I had learned that a number of representatives of companies operating electric arc lights in various towns in Virginia were present and desired to be heard. As they were using potentials up to 3,000 volts, the proposed legislation, if enacted and enforced, would put them out of business, and to this they felt strong objection. Realizing that the views of these men might be expected to have much influence with the committee, it was arranged that some of them should be heard when Captain Garden had finished.

The first of these gentlemen who was called upon had but one leg and used a crutch, but unquestionably he was effective. He expressed himself fluently and with great force. The committee and the audience listened attentively. In closing, he derided the suggestion that 3,000 volts was dangerous and exclaimed: "Why, gentlemen, the pennyroyal bulls of Fairfax County are far more dangerous than that current." I never learned what a pennyroyal bull is, but the committee seemed to feel that the gentleman had made a strong point.

The following morning, the committee met in the Senate room and representatives of local arc lighting companies in Virginia had the floor. Their opposition to the proposed legislation was unanimous and emphatic. The representatives of the Westinghouse company, realizing that such testimony from residents of Virginia might be expected to be more effective than any additional arguments they could present, introduced no further testimony. At the end of the morning session, which lasted only an hour or 2, the Senate Committee decided unanimously in disapproval of the proposed legislation.

Some months after the hearing at Richmond, Mr. Levis and I attended a hearing before a committee of the Legislature of the State of Ohio at Columbus, where a bill had been introduced similar in general tenor to that which had been rejected at Richmond. On this occasion, Harold P. Brown, a man much talked of in those days, appeared in support of the bill. Before the hearing, he had demonstrated the "deadly qualities" of alternating current by using it to kill 1 or 2 animals in the presence of a number of people whom he had invited to witness the demonstration.

At the hearing, Mr. Levis and I presented testimony in opposition to the bill and to Mr. Brown's statements. On this occasion, it was not thought necessary to call upon President Morton or Captain Garden. The efforts of Mr. Brown and his associates accomplished nothing at Columbus.

Attempts to prevent the use of alternating current by legislation—or by inducing the authorities to refuse a permit—were made not only at Richmond and at Columbus, but also at other places in the United States and Canada, but without success.

In his efforts to prevent the introduction of the alternating-current system, Mr. Brown resorted to measures that were strongly resented by Mr. Westinghouse and his associates. The newspapers were filled with articles describing the deadly nature of alternating current. In some way, Brown managed to purchase a second-hand Westinghouse alternator and he was supposed to have been instrumental in securing enactment of a law in the State of New York which provided that the death sentence in criminal cases thereafter should be carried out by electrocution. For this purpose, he strongly and successfully recommended alternating-current apparatus. The fight was a bitter one and was prolonged through several years, but, fortunately, had little ultimate effect upon the introduction and general use of the alternating-current system.

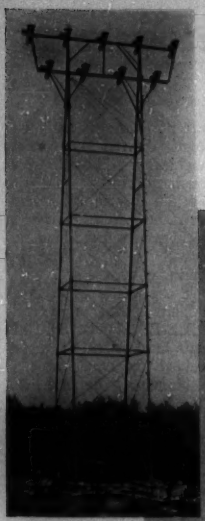
In 1892 the Edison Electric Light Company and the Thomson-Houston Company were combined to form the General Electric Company; and the opposition of the Edison interests to alternating current apparently disappeared. For several years the Thomson-Houston Company had been manufacturing and selling alternating-current lighting apparatus. Elihu Thomson, at a very early date, had experimented with the transformer, but his attention apparently had been centered upon its possibilities in electric welding rather than in lighting.

From the date of its formation, the General Electric Company energetically developed and exploited alternating current; and before the end of that year was competing vigorously and very ably with the Westinghouse company in that field.

Some Transmission Structures

(Right) Mill Creek-Redlands (Calif.) line (1892–3), reported to be the first 3-phase high-voltage (11kv) transmission line. Plant and line are still in service
(So. Calif. Edison Co. photo)

(Below) Modern 300-ft towers carrying 2 220-kv and 12 66-kv circuits over a navigable channel at the Long Beach (Calif.) steam-electric generating station
(Southern Calif. Edison Co. photo)



(Below) The latest thing in transmission towers, the so-called rotated tower that is finding its first application on the 287-kv 200-mile line now being built from Boulder Dam to Los Angeles. Distance between outer conductors about 65 ft
(American Bridge Co. photo)

(Above) Original 60-kv line from Kern River hydroelectric plant to Los Angeles, Calif. (about 1902; suspension insulators added later
(So. Calif. Edison Co. photo)

(Below) Left, Berkeley (Calif.) terminus of the first long distance transmission line to reach San Francisco Bay region; (right) modern counterpart built in 1923.
(Pacific Gas & Elec. Co. photos)

(Left) A 60-kv pole line of the old Standard Electric Co. (about 1902), that brought hydroelectric power from the early Electra plant in the Sierra Nevada Mountains (Calif.)
(Pacific Gas & Elec. Co. photo)

Developments in Electric Power Transmission

By Harris J. Ryan, President A.I.E.E. 1923–24

A brief account of some significant events in the history of electric power transmission related by a past-president of the Institute whose name is closely linked with many of those events and who for many years has been actively engaged in the study of high voltage phenomena.

DURING the early eighties through the studies of Kelvin we learned that economy in the transmission of an electric current would be greatest when the conductor loss and existence costs would be equal. No mention was made at the time of the voltage required for the corresponding economy in the transmission of electric power; that was to come later.

Promptly after his invention of the incandescent lamp, Edison developed in the early eighties the 220-volt 3-wire system with which continuous current could be transmitted economically a distance of a half mile to light incandescent lamps. Thus the industry of incandescent lighting was started in the business districts of New York, Boston, Buffalo, and Chicago.

The practical mind of another great inventor, George Westinghouse, soon became interested in the problem of increasing the distance to which incandescent lamps could be made available from a central power source. The result of his efforts led to the discovery of the practical availability of the transformer and with it the development of a 2-wire alternating current system for supplying current economically to incandescent lamps from a distant power supply. His plan included a generator with a voltage ample to transmit the current economically to the location of the customer where a transformer was placed to reduce the voltage to the amount required for the operation of the customer's incandescent lamps. The effect upon the incandescent lighting industry was immediate, and the practice was rapidly extended to large residential areas.

Early Electric Power Service

During the eighties, while the 220-volt incandescent lighting service was getting under way, no opportunity was overlooked to carry with it a power service with motors and an energy storage service with batteries. By the close of the eighties the advocates of the alternating current incandescent lighting systems felt keenly the want of satisfactory alternating current motors required for power service of many sorts, chief of which was the operation of conversion machinery required for the supply of continuous current and for charging storage batteries.

The alternating current incandescent lighting industries, in this epoch, were joined by many able men who quickly evolved satisfactory alternating current motors and the much desired conversion machinery. Thus the electrical exhibits at the World's Fair in 1893 demonstrated abundantly a world prepared at home and abroad to equip the incoming electrical age.

In the winter of 1886–87 William A. Anthony (president of the A.I.E.E. 1890–91) and his class of students in electrical engineering were received by Dr. Frank J. Sprague (president of the A.I.E.E. 1892–93) at his factory in New York City where he was engaged upon the notable work of manufacturing the motors for electrifying the street railways for the City of Richmond, Va. He showed us 2 of the $7^1/_2$-hp motors that were then completed for such purpose. In talking with Professor Anthony about electric power transmission, Doctor Sprague said he had found in his study that economy in electrical transmission of power would be directly proportional to the voltage and inversely proportional to the distance. This conversation made a profound impression on some of us who were thus started out in life with a never-ending enthusiasm for the study of high voltage phenomena required for the economic transmission of electric power.

The Battle of the Phases

The Niagara Falls-Buffalo, N. Y., 28-mile transmission was established in the early nineties at 22-kv between conductors. It had followed quickly on the heels of the great Frankfort-am-Mein electrical exposition, held in Germany in 1891, with its marvelous demonstration of a 100-mile 3-phase power transmission from a water fall at Lauffen to the exposition. The brief years that intervened between the Frankfort Exposition and the World's Fair witnessed the great economic-technical battle of the phases—3 phase versus 2 phase. The controversy invaded the counsels of the Niagara Falls-Buffalo power transmission development, when suddenly the contest was stopped by the master stroke of Charles F. Scott (president of the A.I.E.E., 1902–03) with his "T-connection" for transformers to connect 2-phase circuits to 3-phase circuits in balanced power relation.

The birth of the American Institute of Electrical Engineers in 1884 followed by the International Electrical Exhibition in Philadelphia during the same year, the Frankfort Electrical Exposition in 1891 and the World's Columbian Exposition in 1893

made all America and much of Europe electrically minded in regard to human communications and energy transmission and distribution with electrical facilities. These great electrotechnical activities and exhibits prepared world civilization to expect the early achievement of radio communication and the long distance transmission of power and its effective distribution.

To the youth of the late eighties and the early nineties there was visioned a rapidly changing world of extraordinary facility for communication and power development. For many it changed their entire outlook upon life. One great group promptly decided to be interested in power, soon to be followed by another group determined to find all they could do in the new field of wireless, later called radio. It has taken an entirely new generation to grasp the more recent outlook upon what to do with electrical facilities in geophysics, bionomics, and the long list of radiations having frequencies above and below those of X rays, also the more recent outlook upon the electrical opportunities for the social rebuilding of civilization in the electrical age.

Those in the power transmission group soon became preoccupied with their own chosen field and lost much of their former interest in what was going on around them. They became greatly interested and concerned with many difficulties encountered on their own road to progress. It soon was discovered that alternating current was an out-and-out necessity in high voltage power transmission because it made the simplicity of the transformer available. Much working enthusiasm was consumed in developing the requisite mathematical study for a satisfactory understanding of alternating current values and characteristic behaviors to be followed finally with a corresponding understanding of current and voltage transients.

In the midst of all this the limitations of the atmosphere as an insulator about the transmission line conductors was encountered in the middle and late nineties. Much thought and study were given to this matter by many power transmission engineers. Along with these difficulties with the atmosphere the practical limits of the single pin-type insulator soon were encountered. For years the power transmission industry was virtually forced to be content with 50- to 60-kv line insulators. The attempt to use higher voltages was not a success because the insulators then available would not "stand up" under the higher voltages. Again the day was saved with dramatic suddenness by the invention of the suspension type insulator. By the use of insulators of this type on a short line in Michigan in 1908 it was found that 110 kv, 3 phase, was entirely feasible.

This speedily was followed by the erection and successful use of a power transmission from a hydroelectric plant on the Feather River near the great storage reservoir, Lake Almanor, a distance of 140 miles to Oakland, Calif., with a terminal voltage of 90 kv. Shortly thereafter, a 3-phase line was erected to transmit power at 104 kv from a hydroelectric plant on the Stanislaus River a distance of 132 miles to San Francisco for the operation of the street cars of that city. This transmission was notable for having the magnetic and electrical constants of the conductors balanced so as to cause the line to operate at substantially the same voltage, 104 kv, at both terminals—generator and receiver.

What Frequency?

The development of hydroelectric power on a large scale at Niagara Falls forced the adoption of alternating current only to be followed by a great uncertainty as to the frequency to be used. Some urged that the magnetic activity of alternating current would preclude the use of all but those low frequencies that were successfully used in continuous machinery. Others in authority advised the use of 1,000 cycles per minute or 16.66 cycles per second because that was the frequency that was used in a 2-pole continuous-current generator running at a speed of 1,000 revolutions per minute. This same authority felt convinced that eventually much of the vast power to be developed at Niagara Falls would have to be applied to continuous current machinery and as direct current for electrolytic purposes. This authority finally was overruled by the controlling engineers and executives of the project who decided to launch it on a frequency of 25 cycles. The first large blocks of power to be sold from the new plant would require continuous current for aluminum reduction and for the operation of the street railways of the city of Buffalo. Makers' designs and tests had demonstrated the assured success of the 25-cycle synchronous converter thus permitting the adoption of that frequency.

Much work of all sorts remained to be done in the new industry. Hydroelectric power in abundance was available on the Pacific Coast and in the intermountain region involving transmissions to available markets over long distances. There quickly developed a need for standards in voltage and current wave forms, units for study and discussion, and application of inductance, capacitance, and leading and lagging reactive power. These needs were quickly supplied with few exceptions; one such was a choice of an intermediate frequency between the extremes then in use, 133 and 25 cycles, that would be more suited to the actual conditions existing in the Far West. It was greatly to the advantage of the hydroelectric power industry that the Far West was available for development closely following development at Niagara Falls. Various frequencies were tried: 40 cycles per second for Portland, Ore., 50 for Los Angeles, Calif., and 60 for the San Francisco Bay region. Fortunately the number of 40-cycle developments have been few and the mechanical differences between 50 and 60 cycles were not so large but that they could be overcome economically with advances in speeds of prime movers and frequency changers for interconnections between the ever-increasing 60-cycle systems in the Los Angeles region and the local 50-cycle practice.

Thus by 1915 the hydroelectric power transmission practice was stabilized at 60 cycles in the Far West, and elsewhere. Much support then was given to the study of the transmission technique required to

handle successfully power lines of indefinite length. Studies of voltage, power factor, and stability control and regulation soon visualized the feasibility, when needed, of the 1,000-mile 60-cycle power transmission line. These studies, however, preceded the great depression that developed in 1929. They had been made in the optimistic days of "reconstruction" that followed soon after the close of the great war—the years in which the transmission line voltages from the Big Creek hydroelectric stations to Los Angeles, 220 miles, were raised from 150 to 220 kv and the stations on the Pitt River were connected with 220-kv lines, 170 miles, to the markets of the San Francisco Bay region. During the depression years that followed 1929 the transmission engineers and their executives made intensive studies of the great rivals of hydroelectric power: the advances in steam power and the internal combustion engine using the available fuels, coal, oil, or natural gas. The purpose was to advance the economic balance of the nation's resources.

In some regions of the Pacific Coast water conservation, irrigation, and hydroelectric power must be coördinated for best economic results. In some of these regions the wisdom of ancient people who learned in the long past to live on irrigated lands, must not be forgotten. They learned that lands long irrigated become salted and that they must be restored to production by fresh water. Delta lands and low lands adjacent to the sea are likely to be invaded by sea water if the supply of fresh water by irrigation or otherwise is not ample.

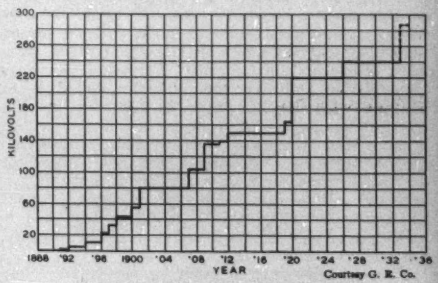
In general, power transmission engineers and executives are remaining alert in regard to the aggregate economics of power supply. This applies to the whole range of physical technique. Our civilization requires energy to carry on. For example, a 132-kv line will and does supply a power hook-up necessary for a synchronized, convenient, interchangeable, and economic supply of electric energy from point to point all the way from Chicago to the Atlantic and Gulf coasts. These points are supplied economically by hauling coal or by piping fuel oil or gas from the mines or wells. Substantially the same practice is developing on the Pacific Coast. This in effect amounts to a new type of power transmission and distribution. As such it is having a controlling effect upon the selection of voltages to be employed in new developments or extensions.

Far Western Conditions Determine Voltages

The December 1933 issue of Electrical Engineering reveals that power transmission engineers continue to learn from the Niagara Falls-Buffalo, N. Y., transmissions and from the Boulder Dam-Los Angeles, Calif., transmissions, that hydroelectric power conditions in the Far West continue to determine the advance in transmission line voltages. One of the remarkable things encountered through life has been the steady advances in voltage used for power transmission starting from the 10-kv single-phase pioneering in Southern California in the early nineties to be quickly followed by the 22-kv 3-phase Niagara Falls-Buffalo transmission. With a surprising approach to uniformity the transmission line voltage has advanced approximately 6 kv per annum, or 240 kv during the last 40 years leading to the projected use of 275 kv on the 300-mile transmission lines now being erected from Boulder Dam in Black Canyon, Colorado River, over the Mojave Desert to Los Angeles.

Through the half century of electric energy transmission for light and power, lightning has caused innumerable interruptions to service and much damage to equipment. A vast amount of study has been made of the origin and behavior of lightning. Real progress has been made in overcoming its hazards. Such studies and their results may be found in the A.I.E.E. Transactions.

All the nation has profited greatly by this exchange of benefit from power transmission and distribution on the extreme sides of our country and through its great interior valley. It is literally true that all the world has thus profited. Most authors of the narratives found in this May 1934 issue of Electrical Engineering will remember their days in college when it often was noted that the highest advances for students in physics, chemistry, and the applied sciences were to be made by European study. It has been a great satisfaction to many of these same authors and to others to find the United States now in readiness to repay such debt to Mother Europe. In recent years Commonwealth Fund fellows have come to our country for 2-year studies from Cambridge and the University of London, England, CRB fellows from Belgium (Commission for the Relief of Belgium Educational Foundation) and a Volta fellow from Italy for the study of electrotechnics in lectures, classes, laboratories, factories, and fields of practice in the United States. From our own experience we realize the profound effect upon these young men that sojourn among us will have. What will they do in Great Britain and the British commonwealths, in Belgium and the Belgian



Trend in Maximum Transmission Voltages

Congo, in Italy and North Africa? Perhaps the electrification of the Nile Valley and the transmission of hydroelectric power from the high level lakes in the Himalayas to Calcutta, India, will be among their achievements.

Water Power Development

By W. S. Lee,* President A.I.E.E. 1930–31

Although energy derived from water has been utilized by man for at least 3,000 years, its greatest development has come within the lifetime of the Institute and after the first hydroelectric "central station" was constructed at Appleton, Wis., in 1882—a "250-light" installation. Since that time the utilization of water power for the generation of electricity has expanded until now the aggregate installed capacity of hydroelectric plants in the United States is more than 15,000,000 hp. Some significant events in this development are outlined briefly in this article.

FROM the crude water driven devices of ancient days, there has developed one of our greatest and most economical sources of energy—the modern hydro-electric development. For at least 3,000 years the energy derived from water has served to lift burdensome tasks from the shoulders of mankind. Today energy derived from water power performs a myriad of tasks to an extent but yesterday undreamed of, thereby serving mankind in providing his needs—food, raiment, and shelter. To outline the course of development through the centuries, from the early current wheels that served the simple needs of grinding grain and lifting water to the modern turbine driven generators that serve the complex needs of civilization today over vast transmission networks, is not attempted in this article.

The origin of the water wheel is lost in the shadows of the past, although over 30 centuries ago current wheels actuated by the energy of moving water were in use on the Nile, Euphrates, and other rivers of the then civilized world. From these free current wheels were developed the undershot, overshot, impulse, and breast wheels which operated in restricted artificial channels so that the water could be directed and controlled and the water head utilized as well as stream velocity. The fundamental principles of the present day turbine—wherein the water acts mainly by impulse or reaction or both, and the velocity has a definite relation to the head—can be distinguished in water wheels constructed in the sixteenth century. The development of the modern turbine can be said to date back to the early part of the nineteenth century when the outward-flow turbine was developed by Fourneyron and the axial discharge type by Jonval and Henschel. The inward-flow turbine, in which the action of the Fourneyron turbine is reversed, was patented by Howe in 1836 and was greatly improved by Francis about 1847, who is regarded by many as the originator of this type. In the course of development radical departures have been made so that the modern Francis turbine is of a combined radial and diagonal inward-discharge type. Impulse wheels were an early development, the first major improvements being made about 1853 by Atkins and developed to extensive use by Pelton, who, in 1882 and subsequent years, made radical changes and improvements in design. This type of wheel is used extensively for high head developments.

The first great water power development in the United States was made on the Merrimack River in 1822 near Lowell, Mass., followed by similar developments on the same river at Manchester, N. H., and Lawrence, Mass. These developments had capacities of 10,000 to 12,000 hp each, using a great number of wheels installed at factories along the various canals. These early developments followed by similar ones at Cohoes, N. Y., in 1828 and at Lewiston, Me., in 1849, were used chiefly by the textile industry which, due to the availability of water power, expanded at a rapid rate throughout the New England-New York area. In fact, this section of the country retained its predominating position in the textile industry until the extensive development of hydroelectric power together with other factors resulted in the movement of a large part of this industry to the South. The water power development of the Connecticut River at Holyoke, Mass., in 1848 and the developments of the Fox River in Wisconsin were devoted largely to paper manufacture. The water power of the Genesee River at Rochester, N. Y. (1856), and on the Mississippi River at Minneapolis, Minn. (1857), were utilized largely for the manufacture of flour. The year 1861 saw the beginning of development of power at Niagara Falls, a canal being constructed and in subsequent years water being delivered to various factories; in 1881 a central powerhouse was built, the energy being transmitted to a number of factories by means of belts, ropes, and shafts. In spite of the fact that the factory had to be brought to the power site and the machinery driven directly from the wheels, the utilization of water power continued to increase, there being in excess of 1,000,000 hp installed by 1870.

When the A.I.E.E. was organized in 1884, hydroelectric power was in an embryonic stage. An arc light machine had been installed at Quigleys Mill in 1881 supplying a few customers in Niagara Falls, and an installation of 250-light capacity had been made in 1882 at Appleton, Wis.; this latter generally is re-

* Deceased March 24, 1934; see ELECTRICAL ENGINEERING, April 1934, p. 636.

Some Hydroelectric and

(Left) A 1,500-kva 200-rpm water-wheel plant of 25 years ago, showing the inefficient method of driving the machines then in use
(Electric Mach. Mfg. Co. photo)

(Above) Little Falls power house of the Washington Water Power Company, showing the 150-rpm, 4,000-volt 5,000-kva horizontal cast frame generators (1909–11)
(General Electric photo)

(Below) Shop assembly of the first completed intake gate for the Boulder Dam development. This lower gate is 26 ft high and 37 ft in diameter, weighing 260 tons
(Westinghouse photo)

(Above) Twilight view of the 108,580-hp "Pit No. 3" hydroelectric station on the Pit River in Shasta County, Calif.
(Pacific Gas & Elec. Co. photo)

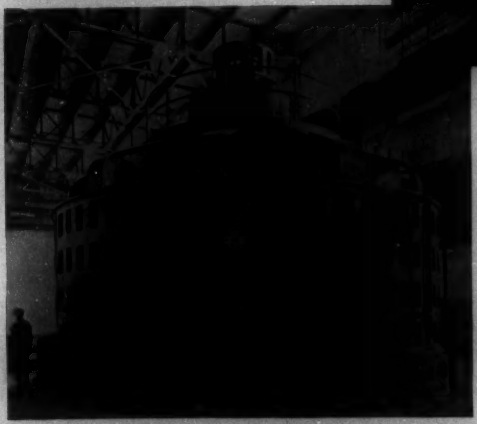
Power Stations Equipment

Old Colgate Plant on the Yuba River, Calif., from which the first 60-kv transmission line was constructed to Oakland, a distance of 110 miles
(Pacific Gas & Elec. Co. photo

(Above) Generator room of the hydroelectric plant at Dnieprostroy, on the Dnieper River, U. S. S. R. These 5 units, each rated 77,500 kva, were the first to be put in service; 9 turbines to develop a total of 750,000 hp have been installed
(General Electric photo)

(Top) Old Brown's Valley hydroelectric plant which was constructed by the Yuba Electric Power Co., in Calif., in 1889; it is now abandoned
(Pacific Gas & Elec. Co. photo)

(Above) Mill Creek No. 1 plant (Calif.) as it appeared in 1902. This plant, which was built in 1892–93, was connected to what is said to be the first polyphase high-voltage transmission line, a 3-phase 11-kv line extending from Mill Creek to Redlands (16 miles). The original installation consisted of 3 250-kw 2,400-volt machines, one of which is still in operation
(Southern Calif. Edison Co. photo)



(Left) One of the famous Niagara Falls 65,000-kva 107-rpm 12,000-volt generators, with air discharge housing removed showing the cast frame construction
(General Electric photo)

Chute a Caron hydroelectric development on the Saguenay River, Canada, about 125 miles north of Quebec and operated by the Alcoa Power Company, Ltd. This development supplies power for the production of aluminum and newsprint

ferred to as the first U.S. hydroelectric central station. In 1889 the first alternating current hydroelectric installation, consisting of 2 300-hp water wheels belted to single-phase generators, was made at Oregon City, Ore., by the Willamette Falls Electric Company, power being transmitted 13 miles to Portland. In 1890 the Telluride Power Company installed at Ames, Colo., 2 150-kw 3,000-volt single-phase generators, directly connected to Pelton water wheels, power being transmitted 5 miles to Telluride. The years 1892–93 saw the beginning of long distance transmission of electric power at San Antonio, Calif., 800 hp being transmitted 28 miles to San Bernardino. In 1893, the first commercial 3-phase installation, consisting of 2 250-kw 2,400-volt Y-connected generators, driven by Pelton wheels, was made by the Redlands Electric Light and Power Company in southern California, power being transmitted $7^1/_2$ miles to Redlands and there used for both lighting and motor applications. During this same year a polyphase plant was installed at Hartford, Conn., 400 kw being transmitted 11 miles at 5,000 volts. No attempt has been made to include all hydroelectric plants constructed in the 10-year period from 1884 to 1894, but only those in the United States representing major innovations and developments. Plants were being projected and built throughout the country, there being about 300 in operation by 1896, and it is entirely possible that the ones referred to are not the first of their particular types.

The year 1895 marked the beginning of the modern central station era and the recognition of the supremacy of polyphase alternating current for generation and transmission when the 5,000-hp units began operation at Niagara Falls. The turbines for these units were of the Fourneyron type, double-wheel, outward discharge without draft tube, and operated at 250 rpm at a head of about 140 ft. The guaranteed efficiency of these turbines was 75 per cent at full gate opening. The generators were of the umbrella type, the rotating field element being external to the stationary armature, 2-phase power being generated at 2,000 volts, 25 cycles. In 1896, power delivery from Niagara Falls to Buffalo began, the initial use being about 1,000 hp for the operation of street railways. Power was transmitted at 11,000 volts, 3 phase, the distance being approximately 22 miles.

Utilization of hydroelectric power resources has proceeded at an ever increasing rate since 1895 and far-flung transmission networks have been evolved. Generating units have increased steadily in size: 31,000-hp units were in operation in 1916, 70,000-hp units in 1924, and at the present time 115,000-hp units are under construction. To transmit the ever increasing blocks of power over greater distances, the transmission voltages have been successively raised: In 1896 the maximum commercial voltage was 25,000 volts; in 1903 the first 60,000-volt line was installed; and by 1909, 100,000-volt transmission was an accepted fact. Since then, 132, 165, and 230 kv lines have been installed extensively and a line is now under construction to operate at 275 kv; the next step is 330 kv and this seems not far off.

Growth of Water Power Development in the United States 1869–1933 as Shown by Capacity of Water Wheels Installed at End of Year

Year	Horsepower	Year	Horsepower
1869	1,150,000	1919	7,590,000
1879	1,250,000	1920	7,800,000
1889	1,300,000	1921	8,050,000
1902	2,050,000	1922	8,270,000
1907	3,250,000	1923	9,090,000
1909	3,870,000	1924	10,040,000
1910	4,220,000	1925	11,180,000
1911	4,530,000	1926	11,720,000
1912	4,770,000	1927	12,296,000
1913	5,480,000	1928	13,572,000
1914	5,790,000	1929	13,808,000
1915	6,140,000	1930	14,885,000
1916	6,470,000	1931	15,620,000
1917	6,800,000	1932	15,802,000
1918	7,110,000	1933	15,930,000

Not only has the size of individual units and of plants increased, but also the efficiency of unit, plant, and system has been steadily improved. Modern turbines in conjunction with the latest types of waterways, show efficiencies at rated load of well over 90 per cent even for low head plants and relatively small units; for the larger units, efficiencies of over 93 per cent have been obtained. Generator and transformer efficiencies have been improved, now being

in the neighborhood of 97.5 and 99.2 per cent, respectively, for large units. Transmission efficiencies due to unified system operation and proper design have been greatly improved. Thirty years ago a plant efficiency of 70 per cent was considered excellent; today 89 or even 90 per cent can be attained. Coördination of steam and water power resources, coördination and control of water storage facilities, coördinated operation of systems and the parts thereof, and coördination and coöperation to secure the maximum economic use of interconnection facilities between systems, have resulted in vast improvement in system efficiency.

The Duke Power Company, with which the author of this article has been connected since its inception, is taken as an illustration of typical power system development. Starting with one plant of 10,000 hp, which in 1904 began operation, generating and transmitting power at 11,000 volts, this system now has 598,000 kw in hydroelectric and 287,000 kw in steam facilities, the annual power generation being in excess of $1^1/_4$ billion kilowatthours. The transmission networks covering the Piedmont industrial area of the Carolinas consists of over 4,000 miles of circuits, approximately $^1/_2$ of which are 100-kv lines. Interconnection is made with adjoining power companies at several points where power interchange is economical and of mutual benefit. Of particular interest are the hydroelectric developments on the Catawba River, where 12 plants utilize over 90 per cent of the total head between el 140 ft and el 1,200 ft, and in conjunction with water storage facilities, provide almost complete regulation and utilization of the river. The Bridgewater, Rhodhiss, and Oxford developments on the upper reaches and the Catawba development located below the junction of the South Fork, have large storage reservoirs for retention of flood waters and excess river flow. The total reservoir storage capacity when utilized over the plants below amounts to 277 million kilowatthours; the development, construction, and coördinated operation of this vast storage with the run-of-river plants, steam, and interchange facilities, has been the result of careful study and a definite plan of procedure. The first development had a plant efficiency of about 70 per cent; many of the modern developments show plant efficiencies at full load of 88 to 89 per cent. Transmission efficiency has been steadily improved and for the year 1933 the efficiency of transmitted power from the generator terminals to the customer's meters was over 86 per cent. While this system has been discussed in some detail, it is but one of the many great hydroelectric systems whose transmission networks cover the nation. In the main, the story of one system is a story of all—maximum utilization of natural resources for the common benefit of power consumers and power producers.

Centralization and coördination of power resources have been effected solely for economic reasons: to give uniform and reliable service; to maintain and even lower power rates in the face of ever increasing costs; to make the investments sufficiently attractive that the properties can be financed; to afford the support of organizations highly trained in efficient planning, constructing, operating, and improving the systems and the parts thereof; and to engage aggressively in the development of additional power uses by domestic, commercial, and industrial consumers. Today the aggregate capacity of hydroelectric equipment installed in the United States is more than 15 million horsepower, generating about 35 billion kilowatthours annually; and the rate of increase is more rapid than for power generation by steam—from 1927 to 1932 installed hydroelectric capacity increased 37.6 per cent while the capacity of all prime movers increased 34.3 per cent.

While our great power industry as now constituted has contributed so much to the needs of mankind and has been such a great factor in the upbuilding of our nation, sinister shadows tend to stunt, if not to kill, future normal growth. We are faced not with constructive regulation for the greatest good to both power producer and power consumer, but with destructive governmental regulation, destructive governmental competition, and destructive taxation. Unless saner judgment prevails, this great industry will see its handiwork sacrificed to political ambition, political oppression, and political aggression—to the lasting benefit of none and to the detriment of all.

Interior of Chute a Caron station. The 4 units operate under a head of 150 ft and are rated 65,000 hp each

Some Reminiscences of Niagara

By P. M. Lincoln, President 1914–15

Although almost microscopic as compared with modern electric generators, the 5,000-hp generators installed at Niagara Falls in 1895 had a capacity of about 4 times that of the largest generator previously built. Some of the early operating experiences at Niagara are related here by a past-president of the Institute who was the first operating superintendent and who was in charge of the construction and operation of the original Buffalo-Niagara 11,000-volt 3-phase transmission line.

ELECTRICAL equipment of the Niagara Falls Power Company, which began operation in 1895, was unique in many particulars. First, it was unique in size. The electric generators installed at Niagara Falls in 1895 were of approximately 4 times the capacity of the largest previous electric generators that had ever been built. They were rated and were capable of carrying 5,000 hp. This rating is, of course, almost microscopic when compared with some of our present-day generators; but nearly 40 years have passed since the starting of the Niagara plant. I think I am correct in stating that the Niagara generators represent the largest *single step forward* that has ever been taken in generator design. It speaks well for the ability of their designer, Mr. B. G. Lamme, to note that these generators are still in operating condition and even now are used occasionally to carry a part of the Niagara Falls Power Company's load. That they have been taken out of regular service is not due to any deficiencies of the generators.

One of the farseeing innovations that Lamme introduced into Niagara generators was the use of mica as the insulation on the armature conductors. This choice of mica was fortunate. Tests made many years later showed temperature rises in the armature conductors that were totally unsuspected during the operation in the earlier years. These later tests showed temperatures of the order of 200 deg C under the heaviest loading conditions. The fact that Mr. Lamme's mica insulation stood up for many years under any such temperatures is not only a tribute to his genius in selecting mica as the insulation, but also is a commentary on the temperature measuring methods of that early day.

Another unique feature of the first Niagara plant was the design of the exciting system. While we can justly say that remarkable foresight and genius marked the design and construction of the first Niagara generators, the total absence of these qualities marked the design of the exciting system. It seems incredible, but it must be recorded, that the only exciters provided for this first Niagara plant consisted of rotary converters, which were to be run from the main bus bars. Fortunately, there was available in a neighboring building a direct-current steam-driven machine which had been used in connection with the construction of the wheel pit and water tunnels; this machine was used to excite the main generator for the purpose of starting the rotary converters that in turn were to be used for exciters. In case of an accident that would shut down the entire plant, we were helpless, of course, without this steam driven machine to enable us to start up again. For the first 2 or 3 years of operation it was therefore necessary to keep this steam driven machine either running or ready to run at a moment's notice, to guard against a total shutdown of the main plant.

A more unsuitable design for an exciter system could not be imagined. At the end of the first 2 or 3 years' operation, water wheel driven exciters were installed; and not until then were we free from the necessity of keeping this steam driven unit constantly ready for instant service. It is a commentary on the state of the art at the time that such an oversight could have occurred in the design of the exciter system.

Still another unique feature of the Niagara plant was the frequency adopted—25 cycles. The circumstances that led to the adoption of this frequency are set forth by Mr. Edward D. Adams in his "History of the Niagara Falls Power Company" (v. II, p. 236–8). As Mr. Adams points out, 25 cycles was a compromise. It is worthy of note, however, that 25 cycles became a standard frequency and was subsequently used to a considerable extent, particularly in the United States.

Niagara was unique in that it was primarily intended for *power* rather than *light* as were most of the preceding electric installations. It was one of the earliest and by far the largest electric power installation of the time. It was unique further in that the methods used for the generation and distribution of power were new and untried—at least on the scale attempted at Niagara—namely, *alternating current, polyphase.* Practically all the users of Niagara service were *power* users. The first user was what was then called the Pittsburgh Reduction Company, now the Aluminum Company of America. That plant started on August 26, 1895; it soon was followed by the Carborundum Company and soon after that by the Union Carbide Company. Other loads followed rapidly. The plant was suc-

Exterior of Niagara Falls power house No. 1

cessful from the beginning. There were troubles, of course, but none insurmountable.

Early users of Niagara power were local, located not over a mile from the power house. With the success of the local use of power, there naturally came consideration of its transmission to neighboring cities, particularly Buffalo. There was naturally quite some misgiving as to our ability to give satisfactory service in Buffalo, but this step was undertaken the year following the starting of the Niagara plant, that is, during the autumn of 1896. Many new problems arose in connection with the transmission of Niagara power to Buffalo. I think I can do no better than to quote from a report that I prepared some 15 years ago for incorporation in Mr. Adams' history of Niagara Falls.

[EDITOR'S NOTE: The remainder of this article is republished from "Niagara Power, History of The Niagara Falls Power Company, 1886–1918," by Edward Dean Adams, v. II, p. 276–86. These 2 volumes were published privately in 1927 by the Niagara Falls Power Company, Niagara Falls, N. Y., on the fiftieth anniversary of its foundation.]

REPORT OF OPERATING SUPERINTENDENT

The supervision of the details of material and erection of the transmission line was the responsibility of the company's resident electrical engineer and operating superintendent, Paul M. Lincoln, who describes his work in this connection by the following statement made in 1920:

The first Niagara-Buffalo transmission line on the American side of the Niagara River went into service during the fall of 1896. As the operating superintendent for The Niagara Falls Power Company, it became my duty to supervise the operations of this transmission line from the time it went into service in 1896 until I severed my connection with The Niagara Falls Power Company in May 1902.

The status of electrical transmission as of that date has been set forth in the preceding chapters. Suffice it to say that at that date the use of alternating currents for lighting was only 10 years old and its use for power purposes was almost unknown. The few previous attempts to use alternating currents for power purposes were exceedingly crude and were on a much smaller scale than that proposed for the Niagara-Buffalo transmission.

In the construction of the Niagara-Buffalo transmission line, such precedents as then existed were followed. These precedents in turn had followed the practice of telegraph construction—the only precedent there was to follow in that day.

The following statement is based on my personal recollections of 6 years' direct contact with this transmission, and is reinforced by the opportunity which has been afforded me of perusing the correspondence that passed at the time when the purchase of equipment for this transmission was contemplated.

The construction of the Niagara-Buffalo line followed the recognized practice of the period for telegraph lines—the only precedent there was to follow at that time. The poles, cross arms, pins, and insulators were of course heavier than those used in telegraph practice, also all poles on curves were either braced or guyed. At corners, double poles were used, but in other than these details construction was very similar to that used in the telegraph practice of the day.

The photographs reproduced herewith show but a single line on the poles; this is because these particular photographs were taken before the second line was erected. To meet the problem of continuity of service it was essential to have more than one transmission line available for use at all times. Two such lines were installed at the beginning, either one of which would easily carry all the power taken by Buffalo during the first few months or year. It was always the policy of The Niagara Falls Power Company to have a sufficient number of lines in service so that at any time one line could be shut down for inspection or repair and the remaining lines could easily carry all the power required.

The Niagara-Buffalo line was a relatively short one, only about 22 miles from the step-up station in Niagara to the step-down substation in Buffalo. Today this would hardly be called a transmission, but rather an enlargement of the distribution area. Also, the voltage used was not high—11,000 volts—3-phase—a voltage that today would be viewed as a distribution voltage. Other plants, even at that time, were transmitting power at higher voltage than that. However, in some aspects the Niagara-Buffalo transmission was unique and of historical importance. In the amount of power transmitted and in the importance of the service rendered by the transmitted power, the Niagara-Buffalo transmission transcended anything that had been attempted previously. The first load in Buffalo to be operated by this transmitted power was the street railways of Buffalo. Any failure of transmitted power was, therefore, heralded immediately throughout the entire community. Other loads were soon added which were almost as important. The first requisite for trans-

Original 5,000-hp 2-phase Niagara generators

Although the a-c system had been pronounced impossible for Niagara, these Westinghouse generators, built in 1894–95 and several times as large as previous a-c machines, are still operating. The external revolving field design prevailed for the first 10, then the internal revolving field was used.

mitted power was therefore *continuity*. It soon developed that the success or failure of Niagara power in Buffalo depended on keeping the supply *continuously* available in Buffalo. Then, therefore, began the long battle for *continuity of service*, a battle that has been waged not only on the Niagara-Buffalo line but on every other transmission line that has gone into service since then.

In 1896, transmission line equipment was not what it is today. Lightning arresters were totally inadequate; the oil switch was not yet known; the insulator was woefully defective and such a thing as reversed power protection was not even dreamed of. The experiences of the Niagara-Buffalo transmission were to have a material effect on the evolution of transmission technique.

Lightning

Lightning was one of the first as well as one of the most formidable enemies that the Niagara-Buffalo transmission had to fight. There never has been a complete answer to the lightning problem, but at that period there was hardly even a beginning to the later progress. The bettering of line insulation and construction has been one of the chief factors that has reduced interruptions from lightning. Nothing has been developed that has eliminated *all* interruptions from lightning and in my opinion there will be no such development. A direct stroke of lightning is almost sure to cause an interruption of service on the line affected; if, beyond this, equipment attached to the transmission line is not destroyed, the operators may consider themselves fortunate. Direct strokes, however, are not common and it is a lucky thing for the transmission of electric power that this is the case. But there are severe strains imposed on the insulation of transmission lines and the equipment connected thereto whenever lightning occurs anywhere in the neighborhood of a transmission line. The severity of these strains depends on the severity of the lightning discharge as well as its proximity. Against these indirect effects it is possible to secure some degree of protection. In 1896 the amount of protection that could be secured was an unknown quantity.

Alexander J. Wurts of the Westinghouse company had been doing valuable work on the problem of lightning protection. (See paper by Mr. Wurts, A.I.E.E. Trans., March 1892 and May 1894.) He had developed a so-called "nonarcing" lightning arrester, a series of cylinders made up of metal that would permit the lightning discharges to pass, but presumably would prevent the generator current from following. These arresters were tried out on the Niagara-Buffalo transmission line with considerable hope that they would perform as expected. However, it was soon found that the low frequency in use on the Niagara system coupled with the large amount of power in the installation back of the line, caused almost a complete failure of the so-called "nonarcing" properties of these arresters. An arrester which would operate with perfect success on a system of a few hundred kilowatts failed utterly to quench the arc when the Niagara generators were back of that arc. This was one of the points where the size of the Niagara system introduced a new problem. It was found that in order to make these arresters suppress the arc successfully it was necessary to introduce a resistance into the discharge circuit to limit the amount of current that could flow. This in turn limited the effectiveness of the arresters.

Both the Westinghouse and the General Electric companies worked ardently on this lightning arrester problem but neither was able to produce a complete solution. In fact it has always been a serious question in my mind if the lightning arrester on the Niagara-Buffalo line accomplished anything at all toward continuity of service. There may have been some occasions when the arresters took care of lightning surges that might have caused damage and interruption of service without them; also there were other occasions when the failure of the arresters to quench the generator current caused service interruptions that would have been avoided if there had been no arresters. The use of lightning arresters on transmission lines is still a mooted question. In general it has been found that the higher the voltage of transmission, the less necessary lightning protection becomes. With the very high voltage used in some of our latter-day transmissions, the voltage strains caused by lightning are but little if any higher than the normal voltage strains. The higher

the voltage used for transmission, the less necessary becomes lightning protection, due to the fact that the operating voltage requires so high an insulation. All this, however, was not known in 1896, and we at Niagara had to pass through the labor pains of the birth of this knowledge.

The design and construction of the first Niagara-Buffalo line incorporated one method of protection against lightning that proved disastrous. Theoretical considerations indicated that grounded guard wires over the transmission lines would be effective, at least to some degree, in shielding the transmitting conductors from lightning. Three such guard wires were installed on the original line. Unfortunately, however, the material selected for these guard wires was standard barbed fence wire. So long as the guard wires remained intact they were undoubtedly effective to a considerable degree in protecting the line. But the material of these guard wires was not equal to the strains put on them in this service and occasionally they would break and fall across the transmitting conductors below. This would cause a short circuit and usually a complete interruption of service. The worst of it was that often service could not be restored until the broken guard wires had been found and removed. Guard wires, therefore, were not found to be conducive to continuity of service in this case. After the experience of a few of these guard wires being broken, the guard wires were removed.

In passing, I might remark that this experience has not shaken my faith in the efficacy of guard wires as protection against lightning. It is still my opinion that guard wires properly installed constitute the best protection available against lightning; however, the "properly installed" should be emphasized.

To recapitulate, lightning was probably the greatest single cause of service interruption on the Niagara-Buffalo transmission, partly because of the severity of lightning storms on the Niagara frontier and partly because of the insufficiency of knowledge in methods of combating the difficulty. Not a small part of this knowledge resulted from our experience on this particular transmission line. While we were not able to obtain perfect protection from lightning, the interruptions we were getting at the end of my 6 years' connection with the Niagara-Buffalo transmission were not so serious as at the beginning. We were continually getting the better of the problem of interruption by lightning. This is evidenced by a record of more than a year's operation without a single interruption of service from lightning or any other cause—a record that has been made by this Niagara-Buffalo transmission.

Line Insulators

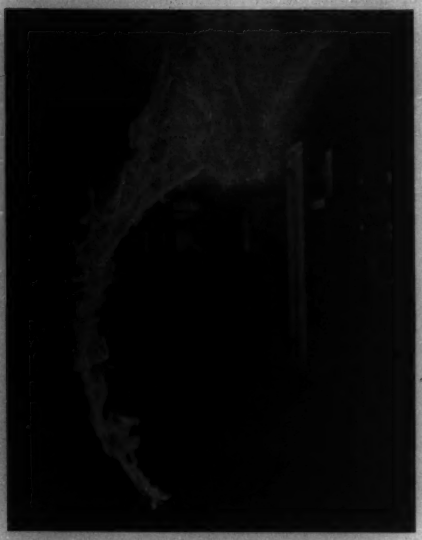
The line insulator constituted another problem that we on the Niagara-Buffalo transmission had to meet and meet with but little previous experience to guide us. The early transmission lines followed the practice already set by the telegraph. The only previous departure from this practice had been the Frankfort-Lauffen transmission in Germany during 1891. In that installation, power had been transmitted from a water-power [station] at Lauffen to the city of Frankfort—a distance of about 100 miles. 30,000 volts was used in this installation—a voltage far above anything that had been used previously. The installation was not intended to be a permanent one. One of its main purposes was to advertise an exposition then going on in the city of Frankfort, and it was more or less of an experiment. The insulators used on this transmission were provided with an oil cup so designed that an oil covered surface was interposed into the path of any leakage current over the surface of the insulator. At that time, it was not considered practicable to use any other type of insulator on so high a voltage. It is also noteworthy to observe that in its earlier proposals for the insulators on the Niagara-Buffalo line (made either late in 1893 or early in 1894) the Westinghouse company proposed to use similar oil filled insulators. Apparently the oil filled insulator idea was later abandoned and both the Westinghouse and the General Electric companies proposed insulators of the general type later adopted. This is of interest as indicating the unsettled state of the transmission art at this early day. The drift of actual practice has been entirely away from the oil filled insulator. So far as I know, the Frankfort-Lauffen transmission was the only case in which oil filled insulators were ever actually used in power transmission, but they were seriously considered in 1893 or 1894 for use on the Niagara-Buffalo line.

Helmet type insulator used on original Niagara Falls-Buffalo transmission line

(Right) Wurt's lightning arresters at Niagara end of Buffalo transmission circuit, 1913

There were a number of designs of insulators tried out on the Niagara-Buffalo line. In every case the material was porcelain, but the shape, size, and method of manufacturing differed. Among other types a large number of porcelain insulators made by the dry process were installed. These insulators were more or less porous and after some months of operation would absorb enough moisture to become slightly conducting. This in turn would lead to the burning of pins, cross arms, and pole tops. Many difficulties of this nature were encountered and

eventually all insulators of this type were taken down and rejected. To eliminate insulators of this character we developed the method of soaking them in salt water, using a salt water bath in which the insulators were partially immersed upside down and then filling the pin hole with salt water and applying the test voltage between the water in the pin hole and that of the bath. After this method of test had been adopted the defective porous insulators were quickly detected and rejected. In all about 40,000 of these dry process insulators were rejected in connection with this transmission. In many cases, however, the rejection did not take place until after the insulator had been in service for some time and



Fuse-release 10-kv Niagara circuit breaker

Melting of a fuse released a hinged arm 4 ft long which fell, drawing a momentary long arc. This type was used on the early Niagara Falls-Buffalo circuit

had had the opportunity to contribute its quota against us in our battle for continuity of service.

Except for our disastrous experience with these dry process insulators, the porcelain insulators we used at Niagara were fairly satisfactory. We knew more about the insulator problem after our 6 years' experience than we did before, of course, and the design and construction of porcelain insulators received a decided impetus from this experience. It is worthy of note, too, that one of the modern underlying types of insulators—the Hewlett-Buck insulator (suspension type now almost universally used on high voltage lines)—had its origin in connection with the Niagara-Buffalo transmission line. This particular type of insulator was not used, to be sure, on this first line but the problems of this line induced its conception.

Switches and Protective Devices

In 1896, protecting devices for transmission lines were conspicuous by their complete absence. The oil switch had not yet been conceived and there was no method known by which a short circuit on an operating transmission line of the capacity we had at Niagara could be opened without shutting down the entire system. The only overload protection we had at the beginning of operations was fuses. It soon developed that the fuse under these conditions was a menace and not a protection. The amount of power to interrupt was so large that the fuses of that day could not begin to interrupt a short circuit successfully. After this fact had been demonstrated by several sad experiences, all fuses were removed. The only alternative was so to arrange that the entire plant would be shut down in case of a short circuit. This was accomplished by causing the field circuit breakers on the generators to trip in case a short circuit came on and persisted. Since most of the short circuits occurred on the Niagara-Buffalo line, it soon became necessary to separate the transmitted load from the local load so that an interruption on one need not involve the other. There were a great many more short circuits on the transmission line than there were on the locally supplied load and the local load users objected strenuously to being shut down every time a short circuit occurred on the transmission lines. Hence the separation of the 2 loads.

The necessity of shutting down the entire system whenever a short circuit occurred pointed strongly to the necessity of securing a switch that was capable of interrupting a short circuit. No such switch existed at that time and the problem was put up to the manufacturing companies for solution. The General Electric Company started the development of the oil circuit breaker while the Westinghouse company preferred a design that used long air breaks. As development proceeded and experience was accumulated it was apparent the General Electric Company had chosen the right path in this case. While air break switches might be satisfactory on the 11,000 volts that the Niagara-Buffalo line started with in 1896, it became evident as experience accumulated that with higher transmission voltages which was expected to be adopted within a few years, the air break switch would not be satisfactory. Even with the 11,000-volt transmission, their operation was far from satisfactory. I personally saw its operation on one occasion when a heavy short circuit caused the opening of one of these air circuit breakers. The arcs drawn were at least 6 feet long and maintained for nearly 15 seconds. The results obtained were so unsatisfactory that we went back to the method of interrupting the entire load in case of trouble.

One of the earliest models of the oil switch was brought to Niagara Falls by the General Electric Company for trial. The early trials indicated that

this method of attack would be successful—and experience later proved this to be the case. Today, no one would think of using anything but an oil switch with voltages and amounts of power such as we were dealing with at Niagara. The General Electric Company was the first to make a move toward using oil to quench the arc in switching, but soon after it had proved successful the Westinghouse company followed and today not only these 2 companies make this type of equipment, but many smaller companies also. The significant thing which I wish to emphasize here is that when the Niagara-Buffalo line began operations, there was no known method of successfully interrupting a short circuit. Our only method of procedure was to shut off the entire power supply under that condition. It was one of the handicaps of being a pioneer in the transmission game. This particular handicap was a very serious one since our battle at Niagara was to secure *continuity of service*. By the method of operation we were obliged to adopt, every short circuit on the transmission system meant a total interruption of power. It was, therefore, our endeavor to reduce the short circuits on the transmission line to a minimum.

Before leaving the subject of switching, perhaps a word concerning the first switchboard installed with the original generators might be in order. One of the items of this board was a series of air operated switches. When these switches were designed and built in 1894–1895 they were the best that the art afforded. It was confidently expected that they would be able to interrupt any load that might be thrown upon them. However, it required but a very brief experience after the first generators had been put into operation to realize that these switches would be totally useless to interrupt short circuits. They were used as synchronizing and disconnecting switches but beyond that they were useless.

In passing it might be observed that this problem of interrupting short circuits on the very large capacity high voltage modern transmission lines has proved to be one of the most difficult that the transmission engineer has met. The oil switch has proved the best means of meeting this problem that has been found, but even the largest and most powerful oil switch made is taxed to its utmost with some of our larger power systems behind it. Continuity of power supply requires that some means be used to disconnect defective portions of a transmission system and allow the remainder of the system to go on supplying service to the unaffected portions of the system. The need of such a switch was recognized in the early days of the Niagara-Buffalo transmission but we had to struggle along without it.

Interruptions From Miscellaneous Causes

Two other causes of service interruption were met on this Niagara-Buffalo line, *viz.*, accident and malicious mischief. While accidents were not common, they did occur occasionally. For instance, on one occasion a dredge operating in the canal, along which ran the transmission line, raised its dipper into the line, thereby short-circuiting the line and temporarily shutting off Buffalo's power. On another

Original Niagara Falls-Buffalo 3-phase 11-kv line

occasion, a cat crawled in behind the lightning arresters in the step-up transformer station and caused a complete short circuit and shutdown. Another very peculiar case occurred when a gang of men were cleaning the right-of-way from trees. A tree being felled, struck the end of a crooked limb lying on the ground and caused it to ricochet into the air; by an unlucky chance it fell across the transmission line and lodged there. The limb was green and just conducting enough to carry some current from conductor to conductor. The limb on the conductors confined this current to the point of contact and the burning continued until the transmission conductor itself was entirely burned apart and fell to the ground. This accident not only interrupted power supply to Buffalo, but it completely disabled that line until repairs could be effected. On still another occasion lightning caused an arc to form between the transmission conductor where it emerged from the step-up substation at Niagara and the edge of a metal canopy that had been erected to protect the conductors at their point of entry. This arc continued until the conductor was burned in two.

Some little trouble was caused by malicious mischief makers. The ubiquitous small boy found that he could cause a very spectacular display of fireworks by throwing a piece of wire over the transmission line. He little realized that he thus deprived momentarily a whole city of its power supply. Proper coöperation with the local police authorities along the line reduced this mischief to a minimum.

I might go on indefinitely giving instances of the difficulties that we encountered on this early power transmission. They all lead to one conclusion; we were pioneers and we suffered the fate of all pioneers. The road we were traveling was not yet illuminated by the light of experience. We had to grope our way. We were not wholly unsuccessful in lighting the way for others to follow. The Niagara-Buffalo transmission was a success both from a financial and from an engineering standpoint. The battle for continuity of service was waged and won. It has always been a matter of no little self-satisfaction that we at Niagara have helped to blaze the trail that since then has become a much traveled highway.

Some Contributions to the Electrical Industry

By C. C. Chesney, President A.I.E.E. 1926–27

Some outstanding individual contributions of the past 50 years to the electrical industry are reviewed here by a past-president who himself has made no small contribution; he says: . . . "as we of the electrical fraternity hope for continued progress, we must remember that our hopes can be fully realized only by remaining true to the greatest of our traditions, 'to produce and to serve.'"

AS WE LOOK BACK into the history of the electrical industry and visualize the past 50 years, we can hope, yea, expect that future accomplishments in the electrical world will be fully as eventful as the unmatched events of the past. Promises that come from home and abroad are filled with predictions of continuous progress.

This optimistic sentiment, emanating not from one but from all of the many responsible sources throughout the world, applies not only to the business side, but also to the scientific side of the industry—to the central station business for furnishing light and power, the core of the industry with its investment values already reaching the $10,000,000,000 mark, a value greater than the combined value of the industries of England of the Gladstone period when Michael Faraday made his fundamental discovery of magnetic induction in 1832. It applies also to the possible future accomplishments of the research laboratories, forecasts of which are to be found in the accomplishments already given to the world by these institutions.

These forecasts are full of hope, so far as it is given to fallible man to read the future, and they may well bring pride to the heart of the electrical engineering fraternity as well as to the whole world. Coupled with that pride is a spirit of gratitude on the part of the present generation of engineers toward those who have given their lives and their leisure in establishing the fundamentals on which electrical science and industry are built.

In that spirit I am prompted at the outset to dwell upon the versatile achievements of Thomas A. Edison. However, as my association has been entirely with that part of the art which had to do with the manufacture of generating machinery for the transmission of power by the use of alternating currents, I propose to review the early history of the electrical profession for outstanding individual contributions peculiar to the development of the science and art of transmitting power by the use of alternating currents.

The salient feature of the art of generating and distributing power at the present time is the superpower system, that is, an interconnection of existing and prospective generating and distributing systems. The broad idea of the superpower system must continue to grow more and more, because it is economically sound. It brings about an improvement in the load factor of the generating system; it allows the metropolitan markets for power to be connected in a continuous system with remote power reserves, and makes the exchange of energy from one part of such a system to another a practical, reliable, and everyday occurrence. Many are the engineering problems involved in the safe operation and satisfactory service of an interconnected system. However, electrical engineers already have solved these problems or are well advanced in their solution. For instance, the spreading of the troubles of one system to the next (bugbear of the past) is prevented by proper relaying and sectionalizing.

The holding of the proper voltage at different points, and the prevention of the flow of wattless current, are accomplished by adjusting automatically, if necessary, the ratio of the transformers so that the voltages at the point of connection may be of the same value and have the same phase relations. The interconnection of electric systems constitutes also an important progress in civilization, because it aims to allow electric energy, like sunlight, to become available everywhere.

It is well known that a discovery in the sciences is not an isolated event. The laws of nature have ordained that progress or change is never by leaps or revolutions. This is true, of course, of electrical engineering and the branch of it that deals with long distance transmission of power by means of alternating current. It has grown as does a snowball, by the process of almost infinitesimal additions. Practically every experiment or new development in the generation, transmission, and conversion of electric power is a modification of an experiment that has gone before. Almost every new theory is built through the contributions of many workers, of many different elements, one adding a little here and another a little there; thus to the observer in retrospect, progress seems to be continuous and uniform.

I wish, however, to emphasize the fact that the changes introduced into the art during the early '90's of the last century by the engineers of that period have placed the whole structure of electrical art of today as applied to light and power, firmly on the use of alternating currents. These changes have made economically possible the generation of large amounts of power in suitably located central stations, and its conversion and transmission to those points where it can be used most advantageously by

industry to operate and to increase the capacity and the economy of our mills and factories; to provide electrical transmission to the small town and country; to extend and improve the processes of metallurgy; and now to place in the homes of the great agricultural classes, through the use of electric power, the comforts and conveniences of the city, and to place in the hands of the farmer the opportunity to extend the economy of the farm to a point where it may compare favorably in efficiency and effectiveness with the factory and the workshop. Thus will the nation be prepared, through the aid of the superpower systems, for a complete decentralization of industry, which is needed ultimately to relieve the economic stress of both farm and city.

Nevertheless, to me the outstanding accomplishments of this period which made for the greatest progress were: the broad generalization of electrical phenomena, and the mathematical formula for the design of alternating current machinery by Charles P. Steinmetz; the invention and development of the modern transformer by William Stanley; the invention of the induction motor by Nikola Tesla;

The original transformer built by William Stanley in 1885

the induction meter by Oliver Shallenberger; the dynamo-electric machine by Benjamin G. Lamme; and the numerous contributions to all branches of electrical machinery by Elihu Thomson.

In 1886, William Stanley, in the first alternating current plant in America, which was engineered and built by him at Great Barrington, Mass., demonstrated how electric power could be generated at a low voltage, transformed into a higher voltage, transmitted at the higher voltage, retransformed to a lower voltage, and used at this voltage as might be required. This feature of adapting the voltage to varying requirements, and of maintaining it substantially constant, irrespective of the load, rendered possible the enormous development and progress in the distribution and transmission of electric energy that have taken place since.

This capability of voltage transformation lies in the transformer itself, insignificant though it may appear. Stanley always spoke of the transformer as the "heart of the alternating current system." Naturally the great development of the art has been accompanied by a similar development of the transformer. Very early Stanley had properly visualized the fundamentals of transformer design, and correctly solved many of its problems in the Great Barrington installation. This revealed a thorough understanding on his part of electromagnetic induction, rather surprising for 50 years ago. The same ability in handling these laws as applied to transformers was shown by Stanley in the construction of the inductor alternator, which had no windings on the rotor, a feature considered of much value at the time. The inductor alternator, as well as the Stanley induction motor and the Stanley induction meter, did not survive; but the transformer did, and is substantially the same as the one originally built by Stanley.

The possibilities of the alternating current system early appealed strongly to the imagination of electrical engineers, both at home and abroad, but they appealed to none more strongly than to William Stanley. At 30 years of age he had a full conception of the alternating current station idea of manufacturing power, that is, the manufacture of power in

An early Stanley commercial transformer with front plate removed showing arrangement of fuses

large volume in some suitable location, transmitting and distributing it to points of consumption by the use of alternating current. With this idea firmly fixed in his mind, and fully determined to find out at

Pittsfield, Mass., whether there were any limits in sight barring the use of line potentials higher than the 2,000 volts then generally employed, he instructed me to design and build, in 1892, transformers and a line for 15,000-volt operation. To this end

Westinghouse Photo

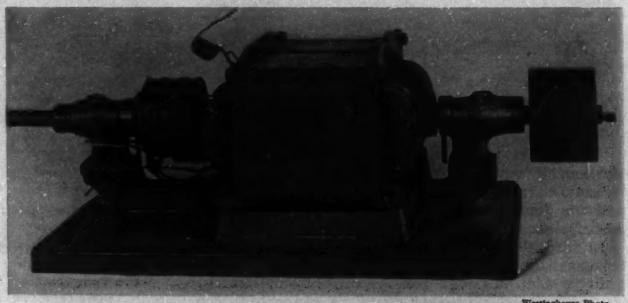
Induction type ampere-hour meter invented by Shallenberger in 1888. This was the first a-c integrating meter, and it is the parent of all a-c watthour meters now in use

we erected a pole line, built a transformer house, and set up the transformers. These increased the potential of the town circuit from 1,000 volts to 15,000 volts. We connected the line to this high potential supply, sent the current around a farm and back to the same transformer house, then retransformed the line potential to 1,000 volts, and operated the distribution transformers of the local company. This little plant was operated during a New England winter with entire success, and the engineering data obtained were the reason for subsequent recommendations by the Stanley Electric Company for the use of potentials much higher than 15,000 volts. I recall these facts only to emphasize the undeveloped state of the art of that early period of which I speak, and how limited and provincial was its outlook compared with our present-day accomplishments.

Nikola Tesla invented the induction motor in 1888. This invention was a great step forward, and it has been stated frequently that the invention of this motor was one of the greatest advances made in the industrial application of electricity. This statement without doubt is true, but the development of the motor was long and costly, and as late as 1895 it was still in the experimental stage. Vital reasons for its slow progress, development, and application were: First, it was primarily a polyphase motor, and the alternating current plants of the day were single phase; second, these plants operated at a frequency of 133 cycles per second, and subsequent studies revealed that this frequency was not well suited for that type of motor. By 1895, however, its development through the aid of many other electrical engineers, was far enough advanced so that a good commercial motor became available.

The invention of the induction meter by Oliver Shallenberger was vital and important in the growth of the electrical industry. Until the invention of this interesting and much needed device, there was no instrument to measure the quantity of alternating current supplied to the consumer. While the meter operated on the same fundamental principles as the Tesla motor, Shallenberger invented the meter entirely independently of Tesla. While Shallenberger was observing the movement of a spring in an alternating current arc lamp, under the influence of a shifting magnetic field, the idea of the induction meter came to him. Within 2 weeks after he had conceived the idea, he designed and built a most successful alternating current meter of the induction type. This meter was accepted immediately as a success by the electrical industry and the public—a long time before the induction motor was accepted as such. While Shallenberger's particular meter has long been discarded, its influence on the development of the struggling industry was great indeed. He died in 1898, before he had an opportunity fully to appreciate or to enjoy the success of his labors.

The engineering talents of the late Benjamin G. Lamme, an engineer and inventor endowed with unusual ingenuity, resourcefulness, and good judgment, presented to the art the synchronous converter, the rotary condenser, and also the electrical design of the 5,000-hp generator—a far bigger generator than had ever been built up to that time—



Westinghouse Photo

Early laboratory model of Tesla motor with wound rotor and slip rings

which inaugurated the hydroelectric power development at Niagara Falls in 1895. This type of generator has persisted to the present day. The single-phase railroad motor and the introduction of the squirrel-cage induction motor with high starting torque, were the individual works of Mr. Lamme.

Of the contributions of Charles P. Steinmetz there is little to tell electrical engineers; they all know, and they knew him and recognized him among the leaders of modern science. His personal contributions to the science and the art of long distance power transmission by alternating current were many and valuable. To me, however, it has always seemed that his greatest contributions to the electrical art of our day were his writings, embracing the results of theoretical and experimental scientific investigations. In these is laid an invaluable mathematical foundation for the design of electrical machinery. His work in this respect has no equal in our day.

Elihu Thomson's contributions to the electrical industry have been so many and are so generic in character that it is almost impossible to select any one contribution from his work of the last half century which overshadows in importance and value any of his others. His remarkable depth and range of scientific knowledge have influenced in a major way the development in every field of electrical endeavor. A master of industrial research, he invented many early types of lightning arresters, magnetic blowout switches, the induction regulator, and the single-phase repulsion motor. From a power transmission and distribution standpoint, one of his most important contributions was his proposition to use oil for insulating and cooling transformers, a practice now universal the world over and upon which the success of the progressive and ever increasing power transmission potentials has depended.

Steinmetz observing artificial lightning flash in his laboratory, February 1922

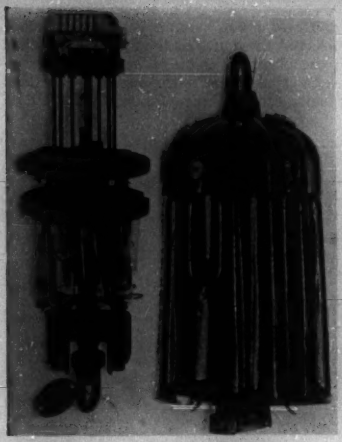
I have selected these men as the most outstanding among all the electrical engineers and inventors of that pioneer period, the closing decade of the last century; their accomplishments more than those of any other group, made possible the high state of the art of transmitting and distributing electric energy as we find it and as we enjoy it today. It was through their insight into, and their solution of, the technical problems that beset them, and by their foresight in reading the future promises of their time, that they were able to blaze the trail not alone for their contemporaries, but for future generations as well. It was their glory to be able to catch a glimpse of what was before us while the rest of the world wondered. On the traditions of the past, a great future for electricity and for the transmission of electrical energy is predicated. However, as we of the electrical fraternity hope for continued progress, we must remember that our hopes can be fully realized only by remaining true to the greatest of those traditions, "to produce and to serve," and by cherishing the ideals and emulating the ceaseless activities of such pioneers as those mentioned.

Thompson induction regulator of the late '90's

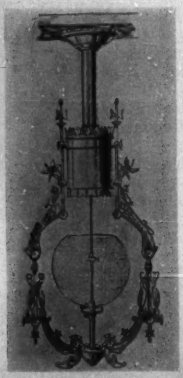
All 6 of these men possessed the scientific spirit. They were truly men of research, with patience and vision, always seeking earnestly and hopefully for new knowledge, more fully to understand Nature's laws as they are, and more effectively to use those laws for the benefit of humanity.

Some Early Forms of Electric Lamps

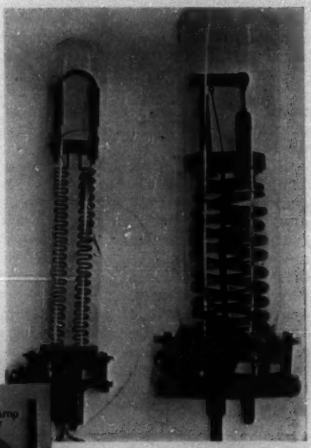
Arc lighting, now practically nothing but a memory, was the electrical industry's first commercial load. The fortifications of Paris were arc-lighted in 1870; in 1875 arc lamps came to America (Wallace Farmer system) where commercial success began about 1880 under the developments of Brush, Thomson-Houston, Weston, Waterhouse, and others. The incandescent lamp, however, and particularly since the development (1906) of metallized filaments, has waged a winning battle. Although, of the total present power output in the United States, lighting accounts for only about 25 per cent, as late as 1912 it constituted half the central station load



The Nernst lamp (above), more efficient than the early carbon filament lamps, burned in the open air and bade fair to win wide acceptance until succeeded by the Mazda
(Westinghouse photo



Right—An early design of ornamental open carbon arc lamp for interior use (list price $651)
(General Electric photo)



Early forms of incandescent lamps said to have been in operation almost a year before Edison developed his commercially practicable incandescent lamp
(Westinghouse photo)

Typical lamps of the 1905–34 period, and an indication of the improved light efficiency of incandescent lamps
(General Electric photo)

Left—from left to right—the "stopper" lamp that lighted the 1893 Chicago Fair; Weston lamp, Weston base, 1882; U.S. Lamp Co. lamp, Weston base, 1882; Sawyer-Mann lamp, 1879, Thomson-Houston base
(Westinghouse photo)

Right—Edison lamp first commercially used; carbonized bristol board "horseshoe" filament, produced Nov. 1879–May 1880; total height 8 1/16 in.; bulb diameter 3 1/8 in.
(General Electric photo)

Lighting "A Century of Progress"

By W. D'Arcy Ryan,* Associate A.I.E.E., General Electric Co., Schenectady, N. Y.

Since the Columbian Exposition at Chicago in 1893 gave to the world its first large outdoor display, electric illumination has played a vital and striking part in the great expositions. At San Francisco in 1915 the illumination was classed by the International Jury of Award as a "Decorative Art"; at Chicago in 1933 the lighting was conceded to be an outstanding feature of the exposition in spite of the fact that it was almost an afterthought. In this short article the author gives a general description of the exterior lighting effects; illustrates some of the equipment used and the results obtained.

—Editor.

IN JANUARY 1933, approximately 4 months before the opening date of the Exposition, engineers of the General Electric Company and the Westinghouse Electric & Manufacturing Company were commissioned to complete the exterior lighting of Chicago's *A Century of Progress* exposition. Obviously, the lighting of a group of buildings of ultra-modernistic or futuristic design such as those comprising the exhibit buildings at this exposition introduced many problems in lighting if the daytime architectural character was to be preserved at night. The late Joseph Urban, with his flair for bold color treatment and effects and ably assisted by his associates Teagan and Scott had skilfully used color to vitalize and unify the grouping of the buildings for daytime effect. At night the medium by which to accomplish these same ends was light.

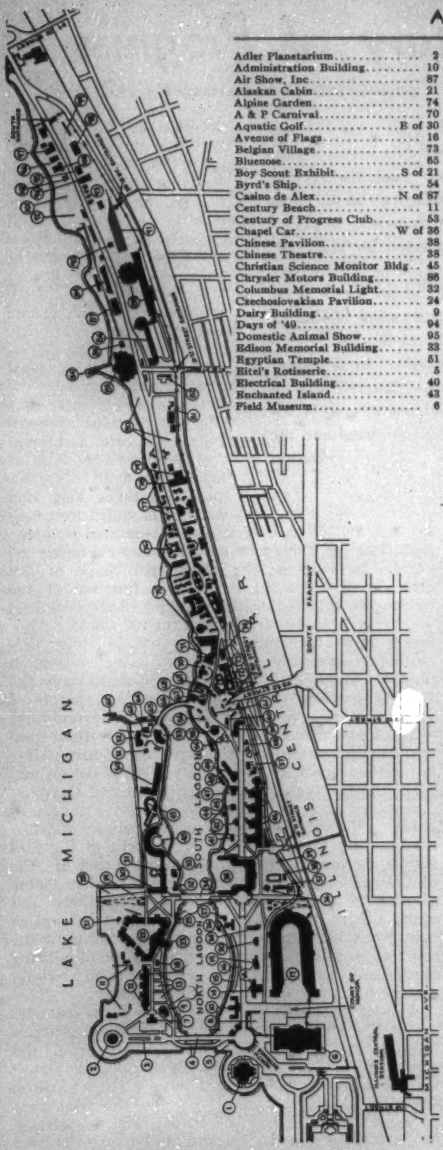
Many engineers and designers contributed to the accomplishment of the lighting results, aided by the tireless and efficient efforts of many contractors in constructing and installing the equipment. I should like to mention by name these many engineers, designers, and contractors who are entitled to share in whatever credit attaches to the results obtained, but I fear that if I were to attempt to formulate such a list I should overlook many worthy contributors. I feel obliged, however, to acknowledge the work of E. D. Tillson who during the period that he was associated with the exposition as illuminating engineer laid the groundwork which proved very valuable to us who followed, and R. E. Barclay whose enthusiastic studies in the application of the gaseous conductor tube resulted in many striking and beautiful effects by these light sources. To C. W. Farrier and his staff is due the credit for the design of many of the lighting standards and much helpful and constructive criticism of the lighting scheme. The installation of the lighting equipment, including the design and installation of the entire electrical distribution system, was under the capable supervision of J. L. McConnell, electrical and mechanical engineer of the exposition, whose willing coöperation made it possible for us to overcome many obstacles.

In this paper I shall confine myself to a general description of the exterior lighting effects, and trust that a more detailed description of the numerous elements entering into the general scheme will be recorded in the technical press by those responsible for their development. Also, although consideration of the lighting of the building interiors and of the exhibits and exhibitors' buildings is outside the scope of this paper, I want to pay tribute to those responsible for the design and execution, for to my mind these lighting effects in many instances exceeded those of the exterior.

The exposition site (Fig. 1) contains approximately 424 acres and forms a strip along the shore of Lake Michigan approximately 3 miles long and varying in width from 450 to 3,200 ft. Northerly Island is separated from the mainland by 2 lagoons covering approximately 80 acres. In view of the attenuated shape of the grounds we regarded it to be a function of the lighting to consolidate the grouping of the buildings and create the appearance of a unified whole. Also, owing to the generally low types of buildings prevailing, it became a secondary consideration in planning the lighting to elevate, psychologically the exposition when viewed from the many points of vantage throughout the grounds. The buildings were of an entirely new style of architecture compared with expositions of the past, presenting large flat surfaces painted in a wide variety of colors, and with viewing terraces at many levels and therefore demanding an entirely new approach from the standpoint of lighting the buildings themselves and the surrounding grounds. The probability of fog and smoke became a factor of consideration in the determination of surface brightnesses and probable viewing distances. All these considerations and many others including a limited budget entered as compromising factors into the determination of the most appropriate and most efficient type of lighting equipment, a detailed description of which would require more space than is warranted here.

The exterior lighting—which we may consider under the topics of building floodlighting, grounds lighting, and spectacular lighting—made up a total connected load of approximately 3,000 kw. Power was purchased from the Commonweath Edison Company and distributed through the secondary network 4-wire Y 120/108 volts. Mr. McConnell has stated that in only one imperative consideration is the electrical installation at *A Century of Progress* directly comparable to ordinary engineering work,

* Deceased March 14, 1934; see p. 636, ELECTRICAL ENGINEERING, April 1934.


LAKE MICHIGAN
SOUTH PARKWAY
ILLINOIS
SOUTH LAGOON
NORTH LAGOON
ELECTRICAL BUILDING
ELECTRICAL BUILDING
ELECTRICAL BUILDING

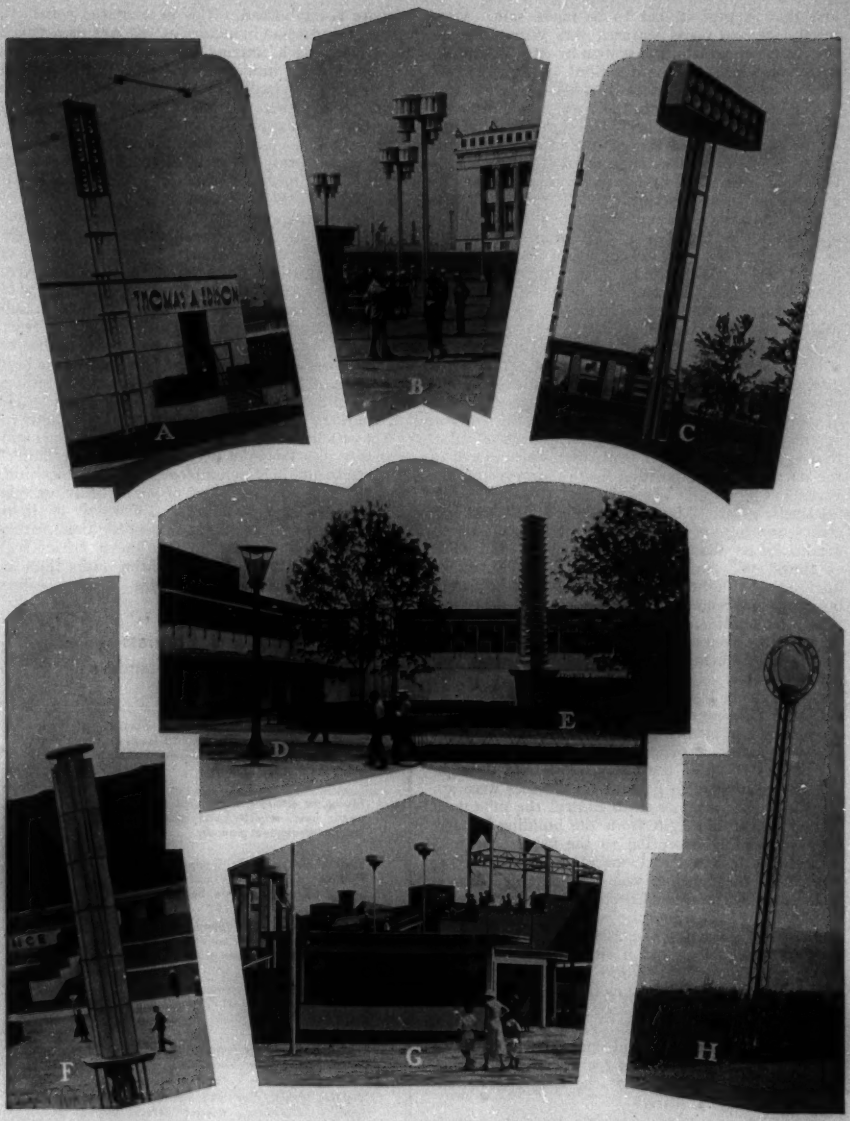


Fig. 2. Some "Century of Progress" outdoor lighting standards

(For description, see facing page)

and that is that it had to be made safe. Many interesting and novel features were introduced into the electrical distribution system by Mr. McConnell, many of which he has described in the April 27, 1933 issue of the *Electrical World*.

The colored plates forming part of this presentation (beginning facing page 736) afford a general idea of the appearance of the exposition at night. Obviously, they lack the intricacy of detail visible to the visitor who viewed the exposition on the grounds, and similarly any description of the lighting is lacking in the details of application so important in obtaining the results. The floodlighting of the building facades was accomplished in general by floodlights either located on the buildings themselves or grouped on structural standards of appropriate design and screened from direct view. All floodlights were of the enclosed type, ranging in capacity from 200 to 1,000 watts. In many instances the floodlights were equipped with colored door glasses, as it was found that much better results were obtained in flooding colored surfaces with light of approximately the same color as the surface. A wide range of colors, having coefficients of reflection of from 4 to 71 per cent, were encountered in the large flat composition-board surfaces of the various buildings. The viewing distances were relatively great. Many of the buildings had balconies serving as promenades. The atmospheric conditions peculiar to the Chicago lake front were, at times, very unfavorable. These conditions influenced the lighting treatment of the different buildings and made each one a subject of study and trial. Difficulties in concealing the lighting equipment were overcome by constructing screens or shields harmonizing with the building architecture where possible.

Gaseous tube lighting of building exteriors had its debut at this exposition and made possible many interesting and beautiful effects. A variety of gases and combinations of gases together with colored glass tubes provided the many colors used throughout the grounds. In general these tubes were applied in such a manner as to conceal the tube itself and to reflect the light from the building surface. One outstanding exception to the use of the tube for indirect lighting, and one of the most striking features of the lighting, was the "cascade" formed at the rear of the electrical court in which approximately 4,650 ft of blue tube was used. An innovation in the application of gaseous tubes was the use of the mercury-neon pylon rising 38 ft above the ground, triangular in section and constructed in louvre form to provide coves for the light sources. Alternate louvres on each face were equipped with mercury arcs and neon arcs. These arc lamps were of the hot cathode type, and operated as half wave rectifiers from an alternating current source, thus making it necessary to start the lamps each half-cycle.

These arcs, in common with all arcs, have a negative voltage characteristic. That is, after they are started, the voltage across the arc decreases as the current increases, at a rate and to a minimum depending upon the constants of the circuit in which the arc is established. This necessitated a ballast, and in this case an induction ballast was used which served also as a starting transformer. Two turns of high voltage insulated wire were placed around each reactor, and all the reactors on one phase were connected in series by means of this primary winding. Starting was accomplished each half-cycle by discharging a condenser through a thyratron tube into these series turns, the time of the discharge being controlled by means of a motor driven timer in the grid circuit of the thyratron.

When starting occurs late in the cycle the effective light is small and, *vice versa*, if the starting is earlier the effective light is greater. Taking advantage of this characteristic, a great variety of tints thus were obtained by controlling the dimming of the 2 sets of lamps in orderly sequence and thus obtaining changing proportions of neon and mercury light. In order to reduce the flicker to a minimum the number of lamps on each phase were kept balanced on each of the 4 faces of the tower. Individual lamps produce 60-cycle flicker, but the composite light on the buildings shows no appreciable flicker.

The problem presented in lighting the grounds and roadways also was influenced by the radically different type of architecture employed at the exposition, and resulted in the design of an entirely unique group of lighting standards. Efficiency of light output suffered very little in developing these futuristic lighting standards; in fact, most critics will give them a higher rating as lighting units than as objects of beauty. A general idea of these stand-

"Century of Progress" Outdoor Lighting Standards

(See facing page)

I Tubular lamp standard. Equipped with 100-watt 32-in. tubular multiple mazda lamps. 22 lamps for single plane standards and 44 lamps for 2-plane standards. Installed along the Avenue of Flags.

J Mushroom standard. Equipped with 150-watt multiple mazda lamp, refractor, and micarta shade. 500 units installed throughout grounds.

K Shell globe standard. Equipped with 500-watt B. F. multiple mazda lamps and shell globes. Installed around Dairy, Agriculture, States, and Electric buildings.

L Shower standard. Equipped with 352 15-watt flame-tint medium-screw-base multiple mazda lamps. 10 standards installed in the Court of States.

M Rainbow standard. Equipped with 4 500-watt floodlights. Installed in Lief Eriksen Drive at south end of grounds.

N Bridge standard. Equipped with a 500-watt floodlight. Installed on 12th Street bridge.

O Lighting Turrett. Equipped with 24 1,000-watt floodlights to illuminate reflecting surface, and 8 24-in. 1,500-watt incandescent searchlights for illumination of flags. Installed in center of 12th Street entrance.

P Tree lighting unit. Equipped with 6 200-watt floodlights. Installed at bases of trees throughout grounds.

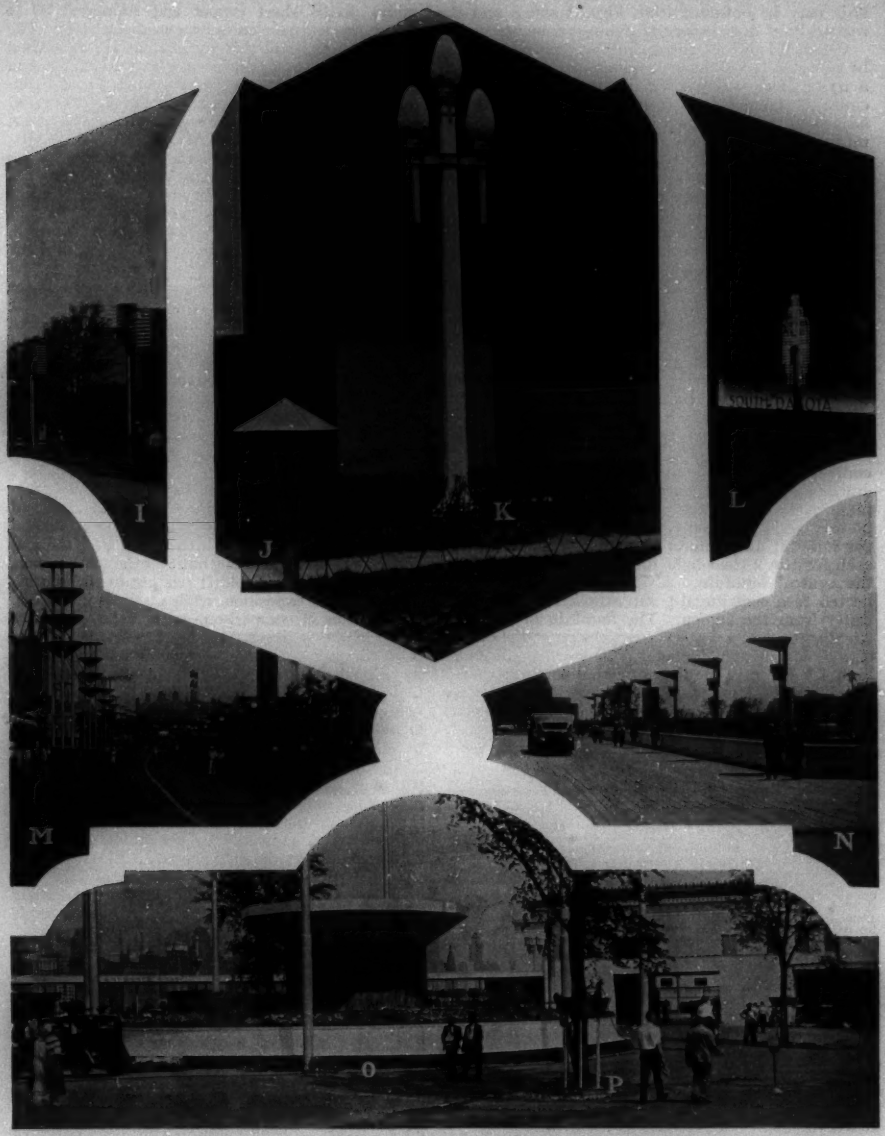


Fig. 3. Some "Century of Progress" outdoor lighting standards

(For description, see facing page)

ards may be obtained from Figs. 2 and 3 and the related brief descriptions of their equipment.

General lighting throughout an exposition must be consolidated if the exposition is to stand apart as a unit. This was particularly true of Chicago because of the elongated form of the grounds and its adjacency to the city with its electric signs, illuminated buildings, etc. Efforts in this direction took the form of a battery of 24 36-in. arc searchlights located at the southern extremity and spreading a fan of light beams over the grounds, a battery of 17 36-in. incandescent searchlights fanning out from the electrical building, and a group of electric fountains, 3 in the south lagoon and 1 in the court of the Electrical Building. The 3 fountains in the south lagoon were located approximately 100 ft off the west shore and 150 ft apart. The center fountain, containing 70 incandescent floodlighting projectors arranged in four colors, was flanked by 2 fountains, each containing 36 similar projectors in clear light. The water effects were identical and were operated in synchronism by means of thrustor valves actuated through a central controller. The color changes in the center fountain were accomplished by means of a thyratron reactor system controlling the 4 circuits of red, green, blue, and amber light in a sequence of combinations the complete cycle of which required 10 minutes to complete. Each fountain circulated 1,200 gal of water per minute; the connected lighting load was 18 kw each for the 2 clear-light fountains and 67.5 kw for the central fountain. A 75-hp motor direct connected to a centrifugal pump supplied the necessary water from the lagoon. The fountain in the electrical court had a 3-step central basin at the center of a pool 60-ft in diameter. The water effects at each level consisted of a spray emanating from a circular ring of jets; the water was illuminated by static colored light, each level in a different color. These bands of color were reflected from a 32-ft diameter cone shaped canopy surfaced with chromium plated sheet copper and supported 50 ft above the fountain on 6 structural steel legs. The reflected light from this specular surface created an interesting mat of mobile color and added a warm glow to the court. A 25-hp motor directly connected to a centrifugal pump circulated 1,200 gal of water per minute through the fountain. The total connected lighting load was 42 kw.

The climaxing feature of the spectacular lighting was furnished by the battery of 24 36-in. arc searchlights spreading a fan of varicolored beams of light over the grounds, and the battery of 17 36-in. incandescent searchlights the beams of which, crossing above the "morning glory" fountain in the electric court, contrasted vividly with the blue of the gaseous tubes forming the cascades and with the warm tints of the fountain colors. The group of arc searchlights known as the scintillator were arranged on a 2-step platform, each light taking 125 amp at 110 volts dc and producing a beam candle power of 60 million or a total of 1,440 million for the 24 units. A trained corps of operators maneuvered the group of lights through fantastic forms and color changes and directed the beams on clouds of steam, smoke bombs, etc., to provide many weird and striking effects.

Each of the group of 17 36-in. incandescent searchlights were equipped with a 3-kw incandescent lamp and each was operated without attendants at a fixed position, the beams intersecting over the axis of the fountain and fanning out over the south lagoon.

Statistical data (Table I) relating to the lighting features of an exposition, while at times interesting for purposes of comparison, are of little value as a guide to the engineer confronted with the problem of lighting an exposition. To determine why this is so we have only to review past expositions and note their variance in architectural style, landscaping, and general character. It is an inherent and fundamental purpose of expositions to mark epochs of time; to show the advances in materials and methods. Consequently the engineer responsible for planning the lighting for an exposition must approach his problem with the purpose of the exposition in mind and intent upon supporting the style and effects contemplated by the architects. Originality and appropriateness should be the outstanding characteristic of lighting installations of this class and these arise from the circumstances surrounding individual expositions rather than from the records of those in the past.

Table I—General Data—A Century of Progress

Number of transformer vaults installed	45
Number of transformers installed (10 to 333 kva)	177
Total connected load (kva)	27,562
Exterior lighting load (kw) (exclusive of amusements)	2,750
Exterior lighting standards—approx	1,150
Incandescent lamps installed (10 to 3,000-watt)	130,000
Primary feeder cable (ft)	300,940
Secondary feeder cable (ft)	252,236
Building feeders (ft)	407,061
Distribution Cable—Roads & Path Lighting (ft)	152,760
No. 00 wire for general distribution (ft)	317,000
No. 12 wire for general distribution (ft)	2,625,000
Pump log for cable runs (ft)	263,000
Raceway for wire runs (ft)	138,000
Gaseous tubes installed (ft)	19,877
Power consumption, total 170 days (kw)	35,111,852
Average consumption per 24-hour day (kwhr)	206,540
Peak load (kw)	18,952
Average watts per sq ft interiors	3.77
Total water requirements per day (gal)	10,000,000
Projector type units purchased by Exposition Company	
200-watt floodlights	1,600
500/1,000-watt floodlights	1,000
24-in. incandescent searchlights	72
36-in. incandescent searchlights	18
36-in. arc searchlights	24
250 to 1,500-watt underwater floodlights	277
Total paid attendance	22,321,497
Average per day, 170 days	131,303
Total area of enclosed grounds (acres)	424
Average of lagoons in grounds (approx. acres)	80
Interior lighting fixtures	7,762
Illumination intensities, building walls and roadways (foot-candles)	0.1 to 9

Additional articles on the subject of illumination as applied at the "Century of Progress" exposition, together with discussion of same, will be found in the February 1934 Transactions of the Illuminating Engineering Society. They are entitled:

1. Illumination of A Century of Progress Expositon, Chicago, 1933. W. D'A. Ryan.
2. Unique Lighting at A Century of Progress. L. A. S. Wood and Charles J. Stahl.
3. Lighting Features of the Fair. J. L. Stair, W. V. C. Foulks and W. E. Folsom.
4. Century of Progress Exhibit Lighting. C. M. Cutler.

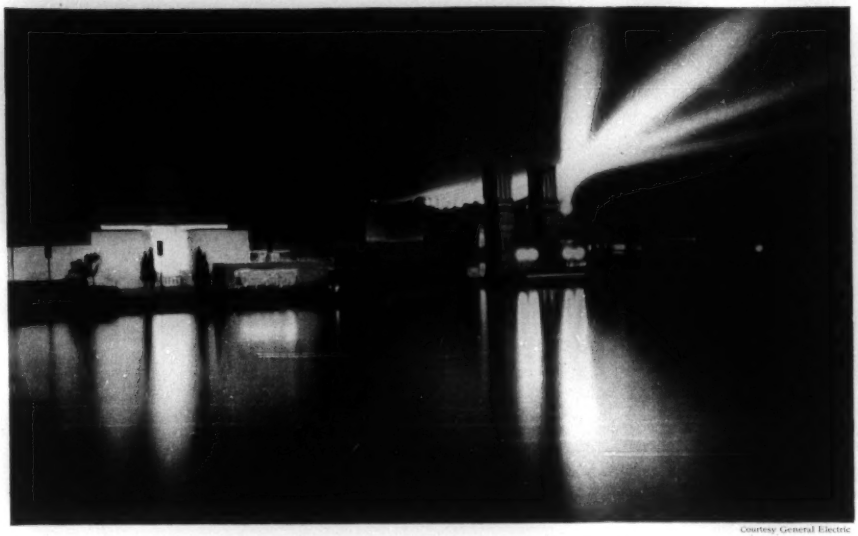
These papers give interesting details and amplification of the material here presented by Mr. Ryan at the request of the A.I.E.E. committee on production and application of light.

Courtesy General Electric

GENERAL VIEW TOWARD NORTHERLY ISLAND

Courtesy General Electric

TWELFTH-STREET ENTRANCE AND BRIDGE



Courtesy General Electric

ELECTRICAL BUILDING, AND RADIO AND COMMUNICATIONS BUILDING

Courtesy General Electric

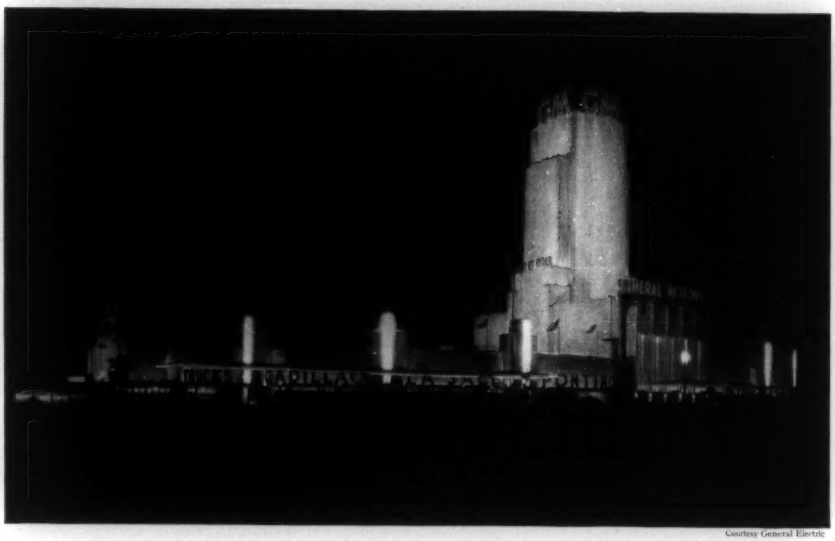
HALL OF SOCIAL SCIENCE, AND RADIO AND COMMUNICATIONS BUILDING

Courtesy General Electric

ELECTRICAL GROUP, VIEWED FROM WEST SHORE OF SOUTH LAGOON

Courtesy General Electric

HALL OF SCIENCE, VIEWED FROM EAST SHORE OF SOUTH LAGOON



Courtesy General Electric

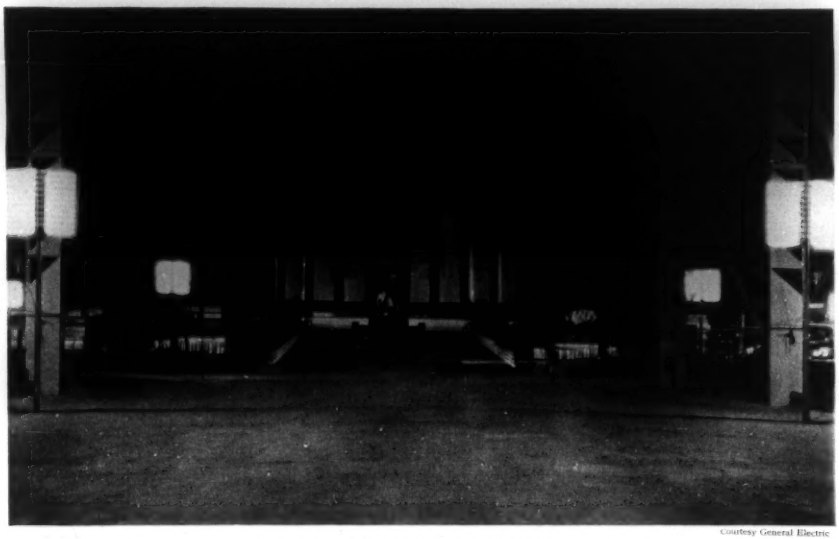
GENERAL MOTORS BUILDING

Courtesy General Electric

GENERAL EXHIBITS GROUP ON LEIF ERIKSEN DRIVE

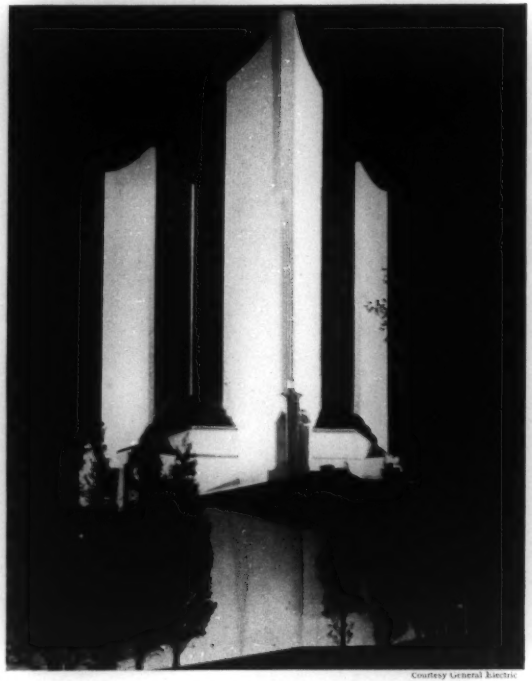
Courtesy General Electric

THE TRAVEL AND TRANSPORT BUILDING



Courtesy General Electric

NORTH ENTRANCE TO THE HALL OF SCIENCE



Courtesy General Electric

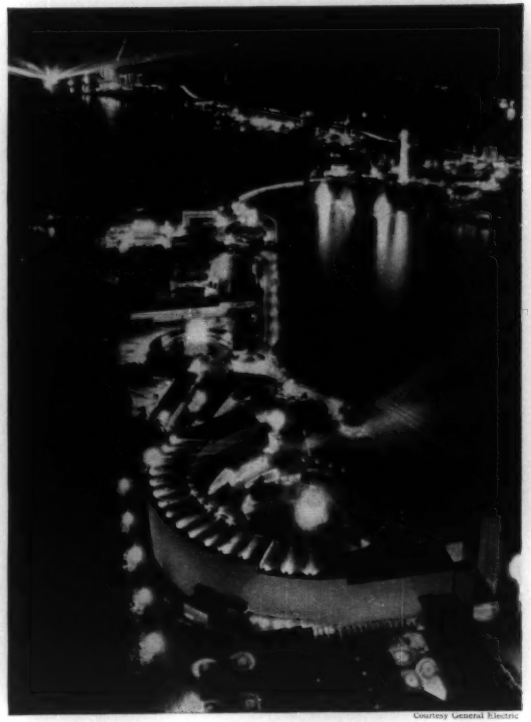
THE FEDERAL BUILDING

Courtesy General Electric

MERCURY-NEON PYLON IN COURT A OF THE GENERAL EXHIBITS GROUP

Courtesy General Electric

COURT OF THE ELECTRICAL BUILDING, "MORNING GLORY"
ELECTRIC FOUNTAIN IN FOREGROUND



Courtesy General Electric

NORTHERLY ISLAND FROM EAST SKYRIDE TOWER

Courtesy General Electric

SCINTILLATOR FAN, AS SEEN FROM THIRTY-FIRST-STREET ENTRANCE

Courtesy General Electric

VIEW LOOKING SOUTH FROM WEST SKYRIDE TOWER

Communication—Past and Present

By Bancroft Gherardi, President A.I.E.E. 1927–28

Pointing out that when the A.I.E.E. was founded in 1884 telegraphy was 40 years old and telephony 8 years old, the author traces briefly the significant developments and tremendous growth of electrical communication and the significance and importance of the parallel growth of the Institute. "Both grew out of the extension of our knowledge of certain laws of nature, and both were encouraged in their growth by the social and economic results that were possible from the application of electricity." The record of 50 years of communication development is traced through a half century of Institute publications.

WHEN in May 1884 a group of men, numbering perhaps a hundredth of our present membership, gathered together to found the American Institute of Electrical Engineers, none of them could foresee what the organization itself would grow to be or the future of the industries which would be founded on electrical knowledge. They were interested in the theory and the practical use of electricity. They must have believed that something well worth while would grow out of the application of electricity to the service of mankind, but the tremendous developments that would result from applying electricity to social and economic purposes were concealed then in the darkness of the future. I feel honored in being asked to perform the pleasant duty of recording at this time, when the Institute is completing the first 50 years of its life, what has happened in the communication art during that period.

From the earliest days until the invention of the telegraph, communication between persons at a distance was essentially a matter of transportation. Either a written message was transported by some one of the means then available or the messenger himself traveled, either on foot, on horseback, by stage coach, by boat, or by railroad. With some negligible exceptions used only for specialized purposes, communication was dependent upon transportation and subject to all its limitations. With the invention and development of the electric telegraph, communication by the written message first became independent of transportation. In the United States the first application was by Morse in 1844. Still, however, communication by the spoken word could not be carried on over distances of more than a few hundred feet and conveniently only over distances of a few feet. Alexander Graham Bell in 1876, by the invention of the telephone, offered the possibility of communication by the spoken word between people separated by considerable distances, so that it was no longer necessary for those desiring such communication to meet at a common point to make conversation possible.

When the Institute was founded, telegraphy was 40 years old. The telephone had been invented only 8 years. Radio-telegraphy and radio-telephony did not exist. From the first, a realization of the advantages to be derived from electrical communication led to the rapid development of both telegraphy and telephony. How much of this has taken place during the 50 years of the life of the American Institute of Electrical Engineers is briefly indicated by the following figures. During 1884, there were sent about 40 million telegraph messages in the United States. In 1929, the peak year, just prior to the depression, this figure had increased to 235 million messages. In 1884, there were 198 million telephone messages sent in the United States, and in the peak year 1930 the usage of the telephone had reached the stupendous total of 27,800 million messages. For several recent years the messages sent electrically have greatly exceeded in number the total of the first-class mail pieces in the United States.

It is not a mere coincidence that the life of the American Institute of Electrical Engineers has been paralleled by the tremendous growth of electrical communication. Both grew out of the extension of our knowledge of certain laws of nature, and both were encouraged in their growth by the social and economic results that were possible from the application of electricity.

The early development of the telegraph was closely associated with the railroads which had an urgent need for this form of communication, and telegraph lines were very generally built along the railroad routes. The wires were generally of iron; hard drawn copper was not invented until 1877, and cable development did not start until about the beginning of our 50-year period. Many of the present forms of telegraph circuit had been worked out, including duplex and quadruplex and Baudot's multiplex and printing telegraph, although this form was not applied in this country until a later date. Harmonic telegraphs which foreshadowed our modern carrier telegraph developments had been worked upon by inventors, including Alexander Graham Bell, for a decade or more, and Gray's harmonic telegraph had been given a trial. Following the first temporary success in 1858, permanent transatlantic telegraph

service by cable was established in 1866. One of my valued possessions is a medal presented by the New York Chamber of Commerce to my father for his part in the early cable laying expedition, as an officer of the U.S. Frigate Niagara.

Fire alarm and burglar alarm systems were well developed and police alarm systems were just coming into general use. Stock quotation systems had been established. Railway signaling systems had been invented, but only one railroad in the United States was equipped throughout its entire length with automatic electric block signals. An editorial in the September 1884 issue of the "Electrician and Electrical Engineer" refers to the adoption of automatic signals as the most important step to be taken in the direction of perfecting our modern railway systems.

In 1884 telephony was still very young. There had been sufficient technical development to produce the fundamentals of a telephone exchange system in early crude form. Early types of the carbon transmitter had been invented and placed in service. The first switchboards had been constructed, and the first multiple board was placed in service in Chicago in 1879. The use of the metallic circuit telephone system had just begun. A beginning had been made in the development of telephone wires in cable and, as already noted, hard drawn copper had just been invented. Long distance telephony was beginning, a line from Boston to Providence having been established in 1881. The first conversation between New York and Boston using hard drawn copper circuits took place in 1884, the year of the founding of the Institute.

It is difficult within the scope of a brief statement to indicate adequately the extraordinary development of the technique of electrical communication that has taken place during the past 50 years, building upon the fundamental technical principles that had been established by 1884 and applying many new technical principles discovered since.

The hand sending method of operating telegraph circuits has been largely displaced by the application of the printing telegraph. Although the idea of having telegraph impulses print the message is as old as telegraphy itself, the present successful forms of apparatus are of modern development representing the culmination of many decades of intensive effort and the creation of successively better forms of this apparatus[10] (references are by number to items in bibliography). The types now in general use were all developed within the last 20 years.[36,41] The scope of practical application of printing telegraph apparatus has been extended by a new method for maintaining synchronism or more exactly isochronism between the machines on the same circuit by the so-called start-stop principle which is utilized in most of the printing telegraph machines now in operation.[41]

Telegraph circuits, where not in cable, are now largely built of hard drawn copper, only about 10 per cent of the telegraph circuit mileage still making use of iron. There has been a great extension in the use of telegraph circuits in cable, a third of the telegraph circuit mileage of the country now being of that type. This use of telegraph in cables has largely come about through the development of successful carrier telegraph systems, realizing at last the dream of the early telegraph workers that a large number of telegraph circuits could be provided on one pair of wires.[38,85] An important requirement for the success of this development was the application of electrical means for separating the channels, whereas the early inventors necessarily tried to use mechanical means.[6] The carrier telegraph art also depends upon the vacuum tube, itself a development of the last 20 years.[1,15]

Many advances were made in the operation of long submarine telegraph cables through loading and other improvements by means of which the message capacity of these cables was increased several fold.[56,85]

A striking technical development of this period is radio, first applied to telegraphy. Although isolated experiments, which were early experiments in radiation, date back to 1842 with Joseph Henry's detection of Leyden jar disturbances at distances of several hundred feet and lightning discharges at distances of 20 miles and while in 1864 Maxwell advanced his electromagnetic theory which showed radio communication to be possible, the birth of radio science is generally associated with Hertz' brilliant work in 1887 and the beginning of practical application came with the work of Marconi in 1896.[6,9,11] From then the development of radiotelegraphy was rapid, transatlantic service being established in 1908 and ships being generally equipped with this valuable means of promoting safety by the year 1913.[19,20,24,92]

Although in 1884 that then novel and primitive device, the telephone, had already been put to work, there being about 150,000 in use in the United States, the technical development of telephone systems had only started. This development has included 3 major groups of problems: (1) apparatus at each telephone station to convert sound energy into electrical waves and back again and to provide signals to attract the attention of users; (2) switching systems at central points for rapidly and accurately connecting together any 2 telephones that might desire to communicate with each other; and (3) means for transmitting the telephonic currents over distances little or great without excessive loss or other modification.

Shortly after the Institute was founded came the first successful granular carbon telephone transmitter, so great an improvement over the earlier forms of transmitter that, by many modifications and improvements, it has become, without changing its essential principle, the highly developed telephone transmitter of today. At about the same time came Carty's invention of the bridging principle to replace for telephone circuits the series types of connection inherited from the telegraph practice.[12] One of its many useful applications was to the signal bells at telephone stations, resulting in a great improvement in performance. The hand set type of arrangement, while suggested early in this epoch and used in a limited way, presented serious technical difficulties which, for the severe requirements for service in the United States, were overcome only in recent years.[80]

Telephone switchboards of the early forms were relatively crude. In the period 1886–1894, the common battery switchboard was invented and introduced into practical use. Through successive improvements, the capacity of the common-battery switchboard was raised from a few hundred lines in the early models to 9,000 lines by the year 1902.[13] Throughout the development of switching systems there was a trend toward the greater use of automatic devices, culminating in the development of the machine switching systems in which, for certain types of calls, the switching is entirely mechanical. The first successful step-by-step machine switching system was placed in service in 1892. The panel machine switching system designed to meet the complex conditions of metropolitan areas was first placed in service in 1915. Today dial system switching has been provided for 40 per cent of the telephones of the country.[18,21,36,37,38,42,73,83]

The transmission of telephone currents over long distances has been almost wholly a development of this era. The first New York-Boston telephone circuit in 1884 using hard drawn copper led to the use of copper for other interurban lines and the development of the first transposition system to prevent interference between numbers of telephone circuits carried on the same pole lines.[4,13,21] Phantom circuits to give 3 independent circuits on 2 pairs of wires were experimented on in 1884, but were not successful until about 1902. In 1899 came Pupin's invention of loading, by which means the transmission efficiency of telephone wires was increased. Loading not only permitted the extension of open-wire circuits to greater distances, but it also made possible long distance telephone transmission over cable circuits.[8,24,60] From small beginnings in 1902, when 49 pairs of a 10-mile cable from New York to Newark were loaded for commercial service, the use of this invention has extended until at the present time there are about 8,500,000 coils in use in the United States. Cables for phantom circuit working were made successful in 1910.

Another great technical step in making possible the extension of long distance telephony was the development of the telephone repeater. The first commercial application of repeaters was in 1904 between New York and Chicago. These were of the mechanical type, the vacuum tube repeater being first used commercially in 1913.[32] The combined effect of these advances in the art led to the opening of transcontinental service in 1915 and the rapid extension of the service toward the ideal of a universal service between all points of the country.[64,78] These developments made possible the use of extensive long distance telephone cable systems, including circuits in cable 2,000 miles or more in length. In this way it was possible to connect together, by means of storm-proof plant, many of the larger cities in the country.[40,46,64]

Carrier telephone systems, by which several independent telephone channels are simultaneously carried on one pair of open wires, marked another step in long distance transmission. They were first applied commercially in 1918 between Baltimore and Pittsburgh.[38,68,76] There are 575,000 miles of carrier circuit in the telephone plant today. Now, through a further series of technical developments, we face the prospect of having in the future carrier telephone methods applied to the toll cable plant giving a still more effective use of the pairs in telephone toll cables.[96]

In 1921 the telephone network, which theretofore had been confined to the continental area of the United States and Canada, began to stretch out to other countries. The first step was the establishment of service between the United States and Cuba through the placing of submarine telephone cables of novel design.[39] In 1915 the first experimental transatlantic telephone communications using radiotelephone links were held, and in 1927 commercial transatlantic service was established.[33,44,69,80] This form of development has expanded so rapidly that today there are a quarter-million miles of intercontinental radiotelephone circuits in service in the world, and it is possible from any telephone in the United States to reach 92 per cent of all the telephones in the world, located in 54 different countries on all the continents of the globe. In the last few years telephone service has been extended to ships at sea by the use of radio, 19 ships being equipped at the present time for connection to the American telephone system.[79] By the application of newly developed materials and an advanced technique, it will be possible to build a transatlantic telephone cable when the continued increase in messages to be handled makes this desirable.

With the rapid development of telephone networks throughout the country, their use for the transmission of music and for other entertainment purposes has been in the minds of the experts. In the early days, however, such transmissions, while interesting scientific demonstrations and well received, did not represent a reproduction of music or even of voices which was technically faithful. With the perfection of the telephone art it became possible to carry out such transmission with increasingly good reproduction, and beginning with about 1915 there was a large development of such service using loud speakers to bring the programs to audiences.[47,49,53,70] The latest step in perfecting the electrical transmission of music, in which the transmission is not only of extreme fidelity but includes the effects of acoustic perspective and also a range of volumes far beyond that which can be produced directly by an orchestra, has just recently been described and demonstrated before this Institute.[97]

Improvements in radiotelephony led to the introduction, in 1920, of radio broadcasting of programs. This has grown to its present large proportions with about 600 radio transmitting stations broadcasting programs to 16 million radio receiving sets in this country.[48,49,53,58,62,66,70] Many of these transmitting stations are linked together in groups by program transmission wire networks, aggregating about 35,000 miles of circuit.[77]

The application of the technique developed for electrical communication has led naturally to its extension to uses other than those contemplated in the original telephone and telegraph systems.[25,37] Private wire telegraph systems have developed a

Some Contrasts

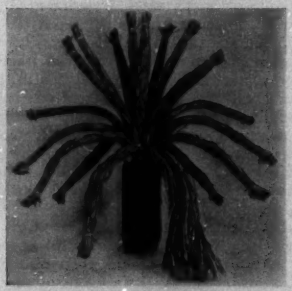
Above Modern dial type and telephone

(Right) Desk stand telephone of 1886. Equipped with "long-distance" transmitter and with exposed transmitter wiring and switch-hook contacts

(Below) View of Harrisburg-Pittsburgh cable route, the 2 cables shown providing more than 1,000 telephone wires

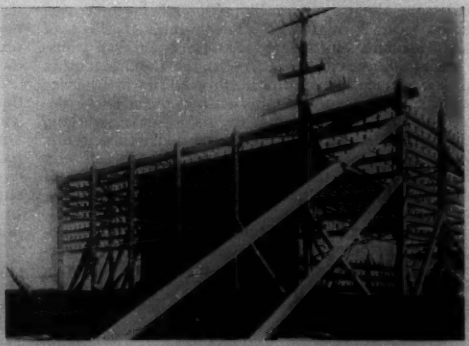
Interior of Chicago manhole containing some 18,000 exchange plant wires, 3,500 toll wires, and 3,200 loading coils

Section of latest type exchange plant cable containing 18 groups of 101 pairs of wire each (total of 3,636 wires) in lead sheath of $2^1/_2$-in. diameter



Pole line erected in New York City in 1887, consisting of 90-ft poles carrying 25 to 30 crossarms (250 to 300 wires)

Central office roof structure (Boston) of 1883 terminating 2,400 wires



in Communication

Equipment

Stock quotation transmitting center, New York 1881

Modern transmitting center for nation-wide stock quotation service with high-speed tickers

Telegraph operating room, New York 1881, showing women sending and receiving telegrams by the key and sounder method

Modern telegraph operating room, New York, showing multiplex telegraph equipment with associated sending keyboards and receiving printers

wide variety of uses, including automatic stock quotation boards and the transmission of weather maps for air navigation.[86,90] The last few years have witnessed the extension of application of electrical communication to assist the law enforcing agencies, including teletypewriter systems between the police offices and radiotelephone for continuous contact with police automobiles.[86] Radio communication has been adapted extensively to the assistance of navigation, both of ships and of aircraft, through the development of methods for direction finding, radio beacons, and similar purposes.[74,75,81,90,95] There has been a rapid extension of remote control and of the transmission of information for a great variety of uses, the remote control of switches in power systems and remote indications of switch positions and of loads and remote indications of water levels.[91,92]

A recent, and in one sense ambitious, development of electrical communication is television. The eye conveys much more information to the observer than the ear, receiving electromagnetic impulses very much more complicated in structure than the acoustic impulses received in hearing. This is illustrated by the fact that in the electrical transmission of photographs over telephone circuits from 5 to 15 minutes is required for the transmission of a photograph, whereas television is equivalent to transmitting at least 16 photographs per second. The very large number of electromagnetic impulses that must be transmitted in a second, or to express it another way, the wide band of frequencies required for the transmission of television signals, raises difficult problems both in the design of the terminal equipment and with reference to the transmitting medium, whether wire or radio. Successful demonstrations of television over a distance of 250 miles were made in 1927, and technical development, hoping for ultimate commercial application, is actively continuing.[68]

The records of the Institute's proceedings are a valuable library of these tremendous technical advances of the past 50 years. This is illustrated by an appended bibliography of selected references from the Institute publications in which are set forth technical discussions of these important developments and to which reference has been made throughout this review. Although no general discussion of these papers is possible within the limits of this article, it is of interest to note in passing the first paper in the Institute's TRANSACTIONS. This was presented at the first technical meeting in October 1884, by Professor Houston and was entitled "Notes on Phenomena in Incandescent Lamps." It discusses the "Edison effect," that is, the discovery that in an evacuated bulb an electric current would flow in one direction between a hot filament and cold cathode, but not in the other direction. This all will now recognize as the first 2-element vacuum tube and the basis of the modern science of electronics which was stimulated 20 years later by De Forest's addition of a third element and the development by many workers of the great possibilities which such a 3-element tube possesses. It is, indeed, interesting and significant that the first Institute paper should be on a subject of such fundamental importance, one on which a large number of the outstanding developments of electrical communication of the past 20 years depend and which today is engaging to an increasing extent the attention of men in the electrical power field as well as in the field of electrical communication.

As a result of the extension of the electrical transmission of the spoken and the written word, in the United States today, where many of the fundamental concepts originated and much of the technical development was done, it is no exaggeration to say that we can have almost instantaneous communication between any 2 parts of our country. While these developments have been most extensively applied in the United States, a somewhat similar statement may be made as to the scope of electrical communication in other industrial countries. In addition, extending between the various nations there is a well developed electrical communication system.

Communication is today an integral part of our social and economic life. That the American Institute of Electrical Engineers has contributed in a substantial way to the accomplishment of these results cannot be doubted. Among the leaders in that organization from time to time have been: Alexander Graham Bell, Michael I. Pupin, John J. Carty, Norvin Green, Frank B. Jewett, and Harry P. Charlesworth, each of whom served as its President. These same men likewise have been leaders in the communication development of which we are speaking. They are but a few of the thousands connected with the communication industry who have been members of the American Institute of Electrical Engineers. Through its proceedings and through the informal contacts with others made possible by its meetings, all of these men have derived some of the knowledge and some of the inspiration necessary for the successful accomplishment of the communication enterprises, built up as they are upon complicated technical working.

As the fiftieth year of the life of our Institute draws near to its end, we look back with satisfaction upon the results of the application of electricity to the welfare of mankind. We surely are warranted in believing that if we could look forward into the years to come we would there see still other and equally extraordinary developments, perhaps more extraordinary developments, which still lie before us and which will minister to the comfort and convenience of the people of the United States and of the world. In these developments the members of of the American Institute of Electrical Engineers, present and future, will play a distinguished part.

Bibliography of Selected Communication References From Institute Publications

1. NOTES ON PHENOMENA IN INCANDESCENT LAMPS. Edwin J. Houston. v. 1, 1884.

2. SYNCHRONISM. Edwin J. Houston. v. 1, 1884.

3. RECENT IMPROVEMENTS IN APPARATUS FOR OCEAN CABLING. Charles Cuttriss. v. 5, 1888.

4. Inductive Disturbances in Telephone Circuits, J. J. Carty. v. 8, 1891.

5. Practical Aspects of Low Frequency Electrical Resonance, M. I. Pupin. v. 10, 1893.

6. Exhibition of Marconi Wireless Telegraph Apparatus. v. 14, 1897.

7. Historical Sketch of the Fire Alarm Telegraph, Adam Bosch. v. 14, 1897.

8. Propagation of Long Electrical Waves, M. I. Pupin. v. 16, 1899.

9. The Possibilities of Wireless Telegraphy—A Topical Discussion. v. 16, 1899.

10. A New Page Printing Telegraph, William B. Vanaise. v. 18, 1901.

11. Speeches at Institute Dinner in Honor of Guglielmo Marconi, v. 19, 1902.

12. The Evolution of the Telephone Switchboard, Thomas D. Lockwood. v. 21, 1903.

13. Transposition and Relative Location of Power and Telephone Wires, P. W. Lincoln. v. 21, 1903.

14. The Telautograph, James Dixon. v. 23, 1904.

15. The Audion, Lee De Forest. v. 25, 1906.

16. Track-Circuit Signaling on Electrified Roads, L. Frederick Howard. v. 26, 1907.

17. Wireless Telephony, R. A. Fessenden. v. 27, 1908.

18. A Study of Multi-Office Automatic Switchboard Telephone Systems, W. Lee Campbell. v. 27, 1908.

19. Alternator for One Hundred Thousand Cycles, E. F. W. Alexanderson. v. 28, 1909.

20. The Modern Telephone Cable, Frank B. Jewett. v. 28, 1909.

21. A Modern Automatic Telephone Apparatus, W. Lee Campbell. v. 29, 1910.

22. American Telegraph Engineering—Notes on History and Practice, William Maver, Jr., and Donald McNicol. v. 29, 1910.

23. Telegraph Transmission, Frank F. Fowle. v. 30, 1911.

24. The Commercial Loading of Telephone Circuits in the Bell System, Bancroft Gherardi. v. 30, 1911.

25. Some Recent Developments in Railway Telephony, Gregory Brown. v. 30, 1911.

26. The Semi-Automatic Method of Handling Telephone Traffic, Edward E. Clement. v. 30, 1911.

27. Automatic Private Branch Exchange Development in San Francisco, Gerald Deakin. v. 31, 1912.

28. Report by the Joint Committee on Inductive Interferences to the Railroad Commission of the State of California. v. 33, 1914.

29. Recent Results Obtained From the Preservative Treatment of Telephone Poles, F. L. Rhodes and R. F. Hosford. v. 34, 1915.

30. Continuous Waves in Long Distance Radio Telegraphy, L. F. Fuller. v. 34, 1915.

31. The Design of Transpositions for Parallel Power and Telephone Circuits, H. S. Osborne. v. 37, 1918.

32. Telephone Repeaters, Bancroft Gherardi and Frank B. Jewett. v. 38, 1919.

33. Radio Telephony, E. B. Craft and E. H. Colpitts. v. 38, 1919.

34. Transoceanic Radio Communication, E. F. W. Alexanderson. v. 38, 1919.

35. Applicability of Automatic Switching to All Classes of Telephone Service, A. B. Smith. v. 38, 1919.

36. Printing Telegraph Systems, John H. Bell. v. 39, 1920.

37. Some Phases of Railroad Telegraph and Telephone Engineering, Stanley Rhoads. v. 40, 1921.

38. Carrier Current Telephony and Telegraphy, E. H. Colpitts and O. B. Blackwell. v. 40, 1921.

39. Key West—Havana Submarine Telephone Cable System, W. H. Martin, G. A. Anderegg, and B. W. Kendall. v. 41, 1922.

40. Philadelphia-Pittsburgh Section of the New York-Chicago Cable, J. J. Pilliod. v. 41, 1922.

41. Printing Telegraph Systems Applied to Message Traffic Handling, A. H. Reiber. v. 41, 1922.

42. Radio Telegraphy, Guglielmo Marconi. v. 41 (*Jl.*), 1922.

43. Machine Switching Telephone System for Large Metropolitan Areas, E. B. Craft, L. F. Morehouse, and H. P. Charlesworth. v. 42, 1923.

44. Transatlantic Radio Telephony, H. D. Arnold and Lloyd Espenschied. v. 42, 1923.

45. The Wave Antenna—A New Type of Highly Directive Antenna, H. H. Beverage, C. W. Rice, and E. W. Kellogg. v. 42, 1923.

46. Telephone Transmission Over Long Cable Circuits, A. B. Clark. v. 42, 1923.

47. Public Address System, I. W. Green and J. P. Maxfield. v. 42, 1923.

48. Electrical Loud Speakers, A. Nyman. v. 42, 1923.

49. High Quality Transmission and Reproduction of Speech and Music, W. H. Martin and H. Fletcher. v. 43, 1924.

50. Measuring Methods for Maintaining the Transmission Efficiency of Telephone Circuits, F. H. Best. v. 43, 1924.

51. Practices in Telephone Transmission Maintenance Work, W. H. Harden. v. 43, 1924.

52. Transmission Unit and Telephone Transmission Reference Systems, W. H. Martin. v. 43, 1924.

53. The Function and Design of Horns for Loud Speakers, C. R. Hanna and J. Slepian. v. 43, 1924.

54. Echo Suppressors for Long Telephone Circuits, A. B. Clark and R. C. Mathes. v. 44, 1925.

55. Voice-Frequency Carrier Telegraph System for Cables, B. P. Hamilton, N. Nyquist, M. B. Long, and W. A. Phelps. v. 44, 1925.

56. The Loaded Submarine Telegraph Cable, Oliver E. Buckley. v. 44, 1925.

57. Metallic Polar-Duplex Telegraph System for Long Small-Gauge Cables, J. H. Bell, R. B. Shanck, and D. E. Branson. v. 44, 1925.

58. Notes on the Development of a New Type of Horntless Loud Speaker, Chester W. Rice and Edward W. Kellogg. v. 44, 1925.

59. Design of Non-Distorting Power Amplifiers, E. W. Kellogg. v. 44, 1925.

60. Development and Application of Loading for Telephone Circuits, Thomas Shaw and William Fondiller. v. 45, 1926.

61. Methods of High Quality Recording and Reproduction of Music and Speech Based on Telephone Research, J. P. Maxfield and H. C. Harrison. v. 45, 1926.

62. Radio Broadcast Coverage of City Areas, Lloyd Espenschied. v. 45, 1926.

63. Refraction of Short Radio Waves, William G. Baker and Chester W. Rice. v. 45, 1926.

64. Transmission Features of Transcontinental Telephony, H. H. Nance and O. B. Jacobs. v. 45, 1926.

65. Symposium on Television. v. 46, 1927.

66. Quantitative Determination of Radio Receiver Performance, H. D. Oakley. v. 46, 1927.

67. A New Electronic Rectifier, L. O. Grondahl and P. H. Geiger. v. 46, 1927.

68. Carrier Systems on Long Distance Telephone Lines, H. A. Affel, C. S. Demarest, and C. W. Green. v. 47, 1928.

69. Transatlantic Telephone Service, K. W. Waterson and O. B. Blackwell. v. 47 (*Jl.*), 1928.

70. Loudspeakers of High Efficiency and Load Capacity, C. R. Hanna. v. 47, 1928.

71. Certain Topics in Telegraph Transmission Theory, H. Nyquist. v. 47, 1928.

72. The Planning of Telephone Exchange Plants, W. B. Stephenson. v. 47, 1928.

73. Tandem System of Handling Short-Haul Toll Calls, F. D. Wheelock and E. Jacobsen. v. 47, 1928.

74. Electrical Aids to Navigation, Robert H. Marriott. v. 48, 1929.

75. Uses of Radio as an Aid to Air Navigation, J. H. Dellinger. v. 48, 1929.

76. Carrier Telephone System for Short Toll Circuits, H. S. Black, M. L. Almquist, and L. M. Ilgenfritz. v. 48, 1929.

77. Long Distance Cable Circuit for Program Transmission, A. B. Clark and C. W. Green. v. 49, 1930.

78. A General Switching Plan for Telephone Toll Service, H. S. Osborne. v. 49, 1930.

79. Radio Telephone Service to Ships at Sea, William Wilson and Lloyd Espenschied. v. 49, 1930.

80. Symposium on Transatlantic Telephone Service. v. 49, 1930.

81. Air Transport Communication, R. L. Jones and F. M. Ryan. v. 49, 1930.

82. The Electrical Engineering of Sound Picture Systems, K. F. Morgan and T. E. Shea. v. 49, 1930.

83. Dial Telephone System Serving Small Communities of Southern California, F. O. Wheelock. v. 49, 1930.

84. Symposium on Coördination of Power and Telephone Plant. v. 50, 1931.

85. The Newfoundland-Azores High Speed Duplex Cable, J. W. Milnor and G. A. Randall. v. 50, 1931.

86. Modern Practices in Private Wire Telegraph Service, R. E. Pierce. v. 50, 1931.

87. The Time Factor in Telephone Transmission, O. B. Blackwell. v. 51, 1932.

88. Vertically Cut Sound Records—Recent Fundamental Advances in Recording and Reproducing Sound Using Vertical Undulations on a Disk, H. A. Frederick and H. C. Harrison. v. 51, 1933.

89. Telephone Handset—A Product of Research. W. C. Jones and A. H. Inglis. v. 51 (Elec. Engg.), 1932.

90. Wire Communication Aids to Air Transportation, H. H. Nance. v. 51, 1932.

91. Report on Telemetering, Supervisory Control and Associated Communication Circuits. v. 51 (Elec. Engg.), 1932.

92. Symposium on Traffic Signaling Systems. v. 51, 1932.

93. Radio Plant of R. C. A. Communications Inc., H. H. Beverage, C. W. Hansell, and H. O. Peterson. v. 52, 1933.

94. Symposium on Railroad Communication and Signaling. v. 52, 1933.

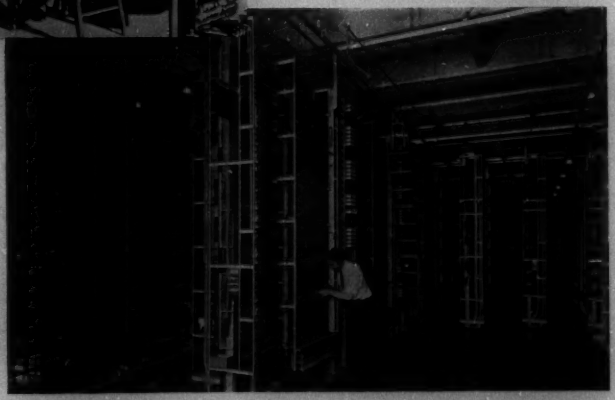
95. Radio Aids to Air Navigation, C. F. Green and H. I. Becker. v. 52, 1933.

96. Carrier in Cable, A. B. Clark and B. W. Kendall. v. 52, 1933.

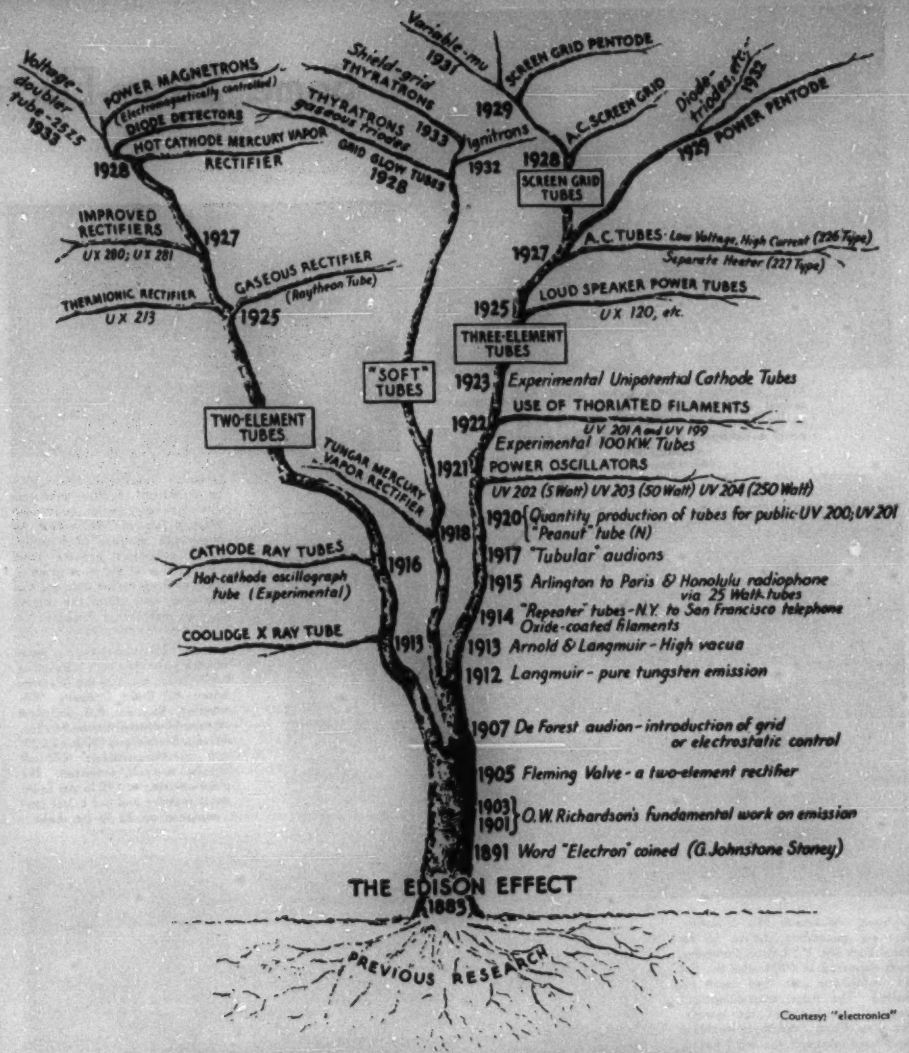
97. Symposium on Auditory Perspective. v. 53 (Elec. Engg.), 1934.

A modern manual subscriber switchboard of 1922. A portion of one of 160 switching units in New York City (including both manual and dial system offices) of types designed for a capacity of about 10,000 lines each

View of panel central office switchroom of Oakland, Calif., now in service. Typical selector frames of the panel type which perform the functions carried out by operators in manual switchboards. Picture shows a small portion of apparatus for one 10,000-line unit



Milwaukee central office of 1883 serving about 700 lines covering the entire city. Switchboard equipped with annunciator type line signals



Courtesy: "electronics"

The Family Tree of the Thermionic Tube

Public attention has generally overlooked that contribution of Mr. Edison's which seems destined to have the greatest influence on the world of the future. This was Edison's discovery in 1883 of the feeble flow of electrons in vacuo coming from the heated filament of his early incandescent lamps—the "Edison Effect." It is interesting to note that this phenomenon was discussed in the first paper presented at the first technical session of the A.I.E.E., held in Philadelphia, October 1884. (The first page of this paper is reproduced on p. 634 of this issue.)

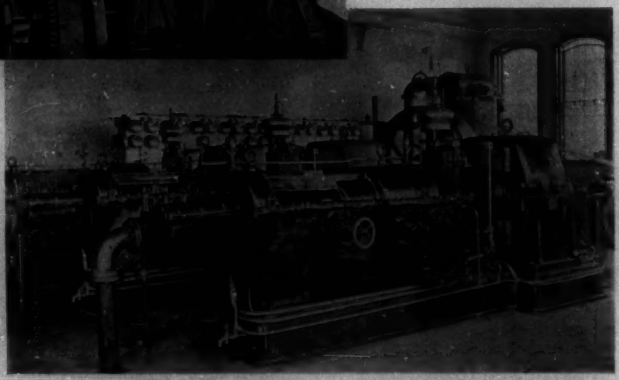
For 20 years this pregnant phenomenon lay unused by the world, until in the early 1900's it formed the foundation for the first electronic tubes which now, in a myriad of forms, have given us radio, broadcasting, long-distance telephony, short waves, sound pictures, television, power control, rectification, electric surgery, electronic music, and a host of other developments. Thus the "Edison Effect" is bound to be increasingly recognized as the most epochal discovery in all the inventor's eventful career.

Some Steam-Electric

Early alternating current power plants had several small belt-driven alternators. This is an a-c plant of about 1886; note the wood panel switchboard and the early type meters mounted on it
(Westinghouse photo)

(Above) Three of the 12 1,000-hp 2,200-volt 2-phase generators that supplied power for the Chicago World's Fair of 1893. Each 2-phase unit consisted of 2 single-phase generators on the same shaft. This was the most powerful plant built up to that time and the machines were then the largest a-c machines in America
(Westinghouse photo)

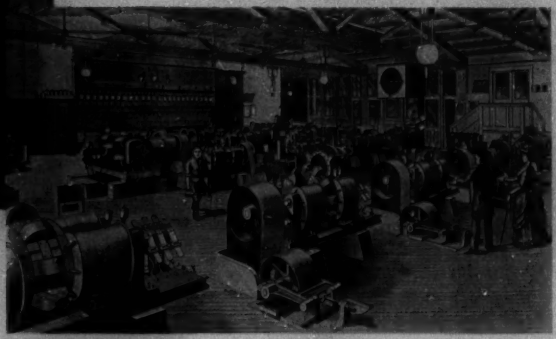
(Below) Three 400-kw a-c steam turbine generating units installed in 1899 at the plant of the Westinghouse Air Brake Company, Wilmerding, Pa., the first important steam turbine installation in America. These turbines drove 400-kw 3,600-rpm revolving-armature 440-volt bipolar 60-cycle generators. The plant operated at 125 lb per sq in. steam pressure and had a fuel consumption of 22 lb per kwhr
(Westinghouse photo)



(Above) Waterside No. 1 station, first a-c generating station of the New York (N. Y.) Edison Company, as it appeared in 1904 after the first 11 3,500-kw units had been installed. The huge cross-compound engines overshadowed the generators they drove. All these machines have been removed, the last 7 having been replaced by 2 35,000-kw turbine-generator units prior to 1919. Originally designed for a total capacity of 56,000 kw, the plant now has an installed capacity of 214,000 kw in the same area
(Consolidated Gas Co. photo)

Generating Stations

Dynamo room of the original electric "central station," Edison's famous Pearl Street station in New York City, which began commercial operation September 4, 1882. All except one of these machines, which is now in the Ford Museum at Dearborn, Mich., were ruined by fire in 1890; they were dubbed "jumbos" because of their huge size, a complete machine weighing more than 60,000 lb
(Consolidated Gas Co. photo)



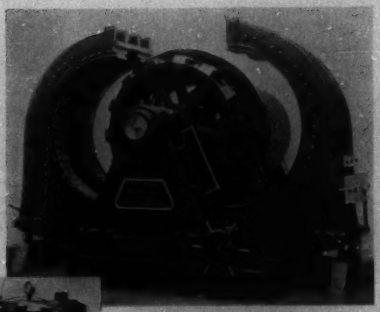
A modern counterpart of the early steam turbine stations shown on this and the facing pages, the Long Beach (Calif.) No. 3 station showing 2 94,000-kw tandem-compound units installed in 1928
(So. Calif. Edison Co. photo)

(Above) Brush central station in Philadelphia of 1883 vintage
(General Electric photo

(Left) An early 350-kw Parsons steam turbine driving 2 700-amp 250-volt dynamos. This unit was brought to the United States from Newcastle-on-Tyne, England
(National Carbon Co. photo)

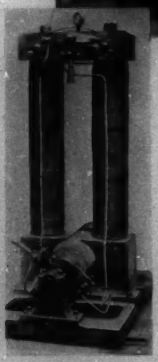
Generators

A 5,000-kw 500-rpm vertical generating unit installed at the Fisk Street station of the Chicago Edison Company in 1903; it consists of a 2-stage Curtis turbine direct connected to a 9,000-volt generator. This machine is one of the first large units of its type and one of the largest of its day
(General Electric photo)



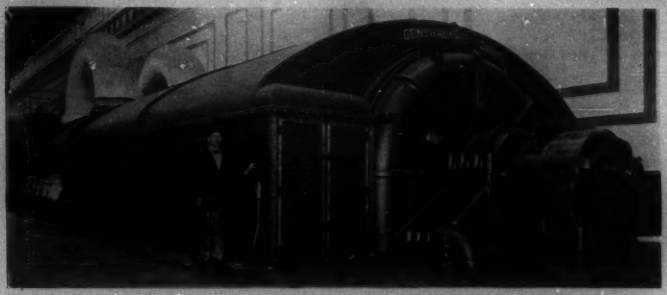
Original Stanley polyphase generator (armature drawn apart); this machine was wound for 6,600 volts and had a capacity of 600 kva; 3 of them were installed at the plant of Montmorency Power Company (Quebec)
(General Electric photo)

An early horizontal type d-c dynamo. This is a bipolar, double-magnetic-circuit machine, with 4 field coils, and was built in sizes ranging from 20 to 80 hp. This machine also was known as the Weston type; it sometimes was built with its long axis vertical
(Westinghouse photo)



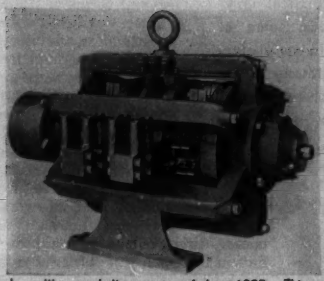
An early Edison type "Z" machine built in 1883
(General Electric photo)

(Above) Original a-c generator, 1886–89. This was a single-phase 133-cycle 1,000-volt machine; it had a smooth armature core, covered with a single layer of wire. The bearings required frequent attention, being lubricated by drip from large oil reservoirs
(Westinghouse photo)



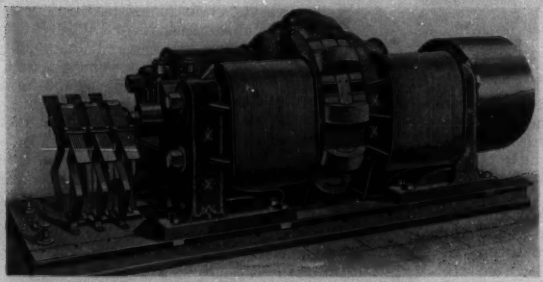
(Left) One of the largest of modern steam turbine generators is this 160,000 kw single-shaft unit in the East River station of the New York Edison Company; it was placed in service in 1929
(Consolidated Gas Co. photo)

# of Various Periods



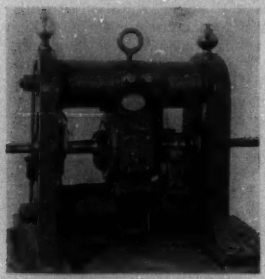
A unipolar or "homopolar" generator of about 1895. This machine, which generates direct current without a commutator, was built in sizes as large as 2,000 kw; unfortunately, however, it is practical for only very low voltages and consequently the demand was very limited. It is now a curiosity (Westinghouse photo

The engine-driven generator, before the coming of the steam turbine, grew to very large sizes. This machine, one of the largest of its type, is a 5,000-kw unit built in 1901 for the New York City Elevated Railroad; the diameter of the generator is 43 feet. Machines of this type were very common prior to 1900 (Westinghouse photo)

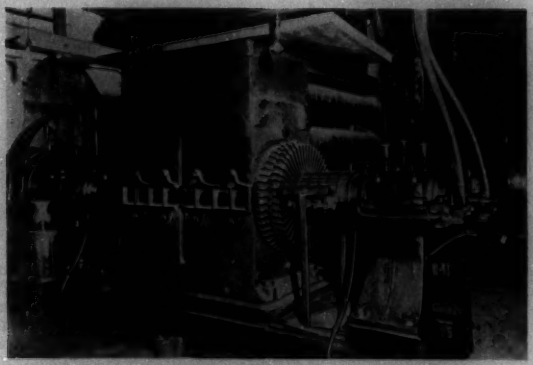


A Brush arc dynamo, one of the early types of generators designed for operating arc lamps in series (National Carbon Co. photo)

The first Edison jumbo dynamo that went into operation in Thomas A. Edison's original central electric light plant, the historic Pearl Street station in New York City, on September 4, 1882. This is the only one of the 6 original dynamos that is still in existence. It is now in Henry Ford's Edison Museum at Dearborn, Michigan (Consolidated Gas Co. photo)



An early Gramme dynamo. The exact date of this machine is not known, but it is a very early type, a similar machine having been used in Germany in 1882 or earlier (Westinghouse photo)



Some High Lights of Electrical History

By Elihu Thomson, President A.I.E.E. 1889–90

These personal reminiscences by a widely recognized leader in the electrical engineering profession touch upon some of the significant developments in early electrical equipment, and reflect many of the colorful personalities involved. This manuscript is based upon the record of a recent interview by Prof. D. C. Jackson.

OUR AMERICAN Institute of Electrical Engineers has now been in existence for a period of half a century, a period covering nearly the whole of electrical application from the time when there was little electrical engineering proper, to and including the major advances which it is the function of our Institute to discuss at its meetings and record in its literature, covering many volumes of proceedings.

As one of the surviving "old timers," I have been requested to outline, from my knowledge of the art, the conditions preceding the period about 1884, when the American Institute of Electrical Engineers began to take shape, a period which would precede the first electrical exhibition held in the United States, sponsored by the Franklin Institute in the fall of the year 1884, and called the "Electrical Exhibition." From that starting point, I shall proceed, in a sketchy way, to tell of the inception, the growth, and the important events in our art, which have characterized one of the major business enterprises with which I have been connected a little more than the full half-century.

I had been, in 1884, for a long time associated as member and as one of the board of managers of the Franklin Institute, and was accustomed to present papers on any new matter that we had been investigating. These papers were presented at the monthly meetings.

Developments Prior to 1884

I may now be permitted to make a brief statement of the conditions regarding the generation of electricity from power prior to the date mentioned, and, of course, subsequent to Faraday's discovery, in 1831, of the conversion of mechanical power into electric current. A great deal of information on this part of the subject is to be found in the two large volumes on "Electric Illumination" by James Dredge published in 1882, much of the material of which is stated to have been taken from the journal *Engineering*. The subject "electric illumination" refers, in fact, to the early efforts to use mechanical power to drive dynamo-electric machines, now called electric generators, and the purpose of the currents so generated was to furnish the electric energy for lighting. It is true that the earliest of these machines or generators comprised both the direct current and the alternating current types. There were several forms of these machines, which consisted mostly of revolving coils in the fields of permanent magnets, and they were applied mostly where a large unit or source of light was needed, such as a large arc, and used chiefly in lighthouse service. Such were the Clark, the Alliance, and the Holmes types of machines. These were followed by the Pacinotti, which was, of course, direct current and laid the foundation for such generators or dynamo machines as the Gramme. There were also the Wilde and Ladd machines, to which I will refer briefly later.

A significant committee was called about this time, which became known as the "C. G. S. Committee," establishing as units measures based upon the metric units, centimeter, gramme and second; the centimeter being the unit of length, the gramme being the unit of weight or mass, and the second the unit of time. This committee included such men as Weber, Gauss, Sir William Thomson, Prof. G. C. Foster, James Clark Maxwell, G. F. Stoney, Prof. Fleeming Jenkin, Dr. Werner Siemens, F. I. Bramwell, and Professor Everett, who was secretary of the committee. The work of that committee was followed, in part at least, by the subsequent electrical congresses in the different countries, usually associated with the great international expositions.

Until the invention by Gramme, in 1871, of the Gramme machine, the continuous current dynamos or generators were such as the Wilde and the Ladd. I happened to be present at an exhibition in Philadelphia in which a Wilde machine was shown, which had been acquired from abroad for the University of Pennsylvania by Prof. Robert E. Rogers, of the department of physics, and I remember the thrills that I experienced in seeing it operate giving direct current and heating a strip of metal to a bright red heat when driven by the power of 2 men. I seemed to feel in this exhibition, modest as it was, that there was the beginning of our art so far as continuous currents were concerned. However, this comparatively crude machine was soon followed by the Gramme, involving the principle of commutation set up by A. C. Pacinotti some time before. The Gramme machine was at once recognized as a type far more perfect for continuous current generation than anything that had appeared before, and while it was developed in France, there were occasional instances of such a machine having been

brought to America. I may add here that it was recognized as perhaps the most perfect type of continuous current machine when announced in 1871 by Gramme.

NOTE—To anticipate, in 1889, at the Paris Exposition, I was invited to take luncheon with the electrical jury, and Gramme was present. I was told that it was very difficult to get him out, and that it might be considered a most exceptional event that he had appeared on this occasion.

The Gramme machine became known in the literature in the early 70's of the last century, and was followed by modifications, such as the Wallace-Farmer machine, made by Wallace & Sons, of Ansonia, Connecticut. It also was followed abroad, as in England, by R. E. B. Crompton taking up and manufacturing the Bürgin machine, which was like the Gramme except that instead of a single iron wire ring with the armature coils carried thereby, there were several rings consecutively placed on the shaft. The copper wire coils of these rings, few in number on each ring, were connected up to a commutator which was practically like the Gramme or Pacinotti. Colonel Crompton still lives in London at the ripe age of 90 years.

Then came the Siemens machine with its cylindrical armature, similar to the Weston, followed by the Brush machine, which, while it had an armature in the form of a ring, was peculiar in its commutation and not at all like the Gramme.

It should be noted here that during the Exposition of 1878 at Paris, the Avenue de L'Opera was lighted, as well as the Place de L'Opera, by a system which existed only for a few years, namely, the Jablochkoff. As I was in Paris at the time, I was able to form an estimate of the possible future of the Jablochkoff system of lighting. It was based on the use of parallel carbons in what was called the Jablochkoff "candle," and these were operated by alternating currents from stations nearby. These stations had been furnished with dynamos which were based on principles similar to the Gramme, but without the commutation. I remember also that one of the railway stations in Paris, I think the Gare St. Lazare, was lighted by a series of arc lamps of the Lontin system, about 6 or 8 in number, during the exposition time, and so far as I know, this was one of the early cases of the use of arc lamps in series. Crompton, in London, I understand, in applying the Bürgin type of dynamo to lighting, did not limit himself to a single lamp, but the machines were made of sufficient voltage to operate 2 or 3 or more in series.

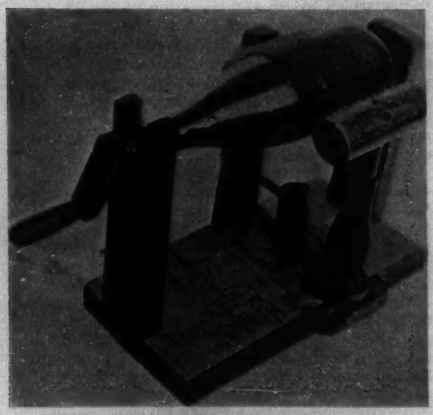


Fig. 1. A model, part of which is the original, of a wine bottle frictional static machine built by Professor Thomson when 11 years old

I can say that at least 10 years before the formation of the American Institute of Electrical Engineers, I began the construction of small model dynamos and armatures. From 1873 up to 1875, I remember making a small dynamo with a Gramme ring, and comparing its operation with the same machine in which the armature of the ring type of Gramme was replaced by what became known as the Siemens armature, though at the time I thought I had invented it, until I had looked it up in the British patents. It was the drum armature, so-called, and the comparison really favored the Siemens type. I still possess this small example of early construction.

Early Experiments in Electronics

Prof. E. J. Houston and I had become associated in electrical work, he being at the head of the physics department, and I teaching in the chemistry department of the Boys' Central High School in Philadelphia, Mechanics being one of the subjects that I taught, and any new ideas which came to us were discussed together. It happened that, about 1875, it was announced by Edison that he had discovered a new force, which he called "etheric force," because it showed no evidence of polarity, plus or minus, positive or negative, and would not affect any of the instruments then in use for detecting electric current. A considerable amount of interest had been taken by the newspapers in regard to this alleged new force, or "etheric force," and, as was natural, Professor Houston and I discussed the matter. I remember saying to him, "That is not a new force; that is electrical, and we can easily prove that it is so." This led to a series of experiments in which finally the discharge of a large induction or Ruhmkorff coil secondary across a spark gap produced sparks about $1^1/_2$ or 2 in. long, from an improvised condenser which consisted merely of a tin vessel supported on a glass jar attached to one of the terminals of the secondary of the induction coil, while the other terminal was grounded on a water pipe beneath the desk or table. This apparatus being set into action, we explored the whole school, which was quite a large building, and found that we could pick up tiny sparks from metallic objects all through the building, which had many rooms and a basement, and that even at the observatory at the top of the building, nearly 100 ft away, these same

indicating sparks could be drawn from almost any metallic object, proving that the "etheric force" was merely rapidly reversed electrical impulses sent out, clearly an embodiment of the subsequent wireless work. We had no doubt at the time that we could have gotten these tiny signal sparks, as we might call them, from any location, even outside the building, if not too far away. Our experiments provided the missing polarity, and showed that a proper instrument would have responded to the waves sent out by each spark. These experiments were described in the *Journal* of the Franklin Institute, and the article was reproduced in the *Scientific American Supplement* No. 21, issued May 20, 1876.

This account would not be complete without brief reference to the conditions in which I was personally concerned, which led me into the art of dynamo construction and arc lighting. At the Centennial Exposition of 1876, there were, as I remember it, 3 exhibits of dynamos; one was the very interesting Gramme exhibit, sent over from Paris and occupying a small space in Machinery Hall; another was a Wallace-Farmer machine, used to provide current for a single arc light; and the third was a solitary machine which I understood had been built at Cornell University by Prof. William A. Anthony, physics professor there, who afterward became a President of the Institute. It was substantially of

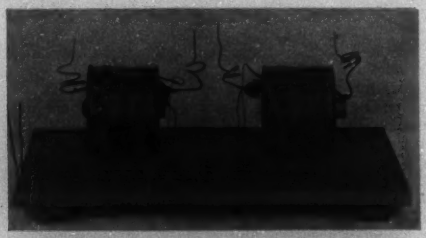


Fig. 2. Experimental pair of transformers as used at the Franklin Institute, Philadelphia, January and February 1879, in pioneer a-c experiments

Gramme construction. When the exhibition had closed, some of the lighting of the building was taken care of by Brush machines temporarily, a single arc on each circuit.

It had been proposed at the Franklin Institute to appoint a committee on Dynamo electric machines, so that measurements of power taken to drive them, measurements of electrical energy used in the various parts of the circuits of the dynamo, especially in the arc circuit, measurements of efficiency in the conversion of power into electrical current energy, and such other things as might seem of interest and of value in regard to the growing importance of such machinery, should be made. These tests were made on several machines offered for test in the early part of 1878, and the record of this may be found in the Franklin Institute *Journal*, "Report of the Committee on Dynamo Electric Machines," so that I need not go into any further detail here.

Early Lectures and Experiments

It is proper that I should mention in this connection that I was requested to deliver a course of 5 lectures early in 1877, at the Franklin Institute, dealing with electricity. I took for my general theme in these lectures the idea that electricity from any source, however produced, was the same in essence and obeyed the same laws. This led me to do some things which I believe had not been done before, such as reversing a Ruhmkorff induction spark coil by sending a high tension discharge from a Leyden battery through the fine wire winding, and noting the effects in the coarse wire primary, so-called, which now became the secondary circuit. As the induction coil itself would be subjected to some strains which might even break it down, I used in this case a coil that I had built for my own use, and which I could rewind if anything happened to it. This reversal of the induction coil led to 2 things; it suggested the idea of the electric welding transformer, which experiment I need not describe, as it has often been described; and it also led to the transformer in wh ch a high potential was put upon the primary fine wire and the working current taken from a short conductor, which ordinarily is the primary but now had become the secondary, leading at once to the idea of the potential reducing transformer or transformer system. I need not dwell on this experiment either, because it has been described, but each of these trials became the fruitful suggestions for later work.

The tests at the Franklin Institute naturally turned my attention to the use of dynamos for working arc lights, and no doubt was a considerable factor which led to the invention of the Thomson-Houston 3-coil machine as a simple dynamo construction, from which we developed a constant current arc lighting system. I had found very soon after running the first of this type of machine, that I could change the position of the brushes on the commutator and even run the machine on a short-circuit without increasing the line current and without any damaging effects.

The first machine embodying these principles was built in a small machine shop in Philadelphia, but when it was ready for test, we did not have power enough to drive it. However, we found a place for it in a bakery nearby where we were able to run it, and this machine became known as the "bakery machine." It is the one that is now at the National Museum in Washington. When we came to build the machine, I had to do all the figuring, and all the proportioning; in fact, all the engineering. I wound every inch of wire on it, because I did not dare to have anybody handle the wire without knowing it was thoroughly insulated. We got it running, and our backer, Mr. Garrett, came in one day while we had 4 20-ampere arcs running from it. He said, "Aren't those lights rather large?" I said, "Yes; I thought you would need smaller lights,

but we have no lamps to test this out. In fact, I have provided for the change to smaller current and higher voltage. The machine is double wound and has 2 wires instead of a single wire circuit running through it. I have only to make a few alterations in coupling these wires, but we have no lamps to make the test." Mr. Garrett replied, "I can borrow a number of lamps, and we can make the test and then restore the lamps to the circuits." With that, he brought along about 10 arc lamps of the Brush type, which, by the way, fitted nicely into our conditions, and in testing we found that at the speed we were driving the dynamo, which was unchanged from the time it was running the 4 lights, we could easily maintain, in a series, 9 arc lamps. This first machine, called the "bakery machine," the first of its type with the 3-coil armature winding, was already a well developed machine for quite a number of arc lamps.

During the time this machine was being run in the bakery, Houston and McCollin, the latter being associated with Mr. Garrett, would come in and find me there looking after the machine, and would say, "My, you will kill yourself," for the thermometer in the room frequently registered 140°F., and the only way I could stay there and watch the machine was by drinking ice water to excess. Before my blood became too hot I cooled it in this way and survived the heat with no ill effects, while both Houston and McCollin were forced to retire from the field because they were overheated; upset by something like sunstroke.

Garrett and McCollin carried on in Philadelphia the construction of machines that were very much like the "bakery machine," and Mr. Garrett started a small business of making and selling these machines with the complement of arc lights.

Design Controversies

It was about this time that our business was transferred to New Britain, Connecticut, the actual establishment of the business in New Britain taking place in the year 1880. A syndicate of local business men, headed by Frederick H. Churchill, made an arrangement with Mr. Garrett to take up the work for the United States, except for the middle states, which Mr. Garrett retained. While the business done in New Britain was not particularly active, and, in fact, was much smaller than it should have been with proper energy and devotion to the new enterprise, it did give me an opportunity for developing certain things that added advantages to what was then known as the Thomson-Houston system of arc lighting. It was fortunate that E. W. Rice, Jr., who was a young man just graduating from the High School in Philadelphia, associated himself with the enterprise, and by his energies was one of the greatest assets we ever had. Recipient of many honors, he became President of the General Electric Company, after having served for years as its technical director at Schenectady.

For a time there was a superstition that the wire over the ends of an armature, such as the drum (Siemens drum or Weston types) was idle wire, since it did not cut the lines of the field, and that, therefore, it would be proper to restrict its amount as far as possible. The correct view, which became the practice in Thomson-Houston designs, recognized the idle wire idea as unsound, and that the form of the armature winding depended on enclosing the maximum of lines of force or surrounding an area by the armature coil or coils as great as possible and

Fig. 3. Professor Thomson's 1878 a-c generator, first shown at the Franklin Institute in Philadelphia, where with 2 step-down transformers connected in parallel it lighted lamps

securing the benefit of a high peripheral speed in cutting the field lines. Hence, if more field lines at high speed could be cut, so much the better the design.

This principle was recognized in the "bakery machine" and in the Thomson-Houston dynamos built in 1879 in Philadelphia, and in the subsequent development of the Thomson-Houston system in Lynn, Mass., with its armature winding short along the axis. When this became generally known, the idle wire theory gradually disappeared, both in electric motors and in dynamo machines.

It was during this period that I designed and built the type of dynamo which became characteristic of the Thomson-Houston system; namely, the spherical armature type, which retained the 3-segment commutator and was provided with a perfected regulator for moving the brushes and keeping the current in the circuit constant, no matter what might be the load in lamps up to the capacity of the machine.

On p. 190 of Sylvanus P. Thompson's "Dynamo Electric Machinery," published, second edition, in 1886, he says:

> Thomson-Houston Dynamo—This machine, which is equally remarkable, was designed by Professors Elihu Thomson and Edwin J. Houston, of Philadelphia. Its spherical armature is unique among armatures; its cup-shaped field magnets are unique among field magnets; its 3-part commutator is unique among commutators.

While the spherical armature machine was developed in New Britain, the capacity of any single machine was limited to 12 arc lights in series, the commutating limit, until during the stay in New Britain another important invention had been made; namely, the air blast for the commutators, the air blast being a device for inserting non-ionized or cold air at the breaks in the commutator, 3 in number.

Fig. 4. A complete Thomson-Houston 3-coil arc dynamo with movable brushes and wall regulator

The number of arcs in series which could be operated from 1 dynamo was increased indefinitely, so that later on as many as 75 arcs were maintained from a single 3-segment commutator, and this arrangement permitted free oiling of the surfaces of the commutator.

Cincinnati Industrial Exhibition, 1883

In regard to the work in New Britain, it may be proper to mention that in 1883 there was held in Cincinnati an industrial exhibition. Electric lighting machinery being then quite novel, arc lights were naturally the subjects of investigation included. This led us to send to the exhibition one of our machines with its complement of arc lamps. The tests made were in charge of Doctors Mendenhall and Eddy, professors in the Ohio State University and the University of Cincinnati, respectively. Their report was favorable to our machine, which, in my judgment, I thought would be the case.

It was an era of intense rivalry. The Brush Company, Weston, ourselves, and others, were rivaling each other, and we were making all the good points we could for our own systems, of course. Some of the prominent electric lighting companies had, according to our view, no satisfactory arc system, one that met all requirements, and in 1882 we had a discussion with some of them in New York about the future of the art, etc. On going back to New Britain, I was called into a meeting of our directors and stockholders, and was presented with a contract all drawn up for me to sign, to cover future service. They would hire me for a certain amount to carry on the work, for so many years; and I said to myself, "What they are after is to put me on the shelf. They think they will satisfy me by giving me a contract for so much a year and for so long." "But," I said, "I see no preamble, saying that the company must carry on the work with due diligence, as per the first contract. That should be there." They said, "All that is understood." "Well," I said, "if it is understood, put it there." I was given to understand that Houston, being 8 years my senior, would be the hard one to deal with, but Thomson would be all right, and I thought, "I will show them. If that is the way they estimate me, they will get to know more." They said again it was not necessary. I said, "I demand it; that is the whole essence of the thing." We spent a whole afternoon arguing, and finally I picked up my hat and said, "Gentlemen, I am going. You need not expect to hear from me unless you put that preamble in the contract," and I left.

Some Early Commercial Developments

The next thing I heard was that the New Britain people had sold out to the Brush Company, of Cleveland, Ohio. George W. Stockley, the head of the Brush Company, had bought a majority interest in our stock. I met him in New Britain, and I said, "Mr. Stockley, do you know what you have bought? You have bought a law suit, and you are bound to lose out on it." I said, "Please look at this contract." I pulled out the original contract; "If the business is not carried on with due diligence and the proper expenditure of time and money, the patents revert to the patentees on presentation of their stock." He read it, and said, "I wouldn't have touched it if I had known that was there; I wouldn't have had anything to do with it."

That is the time that the Lynn people came along; S. A. Barton, H. A. Pevear who was our first President when we got to Lynn, and C. A. Coffin, about 7 or 8 in all; we called them the "Lynn Syndicate." Their interest in our apparatus came about in this way. A promoter named Edwards H. Goff, had bought one of our little machines of several arc lights capacity, and to interest the public had put it in the basement of a building on Tremont Street, in Boston, and so wired it as to put 2 of the lights outdoors. They were good steady lights, and attracted attention, including that of the gentlemen from Lynn, who said, virtually, "Why can't we get this kind of a system for Lynn?" Barton wanted it for his store, and the others were also interested. They happened to look at the nameplate of the dynamo as run in Boston, and found this inscription, "Manufactured by the American Electric Company, New Britain, Conn."

Silas A. Barton and Henry A. Pevear at once made a trip to New Britain, and there met E. W. Rice, Jr., who showed them our apparatus and system. Mr. Rice told them the whole story of how the business stood, and they said, "Why can't we get into this thing?" He told them that he thought that under proper circumstances I would join hands with them and be very glad. That opened the way for the Lynn people to buy the majority interest in the American Electric Company. In fact, they bought Stockley's stock. I made it clear to them that if they bought Mr. Stockley's interest and carried on the business as we hoped it would be carried on, we would join heartily with them, of course.

Thus began the works at Lynn, in 1883. The Lynn contingent built a factory, stocked it with tools, and we soon found that Mr. Coffin was a wonderful man, a business genius, who would come into the works and see us at work at some new thing, and would say, "How soon will you have it?" "Well, we will do it as fast as we can," would be the reply. He would say, "Go ahead and do it, and don't mind the expense; do the thing you think is right." When it came to the street car business it was the same thing, "Go ahead and do it." The foundation of our enterprise in 1882 was the Thomson-Houston arc lamp system.

The Arc-Light Era

In the exploitation of the arc system, we had adopted as a standard current value 9.6 amperes for the larger lights, and 6.8 for the smaller lights. These were always run in series, and the arc lamps could be exchanged from one constant current circuit, say 9.6, to another circuit of 9.6 at will. In the same way, the voltage across the arc was standardized so that the arcs in one of these circuits could replace any others; they were interchangeable.

It also may be mentioned, as an interesting fact, that from the start of our business we had provided on each arc lamp shunting switches, so that if a lamp was not needed, or was to be extinguished, it was necessary only to close the shunting switches or close the shunts around the lamps to be cut out. These advantages were, indeed, very much appreciated, and gave exceptional status to our arc lighting system. The possibility of their being used in this way, of course, followed upon the standardization of the current by the regulator, notwithstanding the changes in the load on the dynamo or on the constant current circuit, or fluctuation of speed in the dynamo.

In the arc lighting field, naturally the Brush Electric Company and the Brush arc system and the Thomson-Houston system operated the majority of arc lamps throughout our cities, the Thomson-Houston system continually gaining, so that in a few years it became the one most extended in use.

While our first arc lighting work included only the d-c carbon arc, this was, as time passed, substituted by the enclosed carbon arc, the luminous arc in which the arc flame itself was the source of light, carrying, as it did, refractory luminous particles, and later by the magnetite arc in Schenectady, as invented by Dr. Charles P. Steinmetz, many thousands of which went into use. We soon took up a general business, including electric motors for d-c and a-c circuits, and the great variety of electric appliances suitable to be worked on the circuits, a-c, d-c, etc. The development and application of the a-c constant current transformer for working the street lights was not the least of these developments, and will probably continue for many years ahead.

The exhibit of the Thomson-Houston Electric Company at the Franklin Institute's electrical exhibition in 1884 comprised several features that had been developed from time to time. For example, the slow feed that was required in arc lamps for the upper or movable carbon, with its holder, was secured by a very simple device which we designated the elastic support of the clutch, and which, in noncritical commercial language, gave what was known as a "sneak feed."

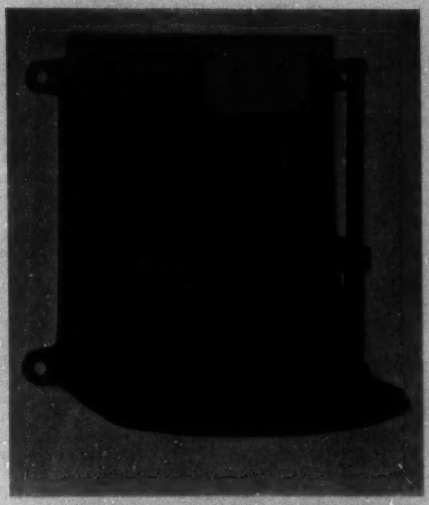


Fig. 5. Early Thomson recording wattmeter that shared first prize in Paris meter competition of 1890

Sometimes it was an apparently small thing, a matter of proportioning, perhaps, that would determine the future history in the practice of our art. Very early in the Thomson-Houston development in Lynn, Mass., came the simple yet effective device called the film cut-out. It was especially applied to a system of incandescent street lamps, in which several series of lights were worked, the film cut-out being placed in the base of each lamp so that if a filament broke an instantaneous shunt around that particular lamp was established, leaving the rest of the system intact.

Again, we developed the contactor control system, which is described in Thomson United States patent No. 617,546, of January 10, 1899, and has

been used widely in the control of trains embodying motor units on several cars of a train of passenger coaches, such as in the elevated train in cities, etc.

Some Early Transformer Developments

Another important invention which was developed along about this time, and which had been applied in New Britain on switches and lightning arresters and controllers for circuits, was the magnetic blowout, and during the period of the development at Lynn, the transformer system which I had created and tried out at the Franklin Institute in 1879 was brought to the point at which it could be commercially used. Although it was the opinion of many that the alternating current with high voltage primary circuits and low voltage secondaries for feeding the local load was dangerous, on account of the possibility of leaks from the high voltage to the low, I withheld the Thomson-Houston Company from going into the field until I could develop proper safeguards, 3 of which were worked out; chiefly the grounded secondary, which became practically universal, having been at first condemned by the underwriters, then tolerated, then recommended, and finally becoming mandatory. This history of the safety grounding gave rise to a resolution by the Western Association of Electrical Inspectors, at its 20th annual meeting, in which they designated me as the "father of protective grounding," the date being September 2, 1925.

Fig. 6. Early model of Thomson constant current transformer

It may be mentioned that the transformer system was completed by the oil immersion of the coils of the transformer and the cooling of the oil by circulation of water, the large and later developments of which have been perfected at Pittsfield, Mass., the seat of the transformer manufacture of the General Electric Company.

Among the many important developments has been, of course, the alternating current motor, known variously as the repulsion motor, the shaded pole, etc. Added to this list of matters which were developed at West Lynn to a large extent, is a system of inventions beginning with the announcement of electric welding, first described in a paper in the *Electrical World* of December 25, 1886, and followed by numerous other modified or detailed patents forming the basis of the Thomson Electric Welding Company, of Lynn, which gave its attention to resistance welding, so-called, and which still carries on that special work under the name of the Thomson-Gibb Electric Welding Company.

The patent records, to show the activity in inventions during the period of business in Lynn up to the present, cover upwards of 700 patents issued to me in the United States alone, sometimes jointly with other inventors. The list of inventions was extended greatly, patents for other inventions being taken out in the individual names of the inventors. Naturally, this list does not include the inventions made at other works of the company, such as Schenectady.

It is an interesting fact, proper to be noted in this connection, that the Brush electric arc lighting system was later transferred, in its manufacture of Brush dynamos, to Lynn, and that many of the larger type of Brush arc machines were built there. Attached to these large generators or arc dynamos was a regulator which answered all the purposes and gave a new status to the Brush dynamos as built at Lynn, making the plant entirely automatic. This was accomplished by the Thomson-Rice Regulator, the patent for which was issued March 30, 1886, No. 339,079. This patent was taken out some time before the absorption of the Brush Electric Company, of Cleveland, Ohio, by the Thomson-Houston Company.

Electrical Measuring Instruments

When the New Britain organization was established in 1880, it was difficult to obtain any measuring instruments, or if they were obtained they involved a large expense desirable to avoid at the time the new enterprise was just beginning. Consequently my first piece of work there was to construct, by my own hands, measuring instruments in our little model shop. This involved the production of a Wheatstone bridge, of the single wire type, with slider; it also involved the production of standard resistances to use with the bridge, and these were copied from standard bobbins that were borrowed for the time, such as units of value, 1 ohm, 5 ohms, 10 ohms, or 100 ohms, etc. It also was found difficult to obtain

an ammeter for measuring current, so that an astatic galvanometer was constructed and employed in connection with the bridge, used for standardizing the voltage and the current flowing in the circuits. Within a short time, however, we made for service such instruments as Thomson-Rice ammeters and voltmeters, some of which are still in existence. There also was constructed, as early as 1880, a testing room dynamometer for measuring the power required to drive the dynamos under various loads. This also was used to measure armature losses.

During the early period from 1883 on, there were some carbon filament incandescent lamps, and a compound wound constant potential self-regulating dynamo adjusted to run at a standard voltage as desired. The brushes on the commutator of these machines were set in position and not changed for different loads, so that this constant potential dynamo, like the arc machine, was self-regulating no matter what the load, so far as the commutation was concerned, but, of course, there had to be provided the variation of excitation by the shunt field.

At the Paris exposition of 1889, and in the exhibit made there by the Thomson-Houston Electric Company of the various appliances and inventions, there were a few meters especially arranged to record the load on the secondary of transformer systems. The electrical jury were advised by me to pay no attention to the exhibit of meters, as there was soon coming a much more perfect instrument of the kind. It happened that the Paris meter competition was to be held the next year (1890) and that a prize of 10,000 francs had been set aside for the winner, or to be divided if there was more than one meter that met all the conditions, chief of which was that the meter should be available without change, on alternating current or direct current. I urged our people to enter the competition, because I felt fairly certain of winning at least a part of the prize. The result was that the Aron meter and the Thomson recording wattmeter were awarded each 5,000 francs, because both the Aron meter and the Thomson meter met the condition of being available on alternating current and direct current. The decision of the Paris meter commission was quite satisfactory, because it seemed inevitable that the simpler construction of the Thomson meter would win out commercially.

At the time of the International Exposition at Chicago in 1893, I happened to meet Prof. W. E. Ayrton, who had been appointed to head the electrical jury of awards. He told me that they expected to use our meter as a standard with which the others were to be compared. Until the development of the simple a-c wattmeters, this meter satisfied all the requirements.

International Coöperation

In the fall of 1884, and during the continuance of the Franklin Institute's electrical exhibition, there was called a conference of electricians to discuss such matters as would naturally fall to a congress of the kind; the use of terms, etc. Before that date, I had become familiar with the increasing growth of the electrical art, not only in the United States, but by visiting the Paris exposition of 1878. The conference of electricians at the Franklin Institute exhibition was the first general meeting in the United States, and was the forerunner of the international electrical congresses of 1893 at Chicago, and of 1904 at St. Louis. Other congresses were held abroad filling in the gaps, as it were, and at which some very important decisions were reached in the nomenclature and units of measure. Thus, the unit of current, which before that time had been called *weber*, was now changed to the *ampere*. It was natural that I should attend the early meetings of the infant society, The American Institute of Electrical Engineers, which has now grown to such great importance and includes an army of membership.

The records of the Institute itself will furnish such information as to papers and discussions in which I have taken part. When elected President of the American Institute of Electrical Engineers in 1889, I presided at one of its meetings at which I delivered a paper.* Later in the year, I went abroad to attend the Exposition Universelle at Paris. The well-known repulsion experiments with alternating currents were shown at this exposition for the first time abroad, as well as several devices based upon the discoveries made. They naturally attracted a great deal of notice here as well as in Europe, and formed the basis of many valuable devices, including the repulsion a-c motor.

Prof. J. A. Fleming requested that the repulsion apparatus, which included quite a series of embodiments showing the repulsion principle, be loaned to him so that he might present it in a lecture to the Royal Society of England. This was done in the famous Fleming lecture, and then followed the request that the set of apparatus be retained in England permanently in the Royal Institution, on the idea that Faraday's work would be supplemented for alternating currents, whereas his work had dealt only with direct current. This gift of the pioneer repulsion apparatus was made, accordingly.

It happened that while I was in Europe, in 1889, I was called upon to represent the A.I.E.E., being then its President, at a conference of a body of engineers in London. This meeting comprised about 300 visiting Americans, including many men at the head of our engineering and manufactures, along with 300 or so British representatives of the arts and industries. It was particularly desired of me that I attend the Guild Hall dinner, as the Institute's first representative abroad. There was a list of speakers representing the British side, as also others representing the American visiting engineers. In a body of the size (600) it naturally became a difficult matter to have the speakers dominate the situation, or speak loud enough to reach the members present and prevent their going off into a buzz, and this is the humorous part of it:

One of our American college professors who was present was seated at the head table several places to the left of my position, and he passed me a note

* Professor Thomson's first formal paper before the Institute was the classical paper entitled "Novel Phenomena of Alternating Currents," presented at the General Meeting on May 15, 1887.

while one of the gentlemen representing one of our metal industries was speaking. It was notable that this man's voice did not reach many feet away from his position at the head table. The professor's note reminded me of the fact, and to quote him (those present were paying little attention to the speaker, and the whole room was filled with a buzzing mass of humanity who, not being able to hear, naturally fell into conversation with neighbors), "Thomson, it is your turn next, and for the Lord's sake, get them back!" I answered his note, "I will if I can." The denouement was that I did get them back, and had the attention of the body present in a few minutes after I began, but it required a tremendous effort of the lungs to reach the more distant part of the audience.

I am reminded that in one of the discussions printed in the JOURNAL of the Institute, reference was made by me at some length to a steam engine of high economy, which was not even condensing, but exhausted its steam directly from the cylinders. We were surprised to find that the same type of engine sometime later was announced to the world as the Stumpf uniflow engine, showing high economy, and that other engines of similar type, one called the "unaflow" instead of uniflow, appeared in the steam engine art. I have at least the satisfaction of having brought this type of engine to the knowledge of the membership of the Institute, describing its construction and its properties before it had been christened the "unaflow" or "uniflow," but I was not present at that ceremony. It was developed by me at the Lynn Works of the General Electric Company.

SOME RAILWAY DEVELOPMENTS

I should not leave this account without reference to another important event, which practically started the work of electrification of street railways by the Thomson-Houston Company. The company already had made arrangements with Bentley and Knight in connection with railway problems, but Mr. Coffin took the position that the wisest and speediest method would be to acquire an active business from some one of the concerns already specializing in that work. He asked me, "Thomson, who is there that has done pioneer work in street railways?" "VanDepoele, of Chicago," I answered. Said Mr. Coffin, "What has he accomplished; how is he getting along?" I said, "He has done much good work, but I believe the conditions of his organization are not satisfactory to him." Mr. Coffin then asked if I thought he would come on for a conference, to which I answered in the affirmative.

On invitation, Mr. VanDepoele did come on to Lynn, and we met in Mr. Coffin's house. Mr. Coffin was soon satisfied that Mr. VanDepoele was, indeed, a valued pioneer in street railway electrification. The business of VanDepoele then became part of the work of the Thomson-Houston Company, especially in the engineering organization. Unfortunately, Mr. VanDepoele contracted an ailment, severe muscular rheumatism, leading to his untimely death, but he had left his impression involving the under-running overhead trolley and the carbon brush. Elsewhere the complete history of the application of our introduction of the carbon brush to electric railway motors is to be found, and need not be repeated here. This use was a suggestion of VanDepoele's. In the same way, the carbon brush became an essential to commutation in the power station dynamos, and, indeed, the almost universal application of the carbon brush in dynamos and motors of the continuous current type followed.

Fig. 7. Professor Thomson and his first (1886) electric welding transformer, with single turn secondary

It is well known that under the circumstances existing in 1891–92, it was desirable that an organization should exist which would supplement the work of such a company as the Edison General Company, which had opposed the use of alternating currents on the ground of danger. It was thought desirable that a company in the expanding field should not be limited by the opinions that this or that should be avoided, when proper safeguards were established. This was the case with our safety devices for alternating current and transmission by transformers at high potential to be lowered at the consumers' end to the potential desired in the apparatus used. This condition was brought to the notice of some of the most important business men in the Edison company, and, of course, the Thomson-Houston Company was informed. Not to go into the details, it was determined by the Edison General Company that it would accept the conditions which would make a well rounded-out organization. Mr. Coffin was called upon, as the leader of the Thomson-Houston Company, and his broad view favored the consolidation of the two companies. Thus, negotiations followed whereby a number of the Thomson-Houston officials became the leading officials of the new organization, the General Electric Company, with Mr. Coffin as its president. In this way, the field for expansion of the electric lighting and power industry was stripped of some limitations, which before had stood in the way.

At the beginning of the present century, I was re-

quested to furnish an article to the New York *Sun*, dealing with the advances in the electrical work that had characterized the century before 1900. That task I undertook, and the article was widely published.

Mention has been made of the International Congress of Electricians, which met in St. Louis in 1904. It happened that I was made the president of this Congress, with a very efficient secretary, Prof. A. E. Kennelly, and treasurer, William D. Weaver who had long been connected with the finances of the Institute. Due to their untiring devotion, the congress was quite a success.

The organization that was started in St. Louis at the time of the exposition was, on the recommendation of some of the members of the congress, made permanent, taking the name of the International Electrotechnical Commission, with Lord Kelvin as its first president, followed by Prof. E. Mascart, who did not, however, survive to take the office. After the death of Mascart, I served the commission for the prescribed period of the presidency, and a permanent secretary, C. LeMaistre, was chosen. Much valuable work in unification and standardization has been carried out by this body, the work of which has continued since that time.

I need hardly say anything to emphasize the valuable work done by the American Institute of Electrical Engineers, as the leading body of electricians and engineers in the United States, during the past 50 years, and which led to the establishment of the Engineering Societies Building at 30 West 39th Street, New York City. The organization now includes a membership of more than 15,000. I need not call the attention of the members of the Institute to the several affiliated bodies having charge of awards: The Engineering Foundation, established by an original gift of $500,000 by Dr. Ambrose Swasey, The American Standards Association, The American Engineering Council, The International Electrotechnical Commission, and many others.

This personal review has naturally been limited to accomplishments growing out of the work of but few persons, and it must be understood that similar histories could be provided by the leaders in the many other organizations of similar character throughout our country, as well as the world. The attempt has been to produce a record which can be referred to by the younger men who devote themselves to electrical applications and enterprises, such as have been the work of the past.

It is natural that numerous technical, or partly technical, papers would have been communicated by our profession of electrical engineering to the societies over so long a period as a half-century. The proceedings of the American Institute of Electrical Engineers contain a most valuable record of the progress in the electric art, and the discussions held at its meetings and embodied in its records have had a profound influence in emphasizing the important steps in the development that has taken place. Can we doubt that this record will be continued in the next half-century?

Interior of the Hoboken Station of the Hudson Electric Light Company in 1897

Public Service Photo

This station was placed in operation in 1892 and shut down in 1902. The machines in service, most of which can be seen, were Thomson-Houston (4) 1,000-volt 2,000-light, (10) 4,000-volt 80-light, (5) 500-volt 100-kw d-c, and (3) 500-volt 500-kw d-c generators; a Brush 125-light arc machine; and 2 Edison exciters

Typical Electric Motors

In addition to the electric motors shown on this page, other rotating equipment is shown on pages 754–5 and 756–7

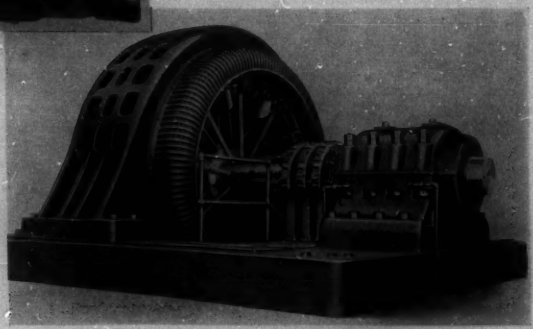
One of the first polyphase induction motors to be placed in commercial use—a 5-hp, 110-volt, 50-cycle machine installed in 1893 and operated until June 1925 (General Electric photo)

(Above) Said to be the "progenitor" of the present d-c railway motor this 1891 motor embodied the slotted armature, symmetrical 4-pole field, single reduction gear, and ironclad construction now universal (Westinghouse photo)

(Right) The Bastet magnetic engine built in 1874, one of the earliest known motors produced commercially (National Carbon Co. photo)

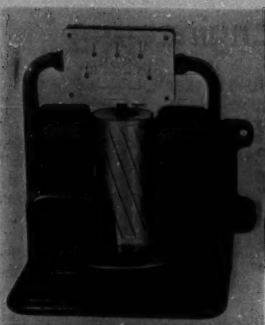
An early Van Depoele electric railway motor—equipped with 2 sets of metal brushes, one for each direction of rotation. The levers for controlling these brushes may be noted (National Carbon Co. photo)

Tesla induction motors—the one on the right, with a 3-in. rotor, being a ½-hp machine. The fan blades are indicative of one of the first widespread applications of induction motors (Westinghouse photo



A modern 6,000-hp induction motor built for steel mill service (Photo courtesy Allis-Chalmers Co. and National Carbon Co.)

Early Electrical Instruments

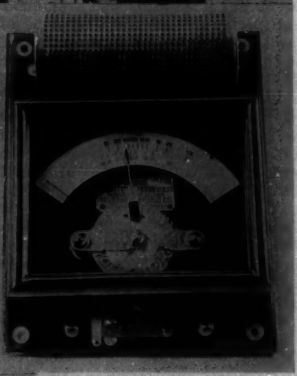


(Above) An a-c watthour meter built in 1892 utilizing a single disk for both driving and damping
(Duncan Electric Mfg. Co. photo)

(Left above) Original Gutmann watthour meter with a cylindrical armature, built in 1899
(Sangamo Elec. Co. photo)

(Right) Testing the insulation resistance of a trunk line telephone cable with a "megger" (1914). The test man is E. C. Barrett (A'27) now general plant supervisor of the Chesapeake and Potomac Telephone Company of Baltimore City
(James G. Biddle Co. photo)

(Above and right) Switchboard voltmeter and ammeter used on a-c systems about 1893
(Westinghouse photo)



(Below) Cardew hot wire voltmeter. These odd looking instruments, the first type used for alternating current, depended upon the expansion of 6 ft of resistance wire as a measure of current, and hence voltage; they had a large current consumption ($^1/_2$ amp), were slow in response, and inconvenient in form
(Westinghouse photo)

(Above) An early type of indicating instrument (1895)
(General Electric photo)

The Evolution of Electrical Engineering

By Dugald C. Jackson, President A.I.E.E. 1910–11

Many colorful personal reminiscences of the exhibit and personalities involved in the 1884 International Electrical Exhibition and related "Conference of Electricians" are given here by Professor Jackson. With this background as an indication of the state of electrical engineering education in 1884, the author outlines its rapid development, emphasizes the strength imparted to it through its early and continued close association with the fundamental sciences, and, looking to the future, sounds something of a challenge to the modern era and modern attitude.

THE YEAR 1884 was significant and auspicious for the American Institute of Electrical Engineers. In that year the Institute was founded. Also, in that year it demonstrated the coöperative spirit possessed in the field of electrical engineering, a spirit which the Institute has maintained untarnished. As a consequence of a circular letter issued in April 1884, followed by a preliminary organization meeting April 15 and an election of officers on May 13, all in New York City, the first formal meeting of the A.I.E.E. for presentation of papers was held at Philadelphia on October 7 and 8 as guest of the then already 60-year-old and distinguished Franklin Institute. The Franklin Institute provided rooms for headquarters and meetings of the A.I.E.E. which were in association with the International Electrical Exhibition then being held.

That exhibition opened September 2 and continued until October 11. It served as inspiration and stimulus for an electrical conference of some official weight as well as for the A.I.E.E. meeting of October 7 and 8. I then was an undergraduate in civil engineering at Pennsylvania State College and spent the summer vacation of 1884 as assistant to William Stanley at Pittsburgh with very little compensation, but with the understanding that I should be sent (with expenses paid) to the Electrical Exhibition in the autumn as an employee of the Stanley Exhibit. Stanley was the central figure in the then new electric light department of the Union Switch and Signal Company which department later became the Westinghouse Electric Company. George Westinghouse, then 38 years of age and already of international distinction through railroad air brake and other inventions, was the leading spirit in both these companies. He was awarded the Edison Medal by the A.I.E.E. in 1911 for his "connection with the development of the alternating current system of electric light and power." He was the third of the great series of Edison Medalists.

International Electrical Exhibition of 1884

The electrical exhibition and the "conference of electricians" brought together a group of men whom we now see as the fathers of electrical engineering. These men were mostly Americans who were from 5 to 20 years older than I was. They impressed my more youthful imagination with their finished accomplishments and maturity. A half dozen years disparity in age, when the observer is a youthful undergraduate in a fresh water college, magnifies like a convex lens as one looks objectively at maturity. My tastes were toward the lighting and power aspects of the infant electrical industries. Consequently, my attraction was toward such as Edison, Thomson, Weston, Brush, Sprague, Van Depoele, and Stanley. Readers may need an explanation of the absence of a number of other names. The causes are manifold. For example, my tastes did not lead me to explore exactingly the exhibits in telegraphy and telephony. Also, for example, Tesla at the age of 27 had only arrived in the United States; Lamme was a freshman in college; W. L. R. Emmett had resigned from the Navy, but had not yet entered engineering; Steinmetz, 19 years of age in 1884, did not come to America until 1889; and so on. I do not remember that E. A. Sperry had an exhibit at the exhibition. If he did, it was my misfortune not to meet him at that time.

The purposes of this paper do not admit of general reminiscences of that exhibition or its exhibitors and comments on the large number of exhibits must be omitted; but comments regarding certain of the leading men and their exhibits are of service here for showing the then state of electrical engineering education.

William Stanley (Edison Medalist in 1912) was 26 years old in 1884. He was co-inventor of incandescent lamps made of carbonized silk threads which had been soaked in a sugar solution and baked. He was an active experimenter in the construction of dynamos and one who was deeply imbued with Ayrton's view that a generator and a motor should have contrasting electromagnetic qualities, but his experiments did not seem to support the view, which gave us some food for thought. It was a year or more later that Mordey published his brief communication pointing out that the electromagnetic structure for the best direct-current motor is the same as that for the best direct-current generator, which perhaps should have been recognized earlier

from the already known reversibility of the machines. Stanley's distinguished career as an inventor in the alternating current field was started with the support of Mr. Westinghouse in the years immediately succeeding 1884.

I became acquainted with O. B. Shallenberger, perhaps through Frank J. Sprague. Shallenberger, who was 5 years my senior in age, had completed his studies at the United States Naval Academy and had made up his mind, following the example of Sprague, to leave the Navy and join the ranks of the electrical industries. We spent many hours together, when I was off duty, hanging over the railings surrounding the various exhibits and discussing our ignorance of their qualities. He introduced me to Lieutenant Bradley A. Fiske, then a Naval Lieutenant, writer of books on electricity and magnetism, teacher of electricity and magnetism at the Naval Academy, and in Philadelphia as a member of the "conference of electricians," but later a rear-admiral distinguished for the invention of numerous electrical and other devices of value in the Navy.

In return, I introduced Shallenberger to Stanley, who was seeking an assistant, as I was returning to college after the close of the Exhibition. Shallenberger fittingly became a leading factor in the technical work of the Westinghouse Electric Company until his death in 1898 cut off his career of research and invention.

Sprague (President of the A.I.E.E. in 1892–93, Edison Medalist in 1910) exhibited several of his inventions and frequently was a personal attendant at his exhibit where he extolled with emphasis and fascinating enthusiasm his self-regulating, constant-speed, direct-current motor, in which the constancy of speed as the load varied was secured by a differential series winding on the field magnet. It was in this year that the Sprague Electric Railway and Motor Company was established and Sprague at the age of 27 was fully launched on his great career of invention and promotion in the electric traction and associated fields. Electrical Engineering owes a deep debt to the American Navy for having relinquished Sprague from its service, so that he could carry on in our field.

Thomas A. Edison's personal exhibit, in charge of Wm. J. Hammer, commanded deep attention because of its manifestation of the origins and development of those many detailed devices relating to the distribution and control of electricity which contributed a large part to the success of Edison's pioneer constant voltage system for the distribution of electric power. Many other devices also were shown. Notable among these was the 3-terminal bulb which exhibited the fundamental effect (then dubbed "Edison effect") of our now much used 3-terminal vacuum tubes, but which Edison did not follow up, apparently because of his absorption in his other developments. His personal exhibit was not the only one disclosing the results of Edison's work, for several of the manufacturing companies established for promoting the use of his inventions in the electric lighting art exhibited a striking array of underground tubes, incandescent lamps, and electric machines. The Edison "Jumbo" dynamo of, according to our present ideas of rating, about 100 kilowatts capacity (direct connected to a "high speed" steam engine) was the generator of largest capacity in the exhibition. I several times caught myself hanging over the rail in front of the machine and speculating on why its field cores were made so long and thin, with several in parallel joining between the yoke and each pole piece. It was told that a large magnetic moment was needed for the field magnets and that this was an economical construction for securing that result. The reason sounded pat, but was not convincing when one compared the jumbo machine with the excellence of operation and compactness of design of the Weston dynamos nearby. I did not then know that Dr. John Hopkinson already had stated the desirability in electromagnetic machines of short magnetic circuits of large cross sections. However, the greatness of Edison's contributions to the development of electrical engineering was already established at even that early date.

Edward Weston (President of A.I.E.E. in 1888–89, A.I.E.E. Lamme Medalist in 1932) and the United States Electric Lighting Company had dynamos and lighting facilities on exhibit that were unrivalled in the combination of rational character of design and excellence of workmanship. This was before Dr. Weston set out on his productive career as designer, inventor, and manufacturer of refined portable electrical measuring instruments, followed by equally refined switchboard instruments; but his dynamos manifested the same clearness of structural lines that have always characterized the construction of the Weston instruments. The magnetic circuits of the dynamos were moderate in length and of large cross section, the armature resistances were low and the resistances of the shunt field windings were notably high. The qualities of these Weston dynamos of 1884 prepared me to accept unreservedly the statement made by Dr. Weston at a conference at the World's Fair at Chicago in 1893 that he used a definite empirical formula in designing the field magnets of his machines for some years before Gisbert Kapp made known his empirical formula for the magnetic circuit and Dr. John Hopkinson published his notable analysis of the magnetic circuit accompanied by the rational formula.

The exhibit of the Brush Electric Company left no very vivid impression on me. It undertook to portray the usefulness of electric motors and electric lighting in the home and factory as far as such usefulness then existed, in addition to arc lighting for exterior areas. But the exhibit seemed impersonal and lacking in verve, probably because it lacked the stimulating presence of an enthusiastic inventor, since Charles F. Brush (Edison Medalist in 1913) was seldom in attendance.

Of all the exhibits except that of Weston, the one maintained by the Thomson-Houston Company of which Prof. Elihu Thomson was the leading scientific figure and leading inventor, has left on me the liveliest memory. It was impressive because of its comprehensiveness in display of commercial apparatus and because of its collection of Professor

Thomson's models and experimental apparatus set up with the various devices arranged for demonstration. In the first or commercial aspect it did not rival the display of constructions arising from Edison's inventions, but in the second it enjoyed the frequent attendance of Professor Thomson (President of the A.I.E.E. in 1889–90, Edison Medalist in 1909) who was incomparable as a lecturer regarding his operative apparatus and as a demonstrator of his scientific experiments. I still retain a vivid picture of Thomson, then 31 years of age, standing in the midst of a demonstration of certain scientific experiments which he was carrying on. He always attracted an appreciative gallery on account of his enthusiasm. His was a scientifically trained mind that commanded great interest.

Of Van Depoele my relations at the exhibition in 1884 were perhaps more personal than with the others mentioned. We not infrequently sat together at luncheon in a little restaurant. He was more than twice my age, but his kindliness of attitude toward his junior and his resourceful spirit endeared him to me. I remember little regarding Van Depoele's exhibit. He was a man without deep learning in science, but his quickness of imagination and his facility in empirically adapting knowledge (gained in his long experience) to improving defective devices or overcoming faulty operation were incomparable. The latter qualities made him a great inventor in spite of absence of scientific learning.

The Meagreness of Electrical Science in 1884

Although the magnetic circuit designs (previously referred to) of Edison and his associates in 1884 were faulty even considering the then state of science, they were far more rational than those of inventors whose erroneous conceptions of the magnetic circuit led to many bizarre designs for dynamos that were shown at the exhibition, but which I will not here describe. Rational scientific efforts in designing electrical machines, systems of electrical distribution, electric lamps, and electrical instruments were still dependent on the individuals in 1884, and had not yet become broadly professional practices. The meagreness of knowledge of magnetic and electric phenomena in 1884 is illustrated further by the armature cores (made of cast iron discs) of the Stanley direct-current dynamos in the exhibit, and also by the paper at the Philadelphia meeting of the American Institute of Electrical Engineers by Prof. C. F. Brackett of Princeton University, entitled "Experimental Method of Testing a Dynamo Machine," and by a lecture on the magnetic circuit by Professor Henry A. Rowland of Johns Hopkins University. It was Professor Rowland's series of publications begun in 1873 when he was 25 years of age and an Instructor in Physics at Rensselaer Polytechnic Institute that gave the first experimental disclosure of the relations of magnetic permeability to magnetizing force in iron and other metals. The phenomenon of magnetic hysteresis and its effects were not recognized until 1885 when J. A. Ewing, now Sir James Ewing of Cambridge (England) but then of University College, Dundee, published the paper disclosing his notable experimental work.

A further illustration of the youthfulness of electrical science in those days may be drawn from the provisions adopted to prevent fire hazard from the electric circuits in the various exhibits and from the circuits used for the general lighting of the exhibition building. E. J. Houston (President of A.I.E.E. in 1893–95) was "electrician" of the exhibition and Carl Hering (President of A.I.E.E. in 1900–01) was "assistant electrician." Professor Houston was chairman of a "committee for the installation of electrical apparatus." The report of the committee on exhibitions of the Franklin Institute submitted after this exhibition was over says of the duties of the "electrician" and the "assistant electrician": "The circuits [i. e., within the exhibition building and annex] were tested daily for 'contacts' or 'grounds' by Professor Houston, or by his assistant Mr. Hering, and all causes of danger removed before the current was permitted in them." I made my first acquaintance with Hering as he daily made his rounds with a hand magneto with which he tested the various circuits of the exhibits and also the general circuits of the Exhibition for "grounds."

Development of Electrical Engineering Curricula

The foregoing reminiscences will bring to the reader's imagination the state of electrical engineering education in 1884 in a more lively manner than would likely be secured by a bare recitation of the then state of science in this educational field. The reminiscences also outline the background for a picture showing the vigor and velocity of growth of electrical engineering during the 50 years since 1884, which background may be used by any one who today looks about him to secure the impressions from which to paint in the foreground of the picture. Of the exhibitors named in the preceding pages, those now dead have left behind legacies of internationally used conveniences that their discoveries and inventions contribute to our modes of life. Sprague at 77 years of age, Thomson at 81, and Weston at 84 still remain to receive the continued plaudits fitting to their great achievements. Their lives measure the span of growth of the expansive and vigorous structure of electrical engineering as we now perceive it. That structure still exhibits a vitality and velocity of growth equalling that of its preceding years, and this must be part of one's vision when planning electrical engineering education.

The chronological sequence for the development of electrical engineering curricula in physics departments of American universities shows that formal education in electrical engineering was well under way by 1890. Obviously, professors of physics during the decade beginning with 1880 found their imaginations inflamed by the intriguing possibilities of electromagnetic machines applied to useful purposes. Consequently subjects relating to the theory and the applications of electricity and magnetism appeared among the emphasized subjects of instruction in physics departments of many univer-

sities. This was the kind of educational environment from which many who became distinguished electrical engineers emerged between 1880 and 1890. Such, for illustration, were: John W. Lieb (President of the A.I.E.E. in 1904–05, Edison Medalist in 1923), Stevens Institute of Technology, Class of 1880; E. W. Rice, Jr. (President of the A.I.E.E. in 1917–18, Edison Medalist in 1932) pupil of Professor Elihu Thomson at Central High School, Philadelphia, Class of 1880; Chas. L. Edgar, Rutgers College, 1882; Chas. F. Scott (President of the A.I.E.E. in 1902–03, Edison Medalist in 1929), Ohio State University 1885; C. C. Chesney (President of the A.I.E.E. in 1926–27, Edison Medalist in 1922), Pennsylvania State College, 1885; and so on.

The natural course of development led to the formulation of 4-year curricula in electrical engineering more or less correspondent to the curricula at that time extant in other branches of engineering, but more heavily charged with the temper of physics and directed by the physics professors. The first such course was proposed and organized in the autumn of 1882 by Prof. Charles R. Cross, Head of the Department of Physics in the Massachusetts Institute of Technology. A similar proposal was made and a course organized a few months later, and apparently quite independently of Professor Cross's proposal, by Prof. Wm. A. Anthony, Head of the Department of Physics at Cornell University. Graduates from each of these pioneer courses in electrical engineering secured bachelor's degrees in 1885. It obviously would be undesirable to make here a résumé of the origin and development of all the more than 150 formal electrical engineering courses now in being in the United States, or even of all of the more notable ones. Each of those to which I later refer is chosen for some historical or geographical reason. I beg that no alumnus may feel offended in case his Alma Mater is not referred to in my further list of those commented on.

A tidal wave in the formal establishment of electrical engineering curricula in the universities and colleges, mostly associated with departments of physics, flowed in 1887. It affected the country at large, as is witnessed by Pennsylvania State College, Case School of Applied Science, Purdue University, University of Minnesota, University of Kansas. During the succeeding 5 years many additional curricula associated with physics departments were established from the East to the West. Another turn came in 1891 when the University of Wisconsin proposed to establish an electrical engineering curriculum. At that time I was consulted on the question of whether it would be better to place the curriculum under the administration of the physics department or to establish a definite department of electrical engineering and make it coördinate with departments of civil engineering and mechanical engineering. At the same time I was invited to leave my employment with the Edison General Electric Company in active engineering planning, estimating and construction and to occupy the first professorship of electrical engineering in that University. On the ground that the content is engineering (i. e., applied science, or perhaps it is better to express it as science and its applications) rather than purely science, my advice was to establish the department of electrical engineering coördinate with the other departments of engineering. This view was adopted and I believe that to be the first department of electrical engineering to be initially so established. The view has proved to be valid and nearly all electrical engineering curricula in the colleges and universities of this country are now related to definite departments of electrical engineering.

That the view had begun to receive recognition

A Group of Past-Presidents in Attendance at the Chicago Convention, June 29, 1911

Those in the group (with periods of presidency indicated in parentheses) are as follows: back row, left to right: Gano Dunn (1911–12), Dugald C. Jackson (1910–11), Louis A. Ferguson (1908–09), Schuyler S. Wheeler (1905–06), John W. Lieb (1904–05), and Bion J. Arnold (1903–04); front row, left to right: Francis B. Crocker (1897–98), T. Commerford Martin (1887–88), Frank J. Sprague (1892–93), and Charles P. Steinmetz (1901–02). Of the 10 past-presidents in the group, 5 still are living and 3 have contributed articles to this anniversary issue

(Photo courtesy Past-President Sprague)

before 1891 is shown by the fact that the administration of the course in electrical engineering at Cornell University had been transferred from the physics department to Sibley College of Engineering before 1890, but it was several years later before such transfers became general. The oldest of the pioneer courses in electrical engineering was retained in the physics department at the Massachusetts Institute of Technology until 1902 when a department of electrical engineering was established and Louis Duncan (President of the A.I.E.E. in 1895–97) was appointed professor of electrical engineering and placed in charge of the department.

The number of men of influence in electrical engineering industry who are alumni of educational institutions in which they pursued undergraduate electrical engineering courses maintained by definite departments of electrical engineering aggregates many thousands; and their service to the nation through their contributions of means which provide convenience in life to populations numbered by tens of millions is beyond calculation. Manifestly, the electrical engineering departments, established in the engineering schools as coördinates with the departments dealing individually with the other and older major branches of engineering, have produced an influence, as departments, that is vastly greater than the effect produced solely on their individual pupils, large though the latter is. However, we owe a debt to the physicists. The remarkably large influence on American engineering industries that has been exerted by electrical engineering I believe arises partially from the early relations from which we have profited. Our modes of thought, our units of measurement, even our processes of education sprang from the science of physics (fortified by mathematics) and from physicists. The precise measurements and controlled experiments introduced into our field from the field of physics gave a tremendous impetus to rational and accurate engineering calculations and also left a scientific impress on electrical engineering teaching. As a consequence, our educational processes and our engineering practice possess a notably large portion of rational application of the underlying science. In this respect we are paralleled by the later developed branches of chemical engineering and aeronautical engineering. Civil engineering, mining engineering, and mechanical engineering, as the older major branches, arising (as they did) before the sciences were adequately expanded to provide a rational foundation for engineering practice, still maintain a large proportion of empiricism in their college curricula. I am of the opinion that the civil engineering and mechanical engineering fields would be benefited were the engineering schools to rigorously prune the curricula in those branches and then inject into them a more rigorous and scientific aspect.

A.I.E.E and Electrical Engineering Education

Organized, as it was, at a date when the science underlying electrical engineering was expanding rapidly, one might assume that the American Institute of Electrical Engineers would lend its ear and its voice to the problems of electrical engineering education. Its first group of officers, among 6 vice-presidents, included one whose principal occupation was in education and also included 2 such among 12 managers. One vice-president (Alexander Graham Bell) and one manager (Elisha Gray) in this group also had previously been teachers, but they had been drawn away from that occupation by the fascinations of full time spent in discovery and invention. A similar proportion of men with their principal occupation in education was maintained among the elected officers for some years. Likewise the sixth president was drawn from education, and this example has been followed many times in the succeeding years. Nevertheless, it was 8 years after the first meeting (namely, in 1892) that the Institute listened to a paper definitely directed to electrical engineering education. Indeed, there were then 2 papers presented at the same session—one prepared by R. B. Owens, professor of electrical engineering at the University of Nebraska, and the other by myself, then located at the University of Wisconsin. Ralph W. Pope, then secretary of the Institute, was dubious about the interest that could be aroused for such papers, but their presentation was followed by an animated and well couched discussion which would occupy as much space as the papers themselves if printed in the same type.

The ice was broken and the problems of formal education for electrical engineers have since come into our proceedings again and again. Ten years later (in 1902) President Steinmetz built the theme of his presidential address at the Great Barrington meeting largely on electrical engineering education; and four papers concerning the subject were presented by competent men at the same meeting. A copious discussion was aroused.

The Character and Testing of Electrical Engineering Education

The following year (1903) the Institute held a joint meeting with the Society for the Promotion of Engineering Education, with the result that 7 papers came into the Transactions along with considerable discussion. At this meeting I again appeared with a paper on electrical engineering education expressing opinions gained by 12 years of experience at the University of Wisconsin where I was having a grand time linking mathematical physics and experimental investigation of a rigorous character with electrical engineering education, recognizing that only by personal experience in grappling with the unknown can students truly gain knowledge and learn its significance in self-reliant use. In that paper I expressed a wish to be delivered from judgment upon the success of my efforts unless such judgment was guided by the attainments reached by my students in a decade to a quarter of a century succeeding graduation from their electrical engineering college course. C. F. Scott (then president of the Institute) expressed some doubt regarding the propriety of such delay in reaching final conclusions about the individual men. He has since

that time become a professor of consequence and a Lamme Medalist of the Society for the Promotion of Engineering Education. I infer that as a consequence of his later experience he now does not disagree with my view, while both of us duly recognize that delay in reaching final conclusions regarding educational efforts should not connote absence of constant scrutiny and comparison of processes that are associated with efforts at pedagogical improvement year by year. Testing the product of engineering education immediately (as one would a dynamo before it leaves the shop door) is serviceable to guide improvements, but is not significant for showing final results. This is because the results in each individual of proper professional education grow richer and more desirable by aging, whereas the results of mediocre types of such education are less influenced by the aging process.

Fifteen years of observation and experience at the University of Wisconsin convinced me that making research an integral part of electrical engineering education is of primary value. I therefore took this tenet as a primary one upon going to the electrical engineering department at M.I.T. in 1907, and it has been there maintained with increased emphasis to the present time. At various times heretofore I have expressed the argument regarding this and need not repeat it here.* Continued observation and experience unqualifiedly confirm the correctness of the method.

Importance of A.I.E.E. Committee on Education

For a further period of years after 1903, papers on electrical engineering education frequently entered the proceedings of the A.I.E.E., and the activity was all serviceable and suggestive. Of recent years, however, the activity apparently has lulled. Some excellent papers have been produced, but they have elicited little comment compared with their value. Why is this? I will endeavor to give an answer to this query; but first I will state unconditionally that the American Institute of Electrical Engineers has excellently proved its continuing official interest in electrical engineering education in various ways, the most notable of which are its coöperation with the board of investigation and coördination set up by the Society for the Promotion of Engineering Education to study both the pedagogical and the human needs of engineering education, and its support of the program proposed by the Engineers' Council for Professional Development. It is to be earnestly hoped that this attitude will be maintained, since the continued high standing of electrical engineering depends partially on this coöperation in education. The student conventions and prizes for student papers also must be recognized as an important element in educational coöperation by the Institute in addition to the maintenance of Student Branches, and likewise must be so recognized the prize presentation of papers by younger members now being fostered in several Section areas.

Now to reply to the query of the preceding paragraph: The answer, it seems to me, is to the effect that a large proportion of our members forget that the Institute (including themselves individually) has a responsibility for maintaining the high level of intelligence and character in the electrical engineering field, and they also forget that mutual consideration and analysis of the problems of electrical engineering education are potent means toward securing the desired end. Therefore they are not impelled into discussions of papers on education. We have an admirable attitude in the concrete matter of encouragement for students, but take less interest in the pedagogical structure of electrical engineering education.

The board of investigation and coördination appointed by the Society for the Promotion of Engineering Education carried out its duties in the spirit of rigorous inquiry, as far as the yet rather undeveloped science of pedagogy admits of rigor, and its reports give data and carefully drawn opinions and (where the data are competent to support conclusions) statements of conclusions. It is this character which has given their wide influence to the reports of this board. Likewise, the expectation that the Engineers' Council for Professional Development will follow the scientist's route of investigating conditions before arriving at conclusions, and expressing the latter only where conclusions are warranted by the data, is a feature that supports the confidence which is expressed in that representative organization.

A corresponding attitude assumed by the A.I.E.E. committee on education might reëstablish the former interest of the individual Institute members in its subject. This is a technical committee of the A.I.E.E. and, in addition to its duty of arranging for the presentation and discussion of papers before the Institute, it is commanded by the by-laws to present an annual report at the summer convention which shall include "a brief résumé of the progress of the art in the particular field" within the scope of the committee, in order that these reports (among others) "may become recognized as authoritative sources of information on the history of electrical engineering development." There is a real opportunity here for this committee, which would raise it from the conventional level of solely a seeker after papers for the Transactions to the level of a stimulator and producer of acclaimed papers of creative type. Effectiveness in the suggested field would call for some degree of coöperation with certain committees of the Engineering Foundation, the Engineers' Council for Professional Development, the Society for the Promotion of Engineering Education, and perhaps of other organizations, in order that the annual reports on the progress of the art of electrical engineering education should be of significant service.

My suggestion may involve work which no committee will undertake in the field, but the "educational series" now in course of publication in Electrical Engineering under the sponsorship of the committee provides a grand background for the production of influential annual reports. The conventional status heretofore sometimes voluntarily

* For example, see The Function of Research in Engineering Education, an address before the Society for the Promotion of Engineering Education, June 1931, published in *Science*, Aug. 21, 1931, Vol. 74, pp. 183–187, and in *Journal of Engineering Education*, Jan. 1932, Vol. XXII, pp. 348–355.

assumed by the committee prevents it at such times from giving effective service to the Institute in the field of electrical engineering education. The teachers themselves are not faultless. Much that is put forward as appropriate for educational processes analyzes into poorly marshalled personal opinions with insufficient backing of exact observation or analyzed experience. The reports suggested for our committee on education would produce a stimulus for the teachers to do closer thinking regarding education in the broad, and regarding the content that should make up an electrical engineering curriculum as well as regarding the processes of teaching the curriculum subjects. One of our difficulties in the engineering schools lies in the fact that it is commonly forgotten that the teachers, as a rule, must not be cloistered men, and that men needed for leadership in engineering education are ones who are practiced and, if possible, great in two professions—the profession of engineering and the profession of teaching. We do not always make suitable provisions in the way of ultimate available salary and freedom in the choice of work to secure such men, on whom we might rely for clear thinking at all times.

A Responsibility of the Engineering Schools

Within the engineering schools, we have the problem of securing well founded and thoughtful criticisms of our practices associated with suggestions for improvement. Many of the individual suggestions that we receive are founded specifically on some one's memory of his own undergraduate days, and exhibit no conception of changes of curriculum and procedure that have occurred in the intervening interval. Efforts at improvement founded on such proposals are not scientific and usually are untenable. We have many articles of reform to be considered, but none should be irrevocably acted upon until conclusions can be reached as a consequence of sound reasoning on the data of controlled experiment, or of cautiously formulated deductive reasoning when data cannot be secured.

For example, the question of length of curriculum required to produce the best aggregate results is again to the fore. The proponents of a 5-year or 6-year formal curriculum argue staunchly for their own favorite idea, using *a priori* reasoning supported on often repeated grounds of an inconclusive nature. As far as I know, they have not gathered data capable of indicating whether or not a *larger proportion* of graduates who have pursued the longer formal curricula have come to distinction than of graduates who have pursued curricula of the usual 4 years' length, which data (if practicable to accumulate) might have some conclusive weight when fairly interpreted. Nor have they gathered corresponding data capable of indicating the proportional achievements of graduates who have followed the longer formal curricula compared with graduates who have pursued usual 4-year curricula followed by one or more years of rigorous graduate professional study in each individual's chosen branch of engineering. My own observation leads me to a tentative conclusion that the longer formal curricula have not produced a larger proportion of eminent men or a larger proportion of happy men, but that such men probably arise in larger proportion from rigorous graduate study of highly advanced professional type which is of the students own choosing. when the longer period of study is embraced. If this inference is correct, then the formal longer college curriculum ought not to be made the general basis of electrical engineering education, but nevertheless it might become recognized as a desirable variant to maintain in a few instances. Those engineering schools which espouse the longer formal curriculum therefore may be encouraged to continue in their chosen path for the present while they gather data that may be marshalled in form to show the comparative results. In the meantime those of us who have to do by preference with 4-year undergraduate curricula where proper freedom is permitted in student selection (and in some instances also direct rigorous professional graduate study) will continue to welcome hospitably into the proper place in our undergraduate work those students who have chosen from their own incentive to secure previously a degree in arts, provided mathematical and physical science provides the main feature of the bachelor of arts course. A voluntary choice in the ordering of his own education is usually an indication of good intellectual fiber in a student, but a slavish following after fashion or habit in education usually indicates the opposite.

Another internal problem which now agitates the engineering schools relates to the proper integration of political economy into engineering education without sacrifice of any of the excellent qualities that have been secured by the integration of science into the engineering education. There is much argument in the circles of engineering education, but little outcome as yet that is definite. There is not opportunity in this article to discuss this feature adequately. I have briefly expressed my opinion in a recent vice-presidential address for the American Association for the Advancement of Science,* and elsewhere have treated the matter more fully. The matter is of great importance to electrical engineering education, and the determination of its correct treatment is a problem lying before us.

These 2 examples are sufficient to indicate that the great problems in electrical engineering education are not yet all solved. There are many important unsolved ones besides the 2 mentioned as examples. To solve some of them with an ultimate solution, we must know more fully from whence spring the peculiar advantages of engineering education, and this obviously will require further intensive investigation. Thus the pedagogical aspects, the science aspects, and the engineering-economics aspects of electrical engineering education possess jointly the absorbing fascination of a great field for exploration and experiment, as well as an important occupation in day-to-day practice. Solving the problems of electrical engineering education is a responsibility of the engineering schools but the American Institute of Electrical Engineers has its own responsibility for coöperating in manners heretofore stated.

* For example, see The Origins of Engineering, *Science*, Dec. 29, 1933, Vol. 78, pp. 589–596, cf. particularly p. 595.

The Engineer a Creator of Leisure

By William McClellan, President A.I.E.E. 1921–22

The Institute, founded at the beginning of a "new deal," now celebrates its 50th anniversary in the midst of another new deal. What of the engineer's part in today's new deal? He must go ahead as enthusiastically as ever with the creation of labor-saving devices and thus with the creation of leisure—not loafing, but a leisure to be filled by satisfying activities.

THIS YEAR we are celebrating the fiftieth anniversary of the American Institute of Electrical Engineers. This 50 years concludes the real development period of what we now call electrical engineering. As I look back over this period it seems clear, although we didn't know it then, that we were at the beginning of a new deal. Faraday, our patron saint, gave us electromagnetic induction in the '30's; but his source of electrical energy, and that of every one else for years after, was the primary battery. That was all that Morse had for the telegraph. Magneto-electric sources were used by the telephone and, on a larger scale, for lighthouse lamps and some other purposes.

Faraday had given us the powerful electromagnet, with the easy manipulation of field control, but it was many years before the commercial development of the so-called dynamo-electric machine started. At that time there were no electrical engineers. Extraordinary men originating in the shop, like Swinburne, met great scientists like Sir William Thomson, as we knew him then, to break new roads on which civilization would travel. The Centennial of 1876 at Philadelphia had little that was electric, and yet only 8 years later there were enough men in electrical engineering to bring the Institute into being. I shall attempt no story of history here, but refer you to the PROCEEDINGS of the Institute, and kindred publications, for it all.

What a splendid flowering there was. The rapidity of the development was dazzling. Designs and inventions jostled each other, and the life of any was marvelously short. The electric lamp and motor, with almost myriad forms of auxiliary and utilization devices, came on in a bewildering rush. Machines grew larger and larger. Apparatus requiring time for construction was obsolete often before it could be installed. Electrical engineers themselves marched on to greater and greater successes, and made it possible for brother engineers in other fields to go on to similar great achievements. Yes, it was a new deal, and everybody, from the lowest to the highest, reaped enormous benefits of one kind or another.

Those electrical engineers transformed home and street lighting. They replaced the old open-flame flickering gas lamps, 500 feet apart on the streets, with brilliant light units, and were not to be denied even when our gas-lighting friends struck back with the Welsbach mantel. They gave industry the electric motor for a million uses. Elevator service was transformed, and the horse car went into limbo. Underground and all forms of rapid transit railways were made possible. Power transmission and distribution systems were developed so that convenient power was at one's elbow, wherever even the smallest group of people gathered. They improved and expanded and multiplied telephone service until men could reach for a telephone as easily as they pick up a pencil, and talk to each other far apart as easily as face to face. Then came radio in its great variety. Maxwell said there were electromagnetic waves, Hertz showed them to us physically, and the electrical engineer made them serve us. So much in the space available, for the activities of the engineer in the old deal; but what about the economic and social results?

A year or so ago, in the course of an impromptu public discussion, I made the remark that "engineers are magnificent creators of unemployment." Of course, it was literally true, but that didn't prevent a host from inveighing against it. Naturally unemployment did not mean idling. We all had been using it for some time to mean "no job at customary gainful work." So later on I remade my declaration into "engineers are magnificent creators of leisure," and hastened to add that leisure did not mean loafing, but an opportunity to do things one wanted to do for pleasure or interest and not just to earn a living. Anyway, true or not, it seemed to some to put the engineer in a bad light, notwithstanding that invention and design of labor-saving equipment really had created, at least in the past, more jobs than they had abolished—millions of electrical workers for the thousands of gas-lighting men and bell-hangers, millions of jobs for factory workers and distributors of a thousand new devices, millions of telephone mechanics and operators of all sorts. The same kind of results obtained in trolley cars, rapid transit systems, and radio; and in other than purely electrical fields the same kind of activity is found. Statistics are not needed to prove the enormous difference in numbers between the livery stable men and cab and horse-car drivers, and the mechanics, garage workers, chauffeurs, and filling station men associated with the automobile. Statistics are not needed, but they prove that machines such as cranes, ditch diggers, road machines, turret lathes, and the like, which apparently threw men

out of work, really put more men to work by making possible a greater volume of construction.

No one took up the point that this increased employment was unimportant to many individuals if they suffered in a variety of ways while waiting for the new jobs to materialize and if many of the same individuals could not then qualify for the new jobs. Of course, this is inevitable. In the onrush of the crowd some are bound to be trampled on—some crushed to death. Sad as it may be, that is the price of progress; and with it all we did create leisure—we passed to the 8-hour day. Only a word more for the other results flowing to our social well-being. These may be epitomized in a few words—leisure, safety, comfort, convenience, and better living.

Has the Engineer Gone Too Far?

Came the depression with all its staggering losses, unemployment and human suffering for all types of workers. Soon was heard the cry that this engineer, this creator of leisure, had gone too far. Many of his machines ought to be scrapped. It would be better if ditches were to be dug with the pick and shovel. Millions of homes again were to be the scene of homespun activities. It would be better if everybody more or less would raise his own spinach and potatoes in his own garden. In fact, a relatively large group was ready to assert that machines, the product of engineering activities, were wrecking civilization.

In the midst of this more or less maudlin discussion, at times bordering on asininity, events conspired to show that the engineer had some kind of a devil in him that just made him persist in his fiendish, civilization-wrecking activities. The very unemployment he had helped to bring about finally got him. Thousands of him lost their jobs. Then what did he do? Well, not being able to do construction work, with the help of his machines and with a compelling impulse not to loaf, he had to turn to working out schemes for a thousand labor-saving devices which he had not had time to develop in the midst of prosperity. A lifetime of engineering activity had made me acquainted with many engineers, young and old, who had lost their jobs. Almost invariably, when I asked these men or their friends: "What is so and so doing?" the answer was: "Oh, he's developing 'this and that.'" A little discussion showed that "this and that" was a labor-saving device or process.

The "New Deal"

And so we come to the "new deal." The outstanding features of it are employment for all and a more abundant life for all. Hours are to be shorter so as to give everybody work, and individual pay is to be higher so as to distribute better the products of industry and to create greater purchasing power. Offhand this seems all right, but soon questions crowd up for answer. The idea seems to be that the same production will be accomplished by more people and at a greater cost. Won't prices for everything go up and therefore a man's "goods wages," that is, his real wages, be less? Can the scale of living be maintained as "goods wages" get nearer and nearer to subsistence wages? Then how about all the men in the luxury industries, and what will be left over in the aggregate for the capital goods industries which depend largely upon investment? It seems almost evident that this plan may reduce unemployment, at least temporarily, but will not bring about recovery. It will create leisure, but will the man's "goods wages" be sufficient to provide not only a desired scale of subsistence, but also the wherewithal and the zest to enjoy the leisure, that is, live the more abundant life? And if we do not insure at least a reasonable return on the real investment involved in the production, what about the millions of people who are not producers but depend upon dividends and bond interest for a living? Finally, do not forget that taxes must be earned by these workers to provide for the expenses of government of all sorts, with its seemingly necessary millions of employees. Indeed, something more is needed than merely shortening hours and raising wages.

In my opinion, if we are to have prosperity, we must increase production to the point where there is sufficient of every kind of goods to satisfy the needs of every one. In addition, we must distribute these goods in accordance with the needs of every one. This is more easily said than done, but it is absolutely essential for permanent prosperity, and therefore for recovery. I believe our present total production is inadequate, but every one knows that even our present production is very much unbalanced among different goods. There is too little of many goods and too much of others.

When I speak of distribution, I do not speak of the mechanical means of distribution. Our means of transport may be sadly imperfect here and there, but that only means inefficiency, not a stoppage or prevention of trade. For years we have known that capital flows to where it will be paid for, but we are just learning that other goods will obey the same law. Proper distribution of goods means a proper distribution of purchasing power—proper distribution of purchasing power among wage earners of all kinds, independent workers such as farmers, white collar men, entrepreneurs, and capitalists. We have set ourselves a Herculean task. We tell ourselves in the same breath that recovery cannot come on in a hurry on wings of words, but through a time consuming and arduous reorganization of our ideas and activities.

How shall the engineer behave in this new deal? Like every other man, and especially every other professional man, he has varied responsibilities. As an engineer he has his specific responsibilities, but he is also a citizen and a member of the social community.

The Engineer's Part in the "New Deal"

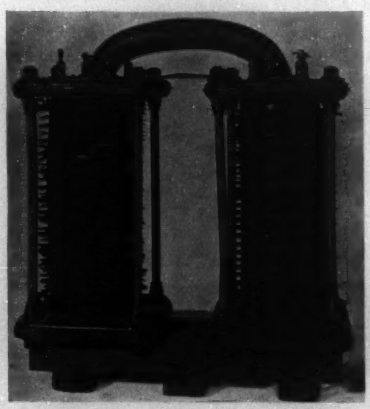
As an engineer, his part is to increase production and the mechanics of distribution. He must go ahead as enthusiastically as ever with the creation

of new machines for this purpose. A labor-saving device is a boon to humanity. It enables the worker to produce his maximum of both goods and leisure. It enables us all to enjoy a more abundant life. It gives us time to express our souls in whatever way may be most satisfying to us. In all these activities the engineer is as necessary to prosperity as the moralist who teaches us the objects of living, the economist who adjusts the various factors in living, and the medical man who keeps our bodies and minds capable of living.

The engineer, however, has to remember that he is also a citizen—a social being. He then must maintain an intelligent sympathy with those who have other responsibilities than his in balancing life. He must give more thought to the far-reaching results of his specific activities. He offers the world the products of his brain and work and he must have an understanding of the specific tasks of other professional men and be responsive when they offer their products. He must understand that all men are created free and equal only in a very narrow sense. He will participate in the necessarily great process of education through which the human family continually must progress before the more abundant life can be attained. He will keep in mind what a multitude of erroneous ideas must be eradicated. He will begin to think that "dying in the saddle" is perhaps not the best ideal and that instead of men dreading the time when they would have to retire or be retired, they would be educated to look upon the "working period" of their lives as a limited period, the end of which they were looking forward to as a time when they could begin to enjoy a leisure they had earned—a leisure to be filled by satisfying activity of their own choosing.

This, to my mind, is the only "new deal" worth while, and the engineer has a glorious part to play in it.

Some of the Early Transformers From Which Modern Power Systems Grew

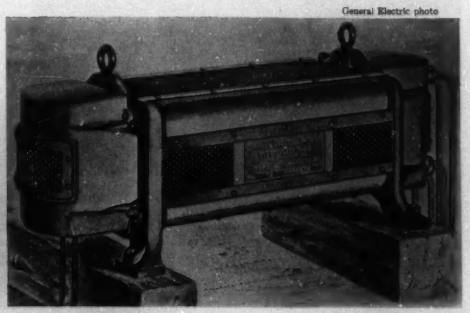


Westinghouse photos

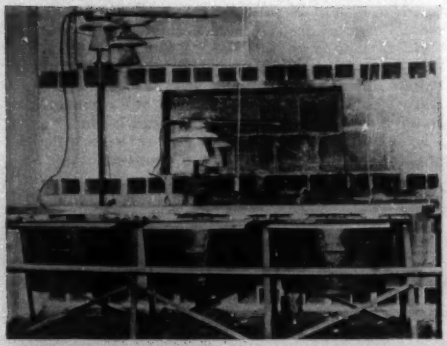
Westinghouse photo

The Gaulard-Gibbs transformer (left) and patent rights were brought to America in 1885 by George Westinghouse who set William Stanley to work at Great Barrington, Mass., to develop with his own hands the first American transformer (above). The first oil filled transformers (below, left) were developed in 1891 for the historic 10-kv line at Pomona, Calif., where they were operated 10 in series at each end of the line. One of Stanley's own 25-kva commerical models of about 1891 is shown below

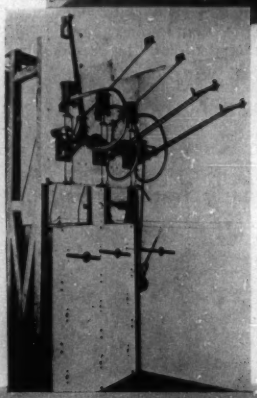
General Electric photo



Some High Lights in the Evolution of Switchgear



(Above) A 60-kv oil switch with fiber washtubs used for tanks; this construction is typical of many of the earliest oil switch installations
(Pacific Gas and Elec. Co. photo)

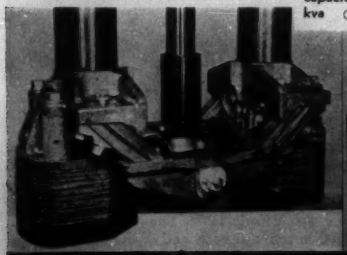


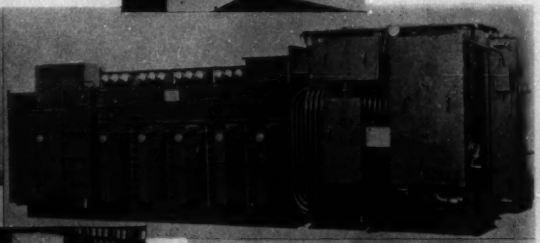
(Below left) Contacts of a modern 15-kv oil circuit breaker equipped with deionizing grids and having a rupturing capacity of 1,500,000 kva (Westinghouse photo)

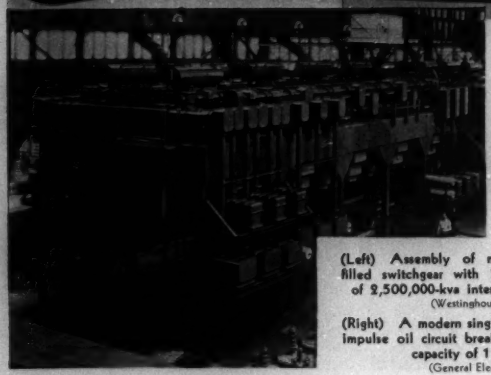
(Above) The switch that put Edison's Pearl Street station, New York City, in regular commercial operation at 3 p.m. on September 4, 1882
(Consolidated Gas Co. photo)

(Left) Combined disconnecting switch and expulsion fuse used before the appearance of the oil circuit breaker in 1900
(General Electric photo)

(Below) A modern combination unit for primary power distribution net works, consisting of totally enclosed 1,500-kva transformer and switchgear
(General Electric photo)







(Left) Assembly of modern metal-clad oil-filled switchgear with 34 vertical-lift breakers of 2,500,000-kva interrupting capacity each
(Westinghouse photo)

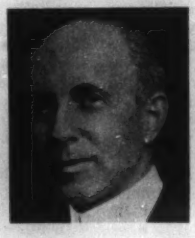
(Right) A modern single-pole unit of a 138-kv impulse oil circuit breaker with an interrupting capacity of 1,500,000 kva
(General Electric photo)

Research and Engineering

By Frank B. Jewett, President A.I.E.E. 1922–23

Crediting the extent and magnitude of the technical advancement of the past half-century to engineering as the motivating force in the application of the scientific knowledge developed through the powerful facilities of the organized and coordinated research that has been developed during the latter part of the half-century just closing, Doctor Jewett believes that from the present point of view there is no reason to expect results any less striking during the next 50 years.

THE PERIOD of 50 years which has elapsed since the organization of the American Institute of Electrical Engineers as a national society in which are associated men interested in the technical phases of electrical engineering, has been a very remarkable half-century of technical advancement. Into this half-century has been crowded a greater amount of applied science, with a corresponding greater amount of collateral social change, than can be credited to many times the same interval in all preceding history.



More striking, even, than the concrete and tangible evidence of science applied to the everyday affairs of life in this half-century, is the fact that for the first time in human existence these advances on a broad front have been grounded in research employing effectively the powerful tool of the scientific method of attack in an organized undertaking of material and social advancement.

When one surveys with a critical and discriminating eye the vast changes that have taken place since the time of the Centennial Exposition it is apparent that the application of science has been the most potent factor in practically every field. The few years which intervened between the Centennial Exposition and the time in 1884 when the American Institute of Electrical Engineers was organized was a period of gestation in which the structure of the succeeding 50 years was being formed. Since there is no sharp line of demarcation in an evolutionary process such as that in which we have been involved, the year 1884 is as good a fiducial mark as any we can select. During the 50 years since that date we have witnessed not only enormous progress in the engineering arts in existence at that time, but, what is more astounding still, we have seen a whole galaxy of new arts come into being and take their places as major factors in our social structure. Many of the things that today bulk large in our daily lives and in our political and social problems were not even dreamed of at the time our Institute was organized.

Coincident with this startling development of old and new engineering arts, and essentially blood brothers of those arts, are new materials and new processes quite beyond the capacity of man to enumerate. In materials alone the new things that man, in his understanding of and control over the forces of science, has produced in the past 50 years compare very favorably with all that man and nature had accomplished previously.

Of the social and political consequences of these revolutionary changes in the physical instruments that we employ in our daily vocations and avocations, volumes have been and can be written. A brief summary like the present is no proper place for even an enumeration of such things. They are matters that will continue to concern society long after the physical developments that gave rise to them have ceased to be novel and come to be as commonplace as the most ancient of man's undertakings.

For our present purpose it will be sufficient simply to look back over the material achievements of the past half-century, to confine ourselves to the achievements in engineering, to select from the wide variety of those achievements a few typical examples, and to see whether a study of them gives evidence of any common motivating force. In our own particular sector, electrical communication, electric illumination, electric power generation, transmission and utilization, and the whole gamut of minor usages of electricity, were scarcely more than embryonic things in 1884. Essentially all that we now have, except some great discoveries like those of Faraday, Henry, Kelvin, and their contemporaries, is the result of man's activity in the past 5 decades.

Engineering the Common Factor

When we turn to other fields of applied science we find that in 1884 there was no internal combustion engine worthy to be called a tool of marked utility, and hence no automotive industry and no airplanes. There was no steam turbine and steam, though already an enormous source of mechanical power, still was generated and employed inefficiently in relatively small units by machines that were essentially kin to the things evolved by Watt. The chemical industry, though very ancient in human history, was in 1884 still an industry dealing with simple processes, largely inorganic in nature and, as compared with the things of today, with a relatively limited list of material. There was then no photographic industry that could be measured by any

such yardstick as we now employ, and the ceramic and paper industries, vast though they had become, were still not very far removed from their progenitors of an ancient time. Agriculture, the most important of all man's undertakings, was, except for the advent of a few labor saving machines, still an art governed solely by the transmitted traditions of preceding generations, devoid of real understanding of soil chemistry or mechanics, of the possibilities of producing new species at will, of disease and insect control, and quite unaware of the vast extension of markets for perishable products obtainable through refrigeration. The number of examples of which the foregoing are but samples could be extended almost without limit.

That such astounding changes in so short a period as 50 years could have come about in so many diverse fields can hardly be attributed to chance. Nor is it easy to assume that the things that have happened could result merely from a general intellectual awakening in which the several parts were unconnected. The very magnitude and diversity of the results obtained in fields widely separated and essentially unrelated bespeak the presence of something common to them all. When we come to trace back in them the current of their development we find that in every case it leads us to a point on the periphery of the same spring. That spring is the scientific method and scientific technique applied through coördinated and organized research, modified in each case merely to fit the peculiar conditions of the particular industry involved.

Viewed in a broad rather than in a narrow sense, the application of science in the various examples just noted and in all others of a similar kind, is engineering. That it may not and frequently does not have to do with structures or the operation of physical things involving power in the commonly accepted sense does not destroy the validity of the designation. This being so, the results of an analysis of some of the examples may, I think, safely be extrapolated to all.

No better illustration of the power of the scientific method and the effectiveness of organized research in the solution of engineering problems is to be found than in the field of electrical engineering. Nor is this surprising when we remember that everything of importance concerned with applied electricity had its origin in a scientific laboratory. The one possible exception to this statement might be the application of terrestrial magnetism as an aid to navigation and surveying. Here probably the utility of the earth's magnetic field in its effect on a free moving lodestone was doubtless an accidental discovery. Even this exception, however, is of relatively minor importance.

When we come to a consideration of what is commonly thought of as the field of electrical engineering we find first a few great fundamental discoveries resulting from scientific research work on which have been pyramided industrial applications developed through enlarged application of the same methods and techniques which gave rise to the original discoveries. In the earlier years of the past half-century these developments were carried on exclusively by technically trained individuals or small groups of such individuals associated together to develop some particular field of prospective utility. As time progressed and it became evident that industries of considerable size based on the utilization of electric energy could be developed, these groups tended to coalesce into larger groups better equipped with trained personnel and better provided with experimental facilities. Coincident with this evolution was an evolution in the universities and technical schools of the processes by which men were trained in the fundamentals and techniques of the scientific method.

Coördinated Research in Electrical Industries

By about the beginning of the present century matters had progressed so far in the field of electrical development that the beginnings of the great industrial research laboratories, as we now know them, commenced to emerge. This process has continued uninterruptedly until at the present time the foundation stones of every great subdivision of the electrical industry are those of a well equipped research laboratory. From the rather fortuitous beginnings at the beginning of the century, these laboratories gradually have assumed the proportions of very considerable industrial machines. They are fully equipped with all the necessary scientific apparatus that ingenuity can devise or money can buy, staffed with specially trained men of high intellectual capacity and organized systematically to attack any problem that may arise as a result either of past experience or from the imaginative consideration of the new knowledge continually poured out from the research laboratories of fundamental science.

In our present day electrical industrial research laboratories practically nothing of importance happens as a result of pure chance. Likewise, substantially nothing of great value happens merely through the operation of the so-called inventive faculty—that comet of brilliance which by intuition bursts out of hitherto dark places. In these research laboratories every problem that seems worthy of consideration, whether it arises from the experience of past practice or from the promise of future values in new knowledge, is carefully analyzed and its several parts put under attack by specialists. It is from their joint, supervised, and directed efforts that we derive the proved new material from which the design engineers build their new structures.

From the great research laboratories like those of the General Electric Company, Westinghouse Electric & Manufacturing Company, and Bell Telephone Laboratories, have come during the past 2 or 3 decades a continuous stream of far reaching improvements in the existing electrical arts, and the radically new things that have brought about the remarkable expansion in the applications of electricity to communication and to generation, distribution, and utilization of electric power. Nor do these laboratories confine themselves simply to research and development work directly in the field of applied electricity. Every collateral field that involves materials or methods involved in the use of electricity has come under attack of the trained scientific

staffs which comprise them. If we were to subtract from what we now have in the field of electrical engineering, the knowledge acquired in the research laboratories during the past 15 or 20 years, our usage of electricity would be incredibly diminished, the whole structure of industry changed, employment diminished, and the social and economic structure materially altered.

What is true as regards the contributions of scientific research in the field of applied electricity is similarly true with regard to many other industries based on science in which progress has been accomplished through application of the scientific research method.

While the history of electrical engineering during the past 50 years presents the picture of a vast modern industry that has evolved almost wholly out of the work of the research laboratory, and is a field in which future progress is entirely dependent upon a continuation of this method of attack, a similar picture is presented in practically all the other great fields of human activity involved with science. That the picture presented in the field of electrical engineering during the past 50 years is a bit more striking than many others is due partly to the fact that its entire life is substantially within that period, partly to the fact that its very existence is rooted in the results of scientific research, and partly to the magnitude to which it has attained and to the multitude of its ramifications.

Scientific Research in Other Fields

If we turn now to some of the other fields in which scientific research has played the major rôle, we find a similar picture of evolution and results, but in different settings. Take, for example, the whole automotive industry, which has been made possible by the development and perfection of the internal combustion engine. Here again substantially all that we now have is the result of scientific research work done well within the period of 50 years and all based on the results of scientific research, some few fundamental principles of which, as in the case of electricity, go back before 1884. Here, too, we see the same evolution of small research groups into larger units and finally into comprehensive research organizations staffed by specially trained men and operating as organized units to solve highly technical problems, to produce new useful information, and to find useful fields of application for the new knowledge that comes out of fundamental research institutions. Collateral with and closely allied to the research work on the automotive machine itself is the research work that has been involved in the development of liquid fuels, which are the life blood of the automotive machines. Were it not for the joint results of research activity in the automotive field and in the field of fuels, we could have no airplane industry. Without an ability to produce large power with small weight from reliable machines, flying in heavier-than-air machines would still be as much of a dream as it was in the time of Darius Green.

In passing it is interesting to note that this whole field of automotive engineering is a vivid illustration of the fact that progress through research in the field of electrical engineering is inextricably tied up with progress through research in many other fields. If we were to subtract from what we now have in the field of automotive engineering the results of research work in the field of applied electricity, the whole automotive industry would collapse. The farther we go along the road marked out by scientific research the more intimate and important do these cross connections become.

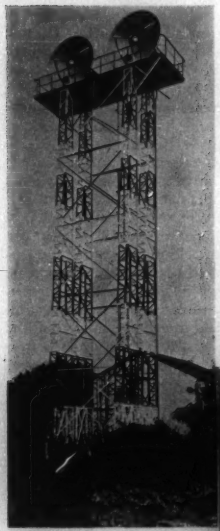
Chemistry and Agriculture

In the field of the chemical industries the story of the past 50 years is substantially similar to that of the electrical and automotive industries. Though far more ancient than either of these industries and with an origin lost in the mists of antiquity, the great advances in the chemical industries have come during the past 50 years and have been the direct result of organized scientific research applied to materials and to the processes by which materials are created. Not only have the materials and processes of inorganic chemistry been amplified enormously, but substantially the whole field of organic chemistry has been created. When we consider the very considerable number of the so-called elements and the incredible number of possible permutations and combinations of them, it seems likely that in the years ahead continuation and amplification of the scientific method in the field of chemistry is more likely than not to dwarf into insignificance the surprising results of our achievements during the past half-century.

Except as regards the application of mechanical devices for the purpose of saving labor, we do not commonly visualize very clearly the effect of scientific research during the past 50 years on that most ancient of man's undertakings, agriculture. In no single sector, however, have the results of scientific research been so extensive or so far reaching in their effect on human well being as in the broad field of agriculture. During the past 50 years, as a direct result of scientific research we have learned more about soil chemistry and soil mechanics than man ever knew before. By the same means we have learned how to produce new species and to adapt old species to new environments. Through organized, intensive research work in the various fields of the botanical and biological sciences we have learned how to control plant diseases and plant pests which would otherwise at times and in places completely destroy many forms of agriculture. The very advances that have resulted from research, particularly in the field of rapid transportation, have changed the whole complexion of the agricultural problem. Plant diseases and plant pests, which in an earlier age were definitely localized in their point of origin because they could not survive the long period involved in transportation to a distant point, became a devastating menace with the advent of rapid transportation. That much of agriculture, as we know it, has not fallen victim to this menace is wholly and solely the result of organized research

designed to ferret out the necessary controls, and of engineering based on this research that has made those controls effective.

A category of examples similar to the foregoing could be extended almost without end. Except, however, as multiplicity of numbers gives weight to proof, such an extension would add nothing to the research picture presented by the progress of the past 50 years. In this field the semi-centennial milestone of the American Institute of Electrical Engineers, which we are this spring unveiling, marks not only a notable period in the life of a great institution concerned with a great group of industries, but also the end of 5 very notable decades in the life of all industries that are organized on bases of applied science. What pictures looking backward in 1984 will show, only our children or their children can see. From our present point of view there is no reason, however, to believe that these pictures will disclose results growing out of industrial research any less striking than those we now see when we look backward over 50 years of progress.



(Right) Combined studio and transmitter of the original KDKA radio station which began broadcasting November 2, 1920
(Westinghouse photo)

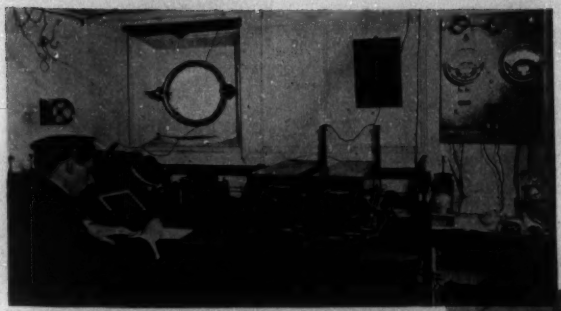
(Below) Transmitting room of a modern radio broadcasting station, WEAF at Belmore, Long Island (RCA photo)

One of the transmitting towers of the Anglo-French micro-ray communication link between Lympe, England, and St. Inglevert, France, a distance of 35 miles. Operating on a wave length of 17.4 cm, this installation represents the shortest wavelength radio telephony in regular commercial exploitation today and may be considered as heralding an era in which the practical advantages of privacy, efficiency, and reliability of these extremely small wavelengths will be exploited to the full
(International Tel. & Tel. Co. photo)

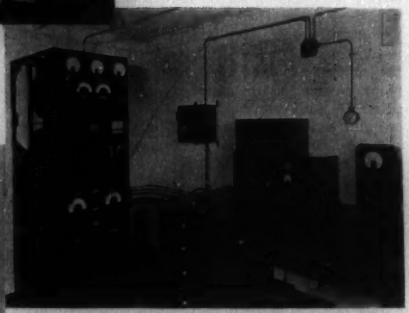
(Right) Back of power amplifier of radio station WEAF at Belmore, Long Island
(RCA photo)

Some Contrasts in Radio Equipment

(This and Facing Page)

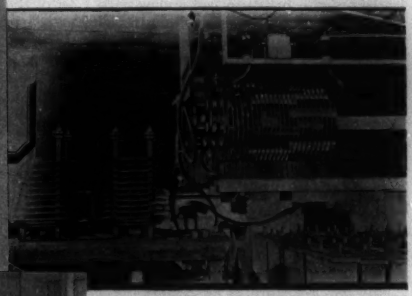


(Left) A 1901 marine radio telegraph set on the S.S. "Philadelphia"
(RCA photo)



A modern marine radio telegraph installation on the S. S. "Gulf Pride", this consists of a 500-watt intermediate and long wave transmitter, and an intermediate wave receiver
(RCA photo)

(Below) Some contrasts in radio transmitting tubes (reproduced in proportionate sizes): 2 modern 100-kw tubes, each more than 4 ft long; transatlantic transmitting tubes of 1927 and 1915 (left below); and a tube used to modulate an Alexanderson alternator in radio-telephone tests between Pittsfield, Mass., and Schenectady, N. Y., in 1914 (bottom)
(Am. Tel. & Tel. and General Elec. photos)



(Above) Early radio telegraph apparatus used in transoceanic communication
(RCA photo)

(Left) A modern 20-kw short wave transmitter with crystal control used for present-day transoceanic telegraph service
(RCA photo)

Great Names Behind the Institute

THE TRUTH of the often-repeated statement that the history of any organization can be traced in the lives of its leaders, is borne out by the records of the American Institute of Electrical Engineers. The names of the leaders of the A.I.E.E. comprise an imposing list, one which any organization would be proud to claim.

The influence which those prominent in the Institute have had on society cannot be over-estimated as it is so far-reaching, and extends in an intangible way through the lives and acts of many thousand individuals. Some conception of the magnitude of the influence which these men have had on their fellow-beings may be gained from the fact that a surprisingly large proportion of the Institute's leaders are not only well known within the electrical engineering profession, but are famous with men in all countries throughout the world.

On this and the following page are listed the names of those who have served as presidents from the founding of the Institute in 1884 until the present day, the names of those who have been elected to honorary membership in the Institute, the names of those who have been awarded any of the 3 medals in which the Institute is most deeply interested, the names of those faithful individuals who have served the Institute either as secretaries or treasurers, and the names of the 6 living charter members of the Institute. On the 37 pages which follow this listing, there are given biographical sketches of these leaders of the Institute, concluding with a list of the 71 pioneers in the electrical industry who, as nearly as can be determined from records at Institute headquarters, were charter members of the Institute.

Presidents of the Institute

FROM the Institute's first president, Dr. Norvin Green, down to and including the incumbent, Dr. J. B. Whitehead, 46 outstanding leaders have served the Institute as presidents. These, together with their term of service, are:

Norvin Green	1884–86	F. B. Crocker	1897–98
Franklin L. Pope	1886–87	A. E. Kennelly	1898–1900
T. C. Martin	1887–88	Carl Hering	1900–01
Edward Weston	1888–89	C. P. Steinmetz	1901–02
Elihu Thomson	1889–90	Charles F. Scott	1902–03
W. A. Anthony	1890–91	Bion J. Arnold	1903–04
Alexander Graham Bell	1891–92	John W. Lieb	1904–05
Frank J. Sprague	1892–93	S. S. Wheeler	1905–06
Edwin J. Houston	1893–95	Samuel Sheldon	1906–07
Louis Duncan	1895–97	Henry G. Stott	1907–08
L. A. Ferguson	1908–09	Wm. McClellan	1921–22
L. B. Stillwell	1909–10	Frank B. Jewett	1922–23
D. C. Jackson	1910–11	Harris J. Ryan	1923–24
Gano Dunn	1911–12	Farley Osgood	1924–25
Ralph D. Mershon	1912–13	M. I. Pupin	1925–26
C. O. Mailloux	1913–14	C. C. Chesney	1926–27
Paul M. Lincoln	1914–15	Bancroft Gherardi	1927–28
John J. Carty	1915–16	R. F. Schuchardt	1928–29
H. W. Buck	1916–17	Harold B. Smith	1929–30
E. W. Rice, Jr.	1917–18	W. S. Lee	1930–31
Comfort A. Adams	1918–19	C. E. Skinner	1931–32
Calvert Townley	1919–20	H. P. Charlesworth	1932–33
A. W. Berresford	1920–21	J. B. Whitehead	1933–34

Honorary Members of the Institute

THE INSTITUTE has elected 31 distinguished citizens of various countries of the world to the highest grade of membership in the Institute, namely, Honorary Member. Previous to the election of Thomas A. Edison to honorary membership in 1928, all Honorary Members with the exception of Prof. Moses G. Farmer and Cyrus W. Field, had been citizens of countries other than the United States. Since 1928, the tendency has been more to honor those who have served the Institute directly.

As an aid to those who may wish to turn to the biographical sketch of some Honorary Member in the pages which follow, these sketches are given immediately after those of the presidents, and are given in the chronological order of election. In the cases of those names in the following list which are followed by an asterisk, biographical sketches will not be found in the group of Honorary Members, but will have been given in the group of presidents, as these Honorary Members also served as presidents.

Sir William Preece	1884	John J. Carty*	1928
Norvin Green*	1889	M. I. Pupin*	1928
Moses G. Farmer	1890	Ambrose Swasey	1928
Lord Kelvin	1892	Elihu Thomson*	1928
Cyrus Field	1892	Herbert Hoover	1929
E. W. von Siemens	1892	Charles F. Scott*	1929
André Blondel	1912	Charles F. Brush	1929
C. E. L. Brown	1912	Motoji Shibusawa	1929
Emil A. Budde	1912	Frank J. Sprague*	1932
S. Z. de Ferranti	1912	W. L. R. Emmet	1933
Antonio Pacinotti	1912	G. A. Hamilton	1933
S. P. Thompson	1914	Arthur E. Kennelly*	1933
Guglielmo Marconi	1917	R. A. Millikan	1933
Oliver Heaviside	1918	E. W. Rice, Jr.*	1933
Ferdinand Foch	1921	Edward Weston*	1933
Thomas A. Edison	1928		

* Included in the group of Past-Presidents.

Edison Medalists

THE EDISON MEDAL Association was originally organized for the purpose of appropriately recounting and celebrating the achievements of a quarter of a century in the art of electric lighting. It was felt by the Association that the most effective means of accomplishing the object for which it was formed would be the establishment of a gold Medal, which should, during the centuries to come, serve as an honorable incentive to scientists, engineers, and artisans to maintain by their works a high standard of accomplishment. The Medal, highest award of the Institute, was established on February 11, 1904, and is awarded once each year to some one resident of the United States of America and its dependencies, or of the Dominion of Canada, for "meritorious achievement" in electrical science or electrical engineering or the electrical arts.

In the cases of those names in the following list which are followed by an asterisk, biographical sketches will not be found in the group of Edison Medalists, but will have been given in the group of presidents or honorary members.

Elihu Thomson*	1909	R. A. Millikan*	1922
Frank J. Sprague*	1910	John W. Lieb*	1923
George Westinghouse	1911	John W. Howell	1924
William Stanley	1912	Harris J. Ryan*	1925
Charles F. Brush*	1913	W. D. Coolidge	1927
Alexander Graham Bell*	1914	Frank B. Jewett*	1928
Nikola Tesla	1916	Charles F. Scott*	1929
John J. Carty*	1917	Frank Conrad	1930
Benjamin G. Lamme	1918	E. W. Rice, Jr.*	1931
W. L. R. Emmet*	1919	Bancroft Gherardi*	1932
M. I. Pupin*	1920	Arthur E. Kennelly*	1933
C. C. Chesney*	1921		

John Fritz Medalists

THE JOHN FRITZ Medal is awarded annually by a board composed of 4 representatives of each of the 4 national engineering societies, the American Institute of Electrical Engineers, The American Society of Mechanical Engineers, the American Institute of Mining and Metallurgical Engineers, and the American Society of Civil Engineers, for notable scientific or industrial achievements, regardless of nationality or sex. It was established by professional associates and friends of John Fritz on August 21, 1902, his eightieth birthday, to perpetuate the memory of his achievements in industrial progress. The first award of the medal was to John Fritz at a dinner given on his eightieth birthday.

Those members of the Institute who have been awarded the John Fritz Medal follow. In this list an asterisk following the name indicates that the biographical sketch is given in one of the preceding groups.

Lord Kelvin*	1905	Ambrose Swasey*	1924
George Westinghouse*	1906	Edward D. Adams	1926
Alexander Graham Bell*	1907	Elmer A. Sperry	1927
Thomas A. Edison*	1908	John J. Carty*	1928
Elihu Thomson*	1916	Herbert Hoover*	1929
Guglielmo Marconi*	1923	M. I. Pupin*	1932

Lamme Medalists

A BEQUEST was made by the late Benjamin G. Lamme, chief engineer of the Westinghouse Electric and Manufacturing Company, to provide for the award by the Institute of a gold medal annually to a member of the A.I.E.E., "who has shown meritorious achievement in the development of electrical apparatus or machinery."

The award is made in accordance with conditions specified in the by-laws of the Lamme Medal committee.

In the list of Lamme Medalists which follows, an asterisk following the name indicates that the biographical sketch of the medalist is given in one of the preceding groups.

Allan B. Field	1928	Giuseppe Faccioli	1931
R. E. Hellmund	1929	Edward Weston*	1932
William J. Foster	1930	Lewis B. Stillwell*	1933

Secretaries of the Institute

THE secretaries of the Institute have in general held office for long terms. Although subject to reëlection or reappointment each year, the terms of service of the 4 secretaries, as indicated below, cover the entire 50-year span of the Institute's history.

N. S. Keith	1884–85	F. L. Hutchinson	1911–32
Ralph W. Pope	1885–1911	H. H. Henline	1932–

Treasurers of the Institute

THE treasurers of the Institute have also included long terms of service. With the unusual record of continuous service from 1895 to 1930 for Mr. Hamilton (see p. 816, 821, and 823), the terms of 4 treasurers span the 50 years, 1884–1934. The 4 treasurers are:

Rowland R. Hazard	1884–86	G. A. Hamilton*	1895–1930
George M. Phelps	1887–95	W. I. Slichter	1930–

Charter Members of the Institute

OF THE 71 individuals who have been definitely determined to have been charter members of the Institute, 6 are now living and still on the rolls. These living charter members, who will be presented with certificates and membership badges through the Sections of which they are members, are:

Charles L. Clarke	Frank B. Rae
E. N. Dickerson	Elihu Thomson*
George A. Hamilton*	Edward Weston*

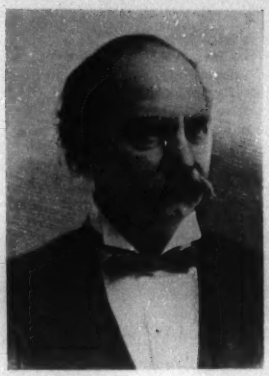
* Included in a previous group.

Norvin Green

(Associate 1884, Member 1884)

President 1884–85–86

Honorary Member 1889



THE INSTITUTE'S first president was a physician, who, having become interested in politics, was placed in a government position which led to his becoming one of the lessees of an early telegraph company, and subsequently president of the Western Union Telegraph Company. This physician was Dr. Norvin Green, a charter member and one of the founders of the Institute.

He was born April 17, 1880, at New Albany, Ind. His early life was spent in Kentucky; here he graduated with high honors at the University of Louisville in 1840. Shortly afterward he became a physician for the Western Military Academy, Drennon Springs, Ky., of which James G. Blaine, who later became a prominent statesman and was twice U.S. Secretary of State, was one of the junior instructors.

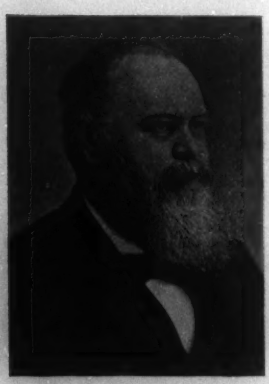
Doctor Green also became interested in politics. He was elected for a number of years as a member of the Kentucky Legislature and in 1853 was appointed a Commissioner of the United States in charge of the construction of national buildings in Louisville. While engaged in these duties he became one of the lessees of the United Morse and People's Telegraph Lines, between Louisville and New Orleans, later becoming president of these interests, united under the name of the Southwestern Telegraph Company.

In 1866, when the America, the United States, and the Western Union companies were consolidated, Doctor Green was chosen vice-president of the Western Union Company, and, which office he held up to 1878, with the exception of the 3 years from 1870 to 1873; during this period he was the president of the Louisville, Cincinnati and Lexington Railroad Company, and again entered politics, barely losing the nomination for U.S. Senator from Kentucky.

In 1878, Doctor Green was elected president of the Western Union Telegraph Company, holding this position until his death, February 12, 1893, at the age of 75 years.

It was from this background that Doctor Green entered heartily into the organization of the Institute. He was an ardent worker for its establishment and set the example of conscientious attention to duty He was sanguine in his prediction of the Institute's future usefulness, and in spite of his many business cares he was at almost all of the council meetings, acting as presiding officer. He had considerable committee work put upon him and was instrumental in laying out the work of the Institute during those first 2 years. It was said of him in those early days that no person connected with the Institute exhibited more interest and did more for its future advancement than did Doctor Green. At the end of his first term of presidency, Doctor Green unanimously was elected to serve as President for another year, 1885–86.

At the end of this period he was elected to serve 2 years as vice-president continuing to give advice and assistance thereafter.



Franklin L. Pope

(Associate 1884, Member 1884)

President 1886–87

SUCCEEDING Dr. Norvin Green, the second president of the Institute was Franklin Leonard Pope, one of the earliest practicing electrical engineers in the country. Mr. Pope, like many of the charter members of the Institute, was act.ve principally in the telegraph and telephone field.

He was born at Great Barrington, Mass., December 2, 1840. After attending the academy in Amherst, Mass., he became a telegraph operator in 1857. In 1859 he entered the drafting department of the *Scientific American* in New York City, but in 1861 reëntered the telegraph service in Providence, R. I. In 1862, he was made assistant engineer of the American Telegraph Company in New York. During the draft riots the following year, he repaired with his own hands the demolished telegraph lines of this company between New York and Boston. When the national telegraphic union was formed in 1863, Mr. Pope was chosen the New York District Secretary; under the pseudonym of "Elektron," he was the first contributor to its publication, *The Telegrapher*.

In 1864, Mr. Pope was appointed assistant engineer and chief of the geographical department of the Western Union Russian Extension Company, and surveyed the route for the proposed Collins Overland Telegraph between British Columbia and Alaska, which was abandoned after the successful laying of the Atlantic cable. Returning to New York in 1866, Mr. Pope resumed the contribution of articles to *The Telegrapher*, and its editor 1867–68.

In 1868, he undertook the development and management of a system of printing the prices of gold and of stock in brokers' offices. In 1869, he entered into partnership with Thomas A. Edison under the name of Pope, Edison & Company, electrical engineers, and in 1870 they invented a one-wire printing telegraph. This firm had but a brief existence, being dissolved in 1870, probably because of the strong personalities of its members. Continuing in active practice, Mr. Pope secured several patents, the majority of them being for a railroad semaphore lock signal system. He was one of the earliest patent solicitors for electrical inventions, and was for many years patent attorney for the Western Union Telegraph Company.

Mr. Pope was the author of "Modern Practice of the Electrical Telegraph" (1871, rewritten 1891), and "Life and Work of Joseph Henry" (1879). In 1884 he became editor of the *Electrical Engineer*, which was later called *The Electrician and Electrical Engineer*, and still later *The Electrical Engineer*. He also edited the electrical department of *The Engineering Magazine*.

In 1894, Mr. Pope returned to Great Barrington, having reconstructed an old brick house built there in 1766. As a pastime, he remodeled the Great Barrington Electric Light Company's system, describing these changes in an Institute paper. Mr. Pope had the primary wires brought into his cellar, and because of an accidental contact with these wires he was killed on October 13, 1895. Mr. Pope had been a member of the Institution of Electrical Engineers (British) since its inception in 1872 and had been one of its first vice-presidents. In 1878 he was vice-president of the American Electrical Society of Chicago. He was an older brother of Ralph W. Pope who, for 27 years, starting in the year 1885, served the Institute as secretary.

T. Commerford Martin

(Associate 1884, Member 1910)

President 1887–88

FOR its third president the Institute chose an editor of electrical magazines, author, and association executive. He was Thomas Commerford Martin, who assumed the presidency of the Institute at the age of 30.

Mr. Martin was born in London, England, July 22, 1856. Owing to the relation of his father to the pioneer submarine cable industry, the boy had the unique experience of spending much of his time on the historic cable-laying steamship "Great Eastern" and of making the early acquaintance of Professor William Thomson (Lord Kelvin). Although educated as a theological student, Mr. Martin came to the United States in 1877; entering the service of Thomas A. Edison that year, he had much to do with several famous inventions, and wrote many articles in the New York papers on them, notably on the telephone, microphone, and phonograph. Due to ill health, he resigned in 1879 and went to the West Indies, where he undertook journalistic adventures and work for the Government of Jamaica. Returning to New York in 1882, he edited *The Operator*, and in 1883, as one of the editors of the *Electrical World*, got out its first issue practically single handed. He remained as its editor for 26 years.

Then, in 1909, he was elected secretary of the former National Electric Light Association, which he had helped to found in 1885. On account of impaired health, he resigned in 1919, becoming advisory secretary. His annual report on the progress of the industry was for many years a leading feature of N.E.L.A. conventions. In 1923 he also became secretary of the New York Electrical Society, of which he had been a charter member, and in 1900, its president. He died May 17, 1924.

Mr. Martin was not only very active in 1884 as a founder and charter member of the A.I.E.E. and as its acting secretary at that time, but he had served in all of its elective offices except that of treasurer. Mr. Martin was also instrumental in the purchase by Doctor Schuyler Skaats Wheeler of the Lattimer Clark Library for the Institute, and the securing of the famous gift of $1,500,000 from Andrew Carnegie for the Engineering Societies Building and Engineers' Club. He served for 4 years on the 2 building committees, and as president opened the new building with Doctor Carnegie in 1907. He was president of the Engineers' Club of New York 1907–08.

Mr. Martin was the author of numerous electrical books, and contributed frequently to the leading American encyclopedias and magazines. As special electrical expert for the U.S. Census Office between 1900 and 1915, his reports on the vast range of electrical industries and utilities were of tremendous importance. He lectured widely in this and other countries. He was decorated by the French Government as Officer de l' Instruction Publique in 1907. He was one of the founders of the American Museum of Safety and of the Illuminating Engineering Society. He had represented the Institute and 3 other American societies at the Kelvin Jubilee in 1896 at Glasgow University. He was a member of several other engineering and scientific societies

Edward Weston

(A '84, M '84, member for life)

President 1888–89
Honorary Member 1933
Lamme Medalist 1932

EDWARD WESTON, now chairman of the board of the Weston Electrical Instrument Corporation at Newark, N. J., and one of the 6 living charter members of the Institute, was elected as the fourth president of the A.I.E.E. The citation accompanying the award to him of the Institute's Lamme Medal in 1932 "for his achievements in the development of electrical apparatus, especially in connection with precision measuring instruments," aptly phrases the outstanding interest of his long and active life.

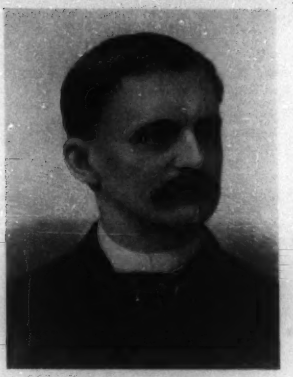
Doctor Weston was born in Shropshire, England, in 1850, and received his formal education in that country. From boyhood he manifested a keen interest in electrical and mechanical investigations. Coming to New York City in 1870, he spent 2 years as chemist and electrician for industrial concerns, then established his own nickel plating business in 1872, maintaining this activity until 1875, when he became a partner in a firm for the manufacture of dynamo-electric machines.

The business of this firm was incorporated as the Weston Company in 1877, and in 1881 was consolidated with the U.S. Electric Light Company, of which Doctor Weston served as electrician until 1888. While in this position he received many patents on dynamo construction, and conducted extensive investigation in the lighting field.

At this time he encountered in all his researches great difficulty in making the necessary electrical measurements with the clumsy, slow acting instruments then available; he therefore developed and built for his own experiments a set of more practical instruments. These were so successful that in 1888 he decided to relinquish his other interests and devote all his time to the research and development necessary to produce accurate and convenient electrical instruments. He established the Weston Electrical Instrument Company, of which he served as vice-president and general manager from 1888 until 1905, and president from 1905 to 1924, when he became chairman of the board. His achievements in developing instruments of a high speed of accuracy and portability are well known. In 1908, the Weston standard cell was accepted as the universal standard of electromotive force.

In addition to being a charter member of the Institute, Doctor Weston was a member of its first board of directors and served as manager 1884–87. Following his term as president, he was vice-president 1889–91. He is a member of several other engineering and scientific societies, being an honorary member of the Franklin Institute. Doctor Weston has received the honorary degrees of doctor of laws from McGill University,

1903; doctor of science, Stevens Institute of Technology, 1904, and Princeton University, 1910. His interest in the younger members of the profession is known by his establishment of a fellowship in electrochemistry, managed by the Electrochemical Society. This fellowship of $1,000 is awarded each year to a candidate under 30 years of age who shows marked capacity in carrying out research in electrochemistry or its applications.



Elihu Thomson

(A '84, M '91, F '13, member for life)

President 1889–90
Honorary Member 1928
Edison Medalist 1909
John Fritz Medalist 1916

ELIHU THOMSON, fifth president of the Institute and one of the 6 living charter members, has a record in electrical engineering that can hardly be paralleled by any other individual living at present. Throughout almost the entire period of the development of electrical theory and apparatus, Professor Thomson has been deeply interested in all phases of electrical engineering. He has freely passed on to others the tremendous store of information that he has collected. As one small note of appreciation of his generous efforts, his friends continue to call him by the title of professor, even though more dignified titles may be applied.

He was born in Manchester, England, March 29, 1853, being brought to the United States in 1858, settling in Philadelphia. Upon graduating from Central High School, Philadelphia, in 1870, he was at once appointed assistant professor of chemistry of that institution. He was full professor from 1876 to 1880, when he resigned to devote his entire time to electrical research.

His unusual inventive genius and his marked ability to learn quickly, were apparent even during his early years. Professor Thomson's first important invention was the 3-coil arc dynamo which, with its automatic regulator and other novel features, was the basis of the successful electric lighting system produced by the Thomson-Houston Electric Company, beginning in 1880. This company was established in Philadelphia in 1879 by Professor Thomson and E. J. Houston, his former colleague at the high school who later, 1893–95, also was a president of the Institute. The company moved to New Britain, Conn., in 1880 and then to Massachusetts in 1883, merging in 1892 with the Edison General Electric Company to become the General Electric Company. In the early years of the new company Professor Thomson was elected chief engineer, many of fundamental inventions upon which the present industry is based being his. Professor Thomson is today consulting engineer of the General Electric Company and director of its Thomson Research Laboratory at Lynn. During his career some 700 patents have been taken out by Professor Thomson, these covering almost every field of electrical activity.

Professor Thomson was the recipient of the Institute's first Edison Medal, and has received some 15 medals in this and other countries, as well as other honors. These include 3 notable medals of Great Britain; in 1916 he was the recipient of the Hughes Medal bestowed by the Royal Society; in 1924 he was honored by the award of the Kelvin Medal, given by all the technical and engineering bodies of England with the concurrence of the leading engineering societies of America; and in 1927 he was presented by the Institution of Electrical Engineers, of England, with the Faraday Medal.

In 1889 he was decorated by the French Government for his electrical inventions, being made a chevalier and officer of the Legion of Honor.

He was awarded the Rumford Medal, in 1901; the Grand Prix at the Paris Expositions of 1899 and 1900; the John Fritz Medal of 1916; and the Elliott Cresson Gold Medal from the Franklin Institute. He has twice received the John Scott Medal for electrical inventions. Honorary degrees have been conferred upon him by several institutions.

In addition to serving the Institute as vice-president 1887–89, and then as president, he has been active on the committee of coöperative research 1898–1900, the committee on standardization 1898–1900, and the Edison Medal committee, of which he was chairman 1911–15. He served as the Institute's representative on the U. S. National Committee of the International Electrotechnical Commission for many years preceding 1930.

William A. Anthony

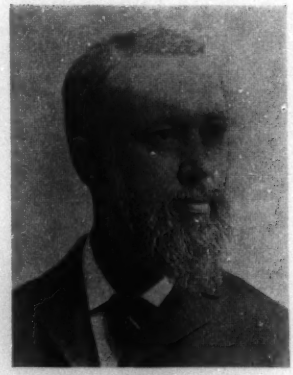
(Associate 1884, Member 1885)

President 1890–91

THE first 5 presidents of the Institute had all been charter members. The sixth president, William Arnold Anthony, was elected an associate December 9, 1884, while a professor of Physics at Cornell University. Although a few months late in getting started, he immediately took an active part in Institute affairs and was elected a vice-president in 1886, serving for 3 years.

He was born at Coventry, R. I., November 17, 1835. He entered Sheffield Scientific School at Yale University and graduated at the head of his class, with the degree of Ph.B., in 1856. For a short time following his graduation he was principal of the public schools at Crompton, R. I., and taught for a year in the Providence Conference Seminary. Following a year in a cotton machinery manufacturing plant, to acquire a knowledge of tools, he resumed teaching, first at the Delaware Literary Institute, Franklin, N. Y., and later at Antioch College, Ohio.

He was professor of mechanics and physics at Iowa State Agricultural College at Ames, from 1869 to 1872 thence going to Cornell University where he remained as professor of physics until 1887. During the 15 years there he did much to originate and develop the course of study in electrical engineering. From 1887 until 1893, he was consulting engineer at the Mather Electric Company, Manchester, Conn. In the latter year he opened an office in New York City as consulting electrical engineer, and in 1894 became connected with the Cooper Union night school of science as professor of physics. In February 1908 he was retired as professor emeritus, and died May 29 of that year.



He was one of the authors of Anthony and Brackett's "Manual of Physics" (1887) and in 1898 he published "Lecture Notes on the Theory of Electrical Measurements." Although of a quiet and unassuming disposition, Prof. Anthony nevertheless received full recognition for his work from an appreciative class of coworkers in the electrical field.

He served the Institute on the membership and the coöperative research committees, and was the first local secretary for the Manchester, Conn., section, 1888. He was a member of the Franklin Institute of Philadelphia, the American Social Science Association, and the Brooklyn Institute of Arts and Sciences.

Alexander Graham Bell

(Associate 1884, Member 1884)

President 1891–92

Edison Medalist 1914
John Fritz Medalist 1907

ALTHOUGH he did much other important scientific work in various fields Alexander Graham Bell has been known the world over as the inventor of the telephone, and thus may be said to have made one of the most revolutionizing contributions to modern civilization to date.

Doctor Bell was born in Edinburgh, Scotland, in 1847, the son and grandson of teachers of vocal physiology and the laws of speech, and this, in addition to the fact that 2 members of his immediate family were deaf, undoubtedly was responsible for his interest in all matters pertaining to the human voice. At 14, he was sent to London for instruction in elocution and phonetics by his grandfather. Later he returned to Edinburgh to study at the University, and in a short time he was assistant to his father who had obtained a post as lecturer in elocution at University College, London. There he met Wheatstone and Ellis and became interested in Helmholtz's work on the electromagnetic control of tuning forks.

When he was 23, the Bell family emigrated to Canada, and the next year Doctor Bell was appointed instructor at the first school for the deaf and dumb in Boston. He was a very successful teacher and later taught at both Boston and Oxford universities. In inventing the telephone he was first seeking some way, perhaps by registering graphically on paper, to show his pupils the variations in tones and the inflections of the human voice. Into the poorly equipped electric shop of Charles Williams, typical of that period when a "laboratory" was unheard of, Doctor Bell took his first problems and ideas of the "harmonic telegraph," "harp telephone," and speaking telephone.

By 1875, after continuous experimentation, he was at work upon the specifications of the patent for the telephone, and in 1876 it was granted. The Centennial Exhibit at Philadelphia in 1875 did much to convince business men that the instrument was practical, and soon thereafter a 2-mile line was installed between Boston and Cambridge over which ordinary reciprocal conversation was carried on. By 1887 long-distance conversations between New York and Boston were possible.

Doctor Bell was an active researcher until the time of his death in 1922. Besides the telephone he invented the photophone, a device which transmitted speech by light beams, induction balance and telephone probe, and helped to develop the graphophone. He constructed a number of tetrahedral aeroplanes and experimented with propellers.

He was a charter member of the Institute,

a member of many American and foreign societies and the recipient of honors from governments and learned institutions, including the decoration of the Legion of Honor from France, Volta Prize (1880), Albert Medal of the Society of Arts (London, 1902), Hughes Medal of the Royal Society of England, and Elliott Cresson Medal of the Franklin Institute.

Frank J. Sprague

(A '87, M '97, F '12, member for life)

President 1892–93
Honorary Member 1932
Edison Medalist 1910

OF THE early developers of electric motors and electric traction, Frank Julian Sprague is preëminent. His unflagging spirit and courage both as an inventor and as a financial manager had much to do with the successful development and operation of the electric trolley, the constant speed motor, the multiple unit, regenerative and remote control systems, and considerable equipment for elevator operation.

Mr. Sprague was born in Milford, Conn., in 1857. He early demonstrated his ability as a "financier" by borrowing money to attend the United States Naval Academy. It was while attending the Academy that the telephone was invented and his interest was aroused in things mechanical and electrical. He carried on experimentations in his free time, and in 1885, he resigned from the Navy and began his career as an electrical engineer, assisting Edison for one year. During this time he devised a mathematical system for determining the characteristics of central station distribution of electricity. Then he established his own enterprise, the Sprague Electric Railway and Motor Company, and immediately began the application of electric motors to all kinds of stationery work, equipping the first electrically trained gun on the S. S. "Chicago." In 1887 he undertook a contract with the City of Richmond, Va., to plan, finance, and put into operation a street railway, the first successful system to be operated. Within 2 years his firm had received more than 100 contracts for similar work all over the country and in Italy and Germany as well.

In the course of his career, he has organized a number of concerns bearing his name, some of which merged with such organizations as the General Electric Company. He is now president of the Sprague Safety Control and Signal Corporation and the Sprague Development Corporation.

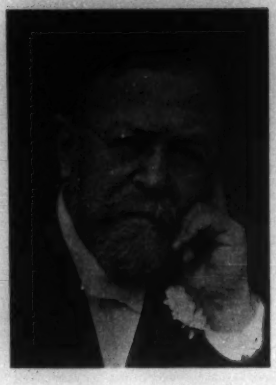
Among his achievements are the introduction of electric high speed and house elevators, development of the automatic signaling and brake train control systems, and invention of the method of operating 2 elevators on the same rails in a common shaft. He has taken a keen interest in electrical traction in general, advocating underground rapid transit through the whole period of its development in New York City; also he has been interested in the electrification of the railroad, having served on the Grand Central Terminal Electrification Commission.

Mr. Sprague has long been active in Institute affairs, serving at various times as committeeman and as vice-president (1890–92). He represented the Institute and Inventors Guild on the U.S. Naval Consulting Board and was engaged in developing fuses and air and depth bombs during the war. He is a member of many technical societies; past-president of the New York Electrical Society, American Institute of Consulting Engineers, and the Inventors Guild; and the recipient of many distinctive awards.

Edwin J. Houston

(A '84, M '84, Life Member)

President 1893–94–95



IN THE days when electric lighting was a new subject Edwin James Houston attained fame by working out the Thomson-Houston system of arc lighting. In collaboration with Professor Elihu Thomson who was a teacher at the same school, Professor Houston made many important contributions to the art, establishing a high reputation as an inventor in addition to his eminence as a teacher, author, and consulting engineer.

He was born in Alexandria, Va., July 9, 1847 and was educated in the Central High School of Philadelphia, from which he received the Master's degree. After teaching for a time at Girard College, he was elected professor of civil engineering in the Central High School, but was soon transferred to the chair of natural philosophy, of which he was professor emeritus at the time of his death, March 1, 1914. He was also professor emeritus of physics at Franklin Institute and professor of physics at the Medico-Chirurgical College.

In 1884 he was appointed a member of the United States Electrical Commission, which convened at Philadelphia, and was elected by the Franklin Institute chief engineer of the International Electrical Exhibition in Philadelphia. This exhibition was well carried out, and the practical tests of electrical apparatus then made were a valuable contribution to the advance of electrical science. By this time Professor Houston had become prominent in electrical research of every sort, and the following year, in 1895, he resigned from his position at the Central High School to become associated with Dr. A. E. Kennelly in the firm, Houston and Kennelly, consulting engineers.

Professor Houston was a very prolific writer both in the technical and popularized fields of science. He was keenly alive to the growing importance of science in education and wrote many textbooks and "popular" essays, as well as numerous purely scientific papers.

The series "Primers of Electricity," published in 1884 in the *Electrical World*, which he wrote in collaboration with Dr. Kennelly, was among the first primers on electrical subjects appearing in any language. His "Dictionary of Electrical Words, Terms, and Phrases" and "Electricity in Every-day Life" are well known today. It was Professor Houston who presented the first paper before the Institute in 1884, "Some Notes on Incandescent Lamps," which dealt with the "Edison effect" and aroused a great deal of comment. The modern electronic tube is based upon this discovery.

He was a charter member of the Institute, a member of the American Institute of Mining Engineers, the American Philosophical Society, the Philadelphia Academy, and many other scientific organizations. He was president of Section C of the Electrical Congress held in Chicago in 1893 and the first president of the electrical section of the Franklin Institute. He received the honorary Ph.D. degree from Princeton University.

Louis Duncan

(A '87, M '87, F '13)

President 1895–96–97

ALTHOUGH prominent in the educational field, Louis Duncan was best known as an electrical traction expert and consulting engineer.

Doctor Duncan was born in Washington, D. C., March 25, 1861, and graduated from the United States Naval Academy in 1880. For about 6 years of service after graduation he was assigned part of the time to special duty at the Johns Hopkins University, to assist in determining the absolute unit of electrical resistance. For this work he received the Ph.D. degree from the university in 1885. In 1886 he resigned from the Navy and joined the teaching staff of Johns Hopkins, where he was in charge of a course in electrical engineering for 14 years. He inspired much original work on the part of his students.

At the same time he was occupied with various electrical engineering problems and was engineer in charge of construction of a number of electric roads in Baltimore, consulting engineer for many of the electric roads in Washington, chief engineer and in charge of construction of the Third Avenue System in New York, engineer for the Baltimore and Ohio Company, equipping the Baltimore tunnel with electric locomotives, and was consultant for a number of other railroad and lighting concerns.

In 1899, he resigned his position at the University and devoted his entire time to his consulting practice, organizing the firm of Sprague, Duncan and Hutchinson, but in 1902 when the Massachusetts Institute of Technology built a new electrical laboratory and separated the course of electrical engineering from the physics department, he was called upon to inaugurate the course, and the idea had such an appeal to him that he accepted and donned the professorial robes again for 2 years, as head of the electrical engineering department. He then returned to his practice and was active as a consulting engineer until his death February 13, 1916.

He took out several patents on devices for electrical machines, as well as patents on secondary batteries.

He did important consulting work for numerous utilities, including the Cincinnati Traction Company, the Indianapolis Traction Company, and many of the railroad companies in the Middle West. He was consulting engineer for the Rapid Transit Commission of New York City, chief engineer of the Keystone Telephone Company of Philadelphia, and of the independent telephone systems at Baltimore and Pittsburgh.

Doctor Duncan was the author of many articles on electrical subjects, and wrote on electricity for the Encyclopaedia Britannica. He was chairman of the board of judges at the Philadelphia Electrical Exhibition in 1885, a member of the board at the Atlantic Exposition and the World's Columbian Exposition at Chicago in 1892, and chairman of the electrical railroad section of the St. Louis Exposition in 1904. Doctor Duncan served as Major in the first volunteer engineers' corps during the Spanish-American War.

He contributed to the upbuilding of the Institute, serving 2 successive terms as president from 1895 to 1897, and also on several committees. He was an honorary member of the Franklin Institute, a member of the Mathematical Society of France, the Physical Society of France, the American Electrochemical Society, the American Philosophical Society, and others. He was associated with many other American and European scientific and technical organizations.

Francis B. Crocker

(A '87, M '99, Life Member)

President 1897–98

FRANCIS Bacon Crocker made his mark in the electrical engineering field as a pioneer designer of commercially successful motors, a distinguished educator, and a very able electrical engineer.

He was born in New York in 1861. From his childhood days he was interested in electricity, then barely known as a science, and as a boy he built successful telegraph and telephone lines. He attended school in New York and was graduated from the School of Mines of Columbia University in 1882, receiving the Ph.D. degree in electrical engineering in 1895. In 1899, he founded the department of electrical engineering and remained head of it for 20 years.

In 1883, Doctor Crocker with Charles G. Curtis organized the firm of Curtis & Crocker, one of the earliest electric motor manufacturing concerns. For 5 years they were engaged in patent and expert work, almost entirely electrical. Among their achievements was the invention and development of the "C. & C." electric motor. Upon the withdrawal of Mr. Curtis, owing to ill health, Doctor Crocker formed in 1888, with Schuyler S. Wheeler, the firm of Crocker & Wheeler, electrical engineers. This was the forerunner of the Crocker-Wheeler Co., one of the most prominent establishments of its kind in the country. Doctor Crocker was a director of the company until the time of his death in 1921.

In addition to his academic and commercial interests Doctor Crocker gave much of his time and energy to the profession in his untiring efforts as an advocate of national and international standardization of electrical equipment. From the very beginning, he took a great interest in standardization, and if he had done nothing else, the excellence of this pioneer work in standardization, the ground work of which has remained virtually unchanged although the industry has undergone a most remarkable period of advancement, would be sufficient to single out Doctor Crocker as a notable in the electrical engineering world. In 1890 he became chairman of the first standardization committee of the Institute, serving several terms. In 1906 he was one of the 2 American delegates to the International Electrotechnical Commission which met in London. In 1913 he was appointed President of the United States National Committee of the Commission, and vice-president in 1916.

During the war Doctor Crocker was advisor for the members of the Naval Consulting Board, refusing to become a member, however, on account of poor health. His researches in aeronautics were of great importance, and many of his discoveries are now in practical application. In 1917 with Peter Cooper Hewitt he developed the first helicopter in this country which was able to fly. Successful inventors frequently sought his advice and information, and while he did not take out many patents in his own name, he was considered one of the best posted men on patents and he was able to aid greatly in the development of many uncompleted devices which others brought to him.

Arthur E. Kennelly

(A '88, M '99, F '13, Life Member)

President 1898–99–1900

Honorary Member 1933

Edison Medalist 1933

AMONG the notables in the scientific and scholastic as well as the practical provinces of electrical engineering is Arthur Edwin Kennelly.

Doctor Kennelly was born in 1861 in East India and was naturalized in 1906. He was educated at various private schools, scattered over Europe, including University College in London. He was awarded the honorary degrees of Sc.D., 1895, by the University of Pittsburgh, A.M., 1906, Harvard, and Sc.D., 1922, Toulouse, France.

His engineering career began at the early age of 14 when he acted as assistant secretary of the Society of Telegraph Engineers (now Institution of Electrical Engineers), in London. He had learned 3 signal systems and was employed as an operator by the Eastern Telegraph Company, by the time he was 15. He passed successively through the positions of assistant electrician, chief electrician of a cable repairing steamer and senior ship electrician on submarine cables. The familiarity gained in this submarine work with the theory and practice of transmission of signals over long lines with distributed capacity, because of the severe demands on his technical knowledge and resourcefulness, undoubtedly formed the basis for his future work in the field of telephony and in the mathematical treatment of the phenomena of transmission lines.

In 1887, when he was 26, he came to America and became the principal assistant to Edison, and later, in addition, was consulting electrician for the Edison General Electric and the General Electric Companies; also, from 1894 to 1901 he was a member of the consulting firm of Houston and Kennelly. In 1902 he had charge of the laying of the Vera Cruz–Frontera–Compeche cable for the Mexican Government.

That same year Doctor Kennelly was appointed professor of electrical engineering at Harvard University, becoming professor emeritus in 1930 of that institution and of Massachusetts Institute of Technology, which positions he now holds. He was also professor of electrical communication, 1913–24, and chairman of the faculty, 1916–18, of the Massachusetts Institute of Technology. Several other educational distinctions have come to him.

He has been a prolific writer, enriching the literature by the publication of more than 300 papers and books. Perhaps the best known of his contributions to scientific knowledge is his explanation of the mechanism of the transmission of radio waves, published in 1902.

Doctor Kennelly has never swerved from his enthusiastic advocacy of standardization of electrical terms from the time when he became chairman of the committee on units and standards in 1890 to the present as chairman of the committee on electrical definitions of the Institute and as president of the International Electrotechnical Commission. He has served the Institute in many capacities and has been an officer and member of numerous other technical societies in this country and abroad, receiving many honors and awards.

Carl Hering

(A'88, M'88, F'12, Life Member)

President 1900–01

ONE of the outstanding figures in the electrical engineering world was Carl Hering, a pioneer in the field of design and construction of electrical apparatus. He was a productive researcher in electrochemical and electrophysical fields, and the discoverer of several fundamental natural laws.

He was born in Philadelphia, March 29, 1860, and was graduated in 1880 with the B.S. degree from the University of Pennsylvania, teaching there the next year as instructor in mathematics and assistant in mechanical engineering. In 1887 he received the M.E. degree and in 1912 the university conferred upon him the honorary degree of Sc.D. In 1882, becoming interested in electrical engineering, recognized then as a new and important branch of the art, Doctor Hering obtained a transfer to the department of physics. The following year he went to Germany to take courses at Darmstadt, teaching in the Polytechnikum there and working in Frankfort as chief engineer for Henry Moehring and Company, which manufactured and installed motors and dynamos. Upon his return to Philadelphia in 1886, he established a consulting practice which he continued until his death, May 10, 1926, specializing in work on electric furnaces, underground electrolysis and electrochemical and electrophysical processes.

He started the first comparative life tests of incandescent lamps in 1884, at the Electrical Exposition in Philadelphia, of which he was the assistant electrical engineer. By 1890 he had made extensive researches into storage batteries, obtaining numerous patents from the results of his work; he also investigated the regeneration of battery solutions. His work on electric furnaces began in 1900 with tests for the reduction of arsenic ores. Some 6 years later, while designing and operating electric furnaces, he discovered the "pinch" effect. He also made other discoveries showing that electromagnetic forces act upon the material of the conductor. In 1909 he applied these forces to impart rapid motion to molten masses and, based upon this principle, he invented an electric furnace in wide commercial use.

Doctor Hering was a voluminous writer, aiming to bridge the gap between pure and applied science. In 1883 he computed conversion factors for electrical and mechanical energy, publishing a comprehensive treatise in 1904; later he recalculated all electrochemical equivalents. In 1892 he was technical editor of the *Electrical World* and in 1893 he established and compiled the "Digest of Electrical Literature."

He served the Institute as committeeman, first local secretary for Philadelphia (1888) and national vice-president (1891–93; 1895–98), standing firmly for the maintenance of Institute ideals throughout the whole period of his membership. He was a founder and president of the American Electrochemical Society and a member of the Franklin Institute, Illuminating Engineering Society, and American Association for the Advancement of Science. He was appointed officer of Public Instruction by the French Government in 1889 and decorated a Knight of the Legion of Honor in 1891. He was a delegate to a number of important national and international conventions.

Charles P. Steinmetz

(A'90, M'91, F'12)

President 1901–02

FOR more than 30 years Charles Proteus Steinmetz was a leader in the electrical industry, devoting his life to research, largely relating to mathematical foundations upon which many of the developments in electrical engineering are based; there was scarcely a detail of any branch of electrical science or mathematics with which he was not conversant. Of his achievements among the most important were his investigations in the field of magnetism and his researches into the theory of direct and alternating current and the phenomena of lighting.

He was born on April 9, 1865 in Breslau, Germany, and was educated at the universities of Breslau and Berlin, and the Polytechnic in Zurich, Switzerland, specializing in mathematics, electrical engineering, and chemistry, and teaching mathematics at the same time. At 24, he left Germany because his socialistic affiliations barred him from preferment, and came to the United States practically penniless and knowing almost no English. Later he was naturalized, and became interested in politics in Schenectady. During a Socialist régime he was appointed president of the board of education of that city in 1912 and held the position throughout succeeding administrations until his death on October 26, 1923.

The first job he obtained was as draftsman at the Osterheld and Eickemeyer factory in Yonkers, N. Y.; soon he was given charge of all the new and experimental work in the establishment. Besides working on inventions for electric motors and generators and electric street cars, Doctor Steinmetz attracted attention by articles he contributed to scientific papers here and in Germany, especially on the theory of alternating currents. He was put in charge of the research laboratory and began to specialize on magnetic testing. In 1892, the firm merged with the General Electric Company and he was sent to Lynn, Mass.; the next year he was transferred to Schenectady as chief consulting engineer, remaining in that position until his death. In 1902 he became also professor of electrophysics at Union University.

He possessed a marvelous insight into all scientific phenomena and an unequaled ability to explain the most difficult and abstruse problems by systematic mathematical methods. He expressed his desire to communicate his fundamental knowledge to others in the stimulating instruction he gave to his assistants at the General Electric and in the publication of a large number of scientific papers and electrical books, which have long been accepted as standard textbooks in colleges, laboratories, and workshops.

Doctor Steinmetz served the Institute as vice-president (1896–98), manager (1892–95; 1898–1901) and as committeeman at various times; he also contributed papers frequently to Institute meetings and publications, his first, in 1892, "On the Law of Hysteresis," marking a new epoch in electrical science. He was a member of numerous scientific and educational organizations. He received 2 honorary degrees, the A.M. from Harvard (1902) and Ph.D. from Union (1903).

Charles F. Scott

(A '92, M '93, F '25, member for life)

President 1902–03

Honorary Member 1929

Edison Medalist 1929

DURING his long and active career Charles Felton Scott has been an outstanding figure in both the engineering and educational fields, a meritorious inventor, a frequent contributor to the literature and a self-sacrificing worker for the benefit of the electrical engineering profession.

Prof. Scott was born at Athens, Ohio, in 1864, and attended Ohio University in Athens, and graduated from Ohio State University with the A.B. degree in 1885. He took postgraduate courses at Johns Hopkins University and received the honorary degrees of M.A. from Yale University, Sc.D. from the University of Pittsburgh, and Engg.D. from Stevens Institute of Technology.

He is perhaps most widely known as the inventor, in 1894, of the "Scott connection" by which 2 transformers are T-connected to change 2-phase alternating current to 3-phase and vice versa. He was closely identified with early single-phase railway electrifications, including the New York, New Haven, and Hartford. He had charge of the design of the transformers for the first high-voltage transmission system in this country, and was connected with the original Telluride installation. In the development of the polyphase induction motor he was associated with Nikola Tesla and was responsible for certain parts of the work. He was early identified with the problem of inductive coördination.

Professor Scott began as a wireman at the Baldwin Locomotive Works, going to the Westinghouse Electric and Manufacturing Company in 1888 as night testing room assistant; in 1891 he became assistant electrician, in 1897 chief electrician and finally, in 1904, consulting engineer. He initiated the Westinghouse Club and the *Electric Journal*. In 1911 he accepted the professorship of electrical engineering at Sheffield Scientific School, Yale University, where he was active head of the department until 1933, when he became professor of electrical engineering emeritus.

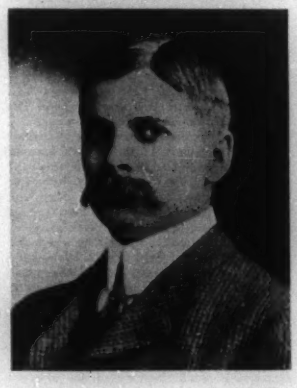
He has given enthusiastic service to the profession and in particular to the Institute. As its president he instituted an active campaign for members, founded the high-voltage transmission committee, stimulated Section growth and established Student Branches. He advocated a building for many engineering societies instead of one for the Institute only and was instrumental in securing funds for the Engineering Societies Building. He was chairman of the building committee and a charter member of United Engineering Society; he served on the Institute development committee in 1919 and on the committee which formed the American Engineering Council.

During 1921–23 he was president of the Society for the Promotion of Engineering Education; he proposed and was active in undertaking a study of engineering education. This work has been an important achievement and contribution to the profession. He also took an active part in organizing the Summer Conferences for Engineering Teachers 1927–33. He is a member of The American Society of Mechanical Engineers, Illuminating Engineering Society, Connecticut Society of Civil Engineers, American Philosophical Society, and Engineers Society of Western Pennsylvania, of which he was president 1902.

Bion J. Arnold

(A '92, M '93, F '12, member for life)

President 1903–04



THROUGHOUT the long and eminently successful career of Bion Joseph Arnold, his initiative, ingenuity and resourcefulness have been recognized not only by his fellow engineers, but also by the general public who know him well for his inventions, extensive consulting practice and the installation and direction of numerous public utility services.

He was born at Casnovia, Mich., in 1861, and was educated in the Ashland, Neb., public schools, the University of Nebraska and at Hillsdale College, Mich. He received the degrees B.S. from Hillsdale, 1884, and M.E., 1887; later he took a postgraduate course in electrical engineering at Cornell, and in 1897 he received the degree E.E. from the University of Nebraska, and, at various times, many honorary degrees.

In his boyhood Col. Arnold constructed models of farm implements, a steam engine, steam plant, bicycle and, most remarkable a working model of the standard Burlington locomotive, complete in all details and $^1/_{16}$ full size. The locomotives which entranced him as a child drew his interest as a young man to the railroad and its problems. Fame first came to him in 1893 by the design and building of the Intramural Elevated Railway at the Columbian Exposition, in Chicago. This was the first commercial installation of the third rail on a large scale, and it led to a wide practice as consulting engineer for steam and electric railways. Later he did the pioneer work of installation for such roads as the Chicago, Milwaukee Electric Railway, and the Lansing, St. Johns and St. Louis Railway, in Michigan. For the latter he developed in 1900 an a-c single-phase system. He converted from steam to electrical operation the Grand Trunk Railroad through the St. Clair Tunnel from Port Huron, Mich., to Sarnia, Ont. The single-phase high-voltage system for heavy electric railway work was adopted here for the first time.

Other important commissions Col. Arnold carried out where the development of the electrification of the Grand Central Terminal, New York, and the development of the subway system of New York. He has been consultant on surface and underground traction matters at various times for cities all over the country, and consulting engineer for numerous railroad commissions. He now maintains headquarters at Chicago.

During the war, Col. Arnold served in various capacities, being assigned as Lieut. Col., Aviation Section, 1917, to make a complete survey of aircraft supply and production conditions for the Army and Navy, and to take charge of the development and production of aerial torpedoes. His most recent commission is Col. Auxiliary Corps, 1925, which he now holds. Col. Arnold has served the Institute on various committees and is a member of numerous other societies, among them, the American Society of Civil Engineers, The American Society of Mechanical Engineers, Western Society of Engineers, and ~~American~~ Society for Promotion of Engineering Education.

John W. Lieb

(A '87, M '92, F '13, member for life

President 1904–05

Edison Medalist 1923

THE INSTITUTE'S Edison medal for 1923 was awarded John William Lieb "for the development and operation of electric central stations for illumination and power." That phrase well summarizes the guiding influence in Mr. Lieb's life.

He was born in Newark, N. J., in 1860, and graduated from Stevens Institute of Technology in 1880. In 1921 he received the honorary degree of doctor of engineering from that institution. Upon graduation he entered the employ of the Brush Electric Company, Cleveland, Ohio, but in 1881 transferred to the Edison Electric Light Company of New York, becoming assistant in the engineering department. The following year he became assistant to Mr. Edison and was engaged in experimental research, working with Mr. Edison in tests on the now famous Pearl Street station. In 1882 he was appointed the first electrician of the company.

In 1883 he went to Milan, Italy, to represent Mr. Edison in connection with the design, installation, and operation of the Milan Central Station. He later became technical director of the Società Generale Italiana di Elettricita Sistema Edison, and for his work in introducing the use of electricity into Italy, was made Knight Commander of the Royal Order of the Crown of Italy, in which he was later promoted to a Grand Officer. He was also made an officer of the French Legion of Honor.

In 1892 Mr. Lieb returned to New York as assistant to the vice-president of the Edison Electric Illuminating Company. He was later made vice-president and general manager of the company, and when the New York Edison Company was organized he became associate general manager and then appointed vice-president in general charge of operations. He later became general manager and upon the consolidation of the New York Edison Company with other utility companies in the New York Metropolitan area in 1928, Mr. Lieb became senior vice-president. He held this position at the time of his death, November 1, 1929.

For many years following 1900, Mr. Lieb also was president of the Electrical Testing Laboratories of New York. Mr. Lieb held office in several other utility companies. During the war, Mr. Lieb rendered valuable service as chairman of the national committee on gas and electric service.

Mr. Lieb took a prominent part in the work of many of the organizations in the electrical and allied field. He was a past-president of several such organizations. For the Institute, he has served on several committees as well as holding the presidency for one year. His work was recognized by many foreign societies and he was a member or honorary member of several of these.

Beside taking a part in the deliberations of foreign societies (he spoke 4 languages fluently) Mr. Lieb was an outstanding figure in the promotion of amity, peace, and good-will among the technical and engineering men of the world.

Schuyler Skaats Wheeler

(A '85, M '85, F '12, Life Member)

President 1905–06

THE presentation to the Institute by Schuyler Skaats Wheeler of the Latimer Clark Library in 1900, is of itself sufficient to insure Doctor Wheeler a permanent place in the rôle of those who have given outstanding service to the Institute. This act, however, was but one of the many contributions which he made. During the early development of the industry, he was responsible for many inventions and applications of electrical equipment.

Doctor Wheeler was born in New York, N. Y., May 17, 1860. He was educated at Columbia College, and was awarded the honorary degree of doctor of science by Hobart College in 1894, and that of master of science by Columbia in 1912. At the age of 21 he left college to become assistant electrician of the Jablochkoff Electric Light Company, and in 1882 joined the engineering staff of Thomas A. Edison, in charge of work at the first power station. He was in this position in 1893 when the incandescent light was introduced. He installed and operated several other stations during the next 2 or 3 years.

In 1886 he left the Edision Company and became connected with the C. & C. Electric Motor Company, which, with Charles G. Curtis and Francis B. Crocker, he helped to organize. They were the pioneer manufacturers of small electric motors.

In 1888 the firm of Crocker & Wheeler was organized, which shortly was incorporated as the Crocker-Wheeler Motor Company, of New York, and subsequently became the Crocker-Wheeler Company, of Ampere, N. J. Doctor Wheeler was the president of this concern from 1888 until the time of his death in 1923. During the many years that he was active head of the company, he was particularly prominent in development of the electric motor and its application to machine tool drives.

Doctor Wheeler was electrical expert for the Board of Electrical Control of New York from 1888 until 1895. He was the inventor of many electrical and mechanical devices, such as the electric elevator, electric fire engine, series multiple motor control, and paralleling of dynamos. In 1904 he received the John Scott Medal of the Franklin Institute for the invention of the electric fan in 1886. Doctor Wheeler was 1 of the 9 incorporators of the United Engineering Society in May 1904, being 1 of the 3 representatives of the Institute. The Latimer Clark Library, which Doctor Wheeler purchased in London in 1900 had been owned by the late Latimer Clark and was the largest collection of rare electrical works in existence. Doctor Wheeler presented this library to the Institute, thus forming the foundation of the electrical section of the large library now housed in the Engineering Societies Building in New York.

It was from the presidential address of Doctor Wheeler in Milwaukee in 1906 that the ideas were taken for the "code of ethics" for electrical engineers finally adopted by the Institute's board of directors in 1912. Among the many committees on which he served was the committee on code of principles of professional conduct of which he was chairman at the time of his death. Doctor Wheeler had served the Institute as manager from 1887 until 1904, and also in 1904–05; he had served 3 years as a vice-president.

Samuel Sheldon

(A '90, M '91, F '13, Life Member

President 1906–07

ONE OF the foremost educators in the engineering profession, Dr. Samuel Sheldon, was enthusiastic in his devotion to the advancement of the electrical engineering profession, and in his unbounded faith in the future importance of the Institute. His unfailing support of every movement looking to the logical position of the Institute as the exponent of the highest standards of the electrical art, marked his development as a leader, not only with confidence in himself, but thoroughly appreciative of the work of his associates.

Doctor Sheldon was born in Middlebury, Vt., on March 8, 1862, graduating from Middlebury College in 1883, and remaining there 2 years as instructor in mathematics; he received the degree of A.M. there in 1886. In 1888 he received the degree of Ph.D. at Wurzburg, Germany. During part of this time he was associated with Kohlrausch, the distinguished physicist, in the determination of the ohm as a unit of electric resistance. He was awarded the honorary degree of doctor of science from the University of Pennsylvania in 1906, and from Middlebury College in 1911.

Doctor Sheldon went to the Polytechnic Institute of Brooklyn, N. Y., in 1889, after a year spent at Harvard University as instructor of physics, and was immediately honored with a full professorship in physics and electrical engineering in the newly organized department of electrical engineering. Although only 27 years old, he had a thorough command of his subjects, together with enthusiasm and energy, which he exhibited in the lecture rooms. In addition to having an analytical mind, he had an inspiring and sympathetic personality, which made him valued as a teacher. Under his supervision the shop, mechanical engineering, physical and electrical engineering laboratories were installed. Illness in 1909 necessitated a long vacation which he spent mostly in Europe, where he had an opportunity to visit the principal engineering schools. He returned to the Polytechnic Institute of Brooklyn, and was professor of physics and electrical engineering until the time of his death, September 4, 1920.

Doctor Sheldon was frequently called upon to give testimony in both the state and federal courts, and for many years following 1903 was an expert of the Swiss Department of Justice and Police. He also carried on an extensive consulting engineering practice in all branches of engineering.

He served the Institute as manager for 6 years, and vice-president for 2 years, in addition to holding the presidency. He had been chairman of the papers committee, 1902–06; chairman of the standards committee, 1907–08; chairman of the library committee for a number of years following 1910, besides serving on various other committees.

Dr. Sheldon was a past-president of the New York Electrical Society and a member or fellow of a number of other technical and scientific societies. He was the author and joint author of several college text books, had written a number of papers on various topics, and contributed extensively to encyclopedias and engineering handbooks. For several years following 1900 he was editorial critic for a publisher of technical books.

Henry G. Stott

(A '95, M '96, F '12)

President 1907–08

HENRY GORDON STOTT was for many years active in the design, construction, and operation of the power systems supplying subway, elevated, and surface lines of New York City. He was also a firm believer in coöperation among engineers, through the agency of engineering societies, and devoted much of his time and ability to the welfare and development of these professional organizations.

He was born at Stennis, in the Orkney Islands, Scotland, May 13, 1866. After preliminary study he was a student at the Watson Collegiate School, Edinburgh, and then entered the college of Arts and Sciences at Glasgow, graduating in 1885 from a course in mechanical engineering and electricity. In the previous year he had entered the employ of the Electric Illuminating Company of Glasgow. Upon graduation he was assistant electrician on the S.S. "Minia," belonging to the Anglo-American Telegraph Company, and for $4^1/_2$ years saw much service in connection with repairs to telegraph cable lines.

In 1889 Mr. Stott was made assistant engineer of the Brush Electric Engineering Company plant at Bournemouth, England. The following year he became assistant engineer in the construction of underground cable and power plants at Madrid, Spain, for Hammond and Company.

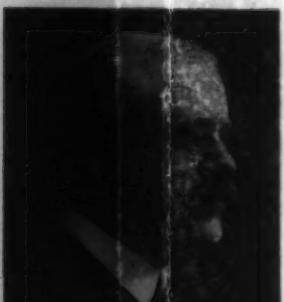
In 1891 he came to the United States to install an underground cable and conduit system at Buffalo, N. Y., for what was then the Buffalo Light and Power Company, becoming engineer of the company shortly thereafter. From that time until 1901 he was one of the most active figures in the industrial progress of Buffalo.

In 1901 he was appointed superintendent of motive power for the company which later became the Interborough Rapid Transit Company, of New York City. Before starting actual work, it was necessary for him to organize an operating force. In 1904 he undertook the construction of a power plant for the Interborough Rapid Transit Company, and from that time until his death on January 15, 1917, he was in charge of the design, construction, and operation of the power generating stations and the distributing system of the Interborough.

Mr. Stott served the Institute as a member of the board of directors for 3 years preceding his presidency, and was a member of a number of the Institute's committees. He served as a vice-president of The American Society of Mechanical Engineers, 1912–14, director of the American Society of Civil Engineers, 1911, and was vice-president and trustee of United Engineering Society at the time of his death.

Mr. Stott was known for his minute analysis of engineering problems, and he had passed his information on to others through the presenting of a number of papers before the Institute and other societies.

Mr. Stott was a remarkable figure in the engineering world because he was in the front rank of both electrical and mechanical engineers, because in both branches of the art, he was a master of theory and practice, and because with these technical qualifications he combined a rare executive ability, a power of inspiring the confidence of his employees and of bringing out the best that was in the men who worked for him.



Louis A. F

(A'09, M'1

President T

THE life of Louis Alovius Ferguson has been intimately connected with the tremendous growth of the electric light and power industry. When he entered the service of the Chicago Edison Company, now the Commonwealth Edison Company, Chicago, the original Adams Street station

of this company with
condensing engines and
was just nearing comp
Ferguson is vice-presid
and its combined ge
over 1,000,000 kw.

Mr. Ferguson was
Mass., August 19,
graduated from the
course at Massachusett
nology, Cambridge, w
From there he went di
ground distribution
Chicago Edison Compa

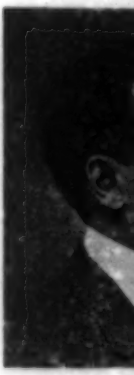
In 1890 he was app
fner in charge of all
and electrical constru
company. Three years
in addition, the superv
and contract work, in
especially successful i
tiations with large mer
establishments. In 18
general superintendent
Electric Company and
the same position in

Lewis B. Stillwell

(A'92, M'92, F'12, member for life)

President 1909–10

Lamme Medalist 1933



THE INSTITUTE'S Lamme Medal for 1933 is to be presented at the 1934 summer convention to Dr. Lewis Buckley Stillwell "for his distinguished career in connection with the design, installation, and operation of electrical machinery and equipment." This distinguished career extends over a period of nearly 50 years and includes not only the development of a number of pieces of electrical equipment used in the early days of the industry, but the supervision of an impressive list of modern installations, particularly in railway electrification.

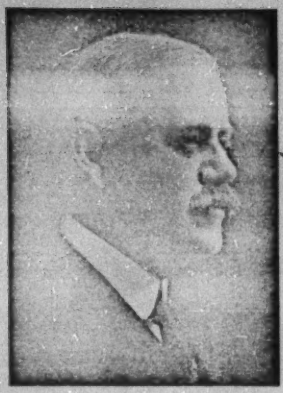
Doctor Stillwell was born at Scranton, Pa., in 1863. He was a student in the Latin scientific course at Wesleyan University, Middletown, Conn., 1883–84, and took a special course in electrical engineering at Lehigh University, Bethlehem, Pa. In 1885 he received the degree of electrical engineer from Lehigh University. He also has received the honorary degrees of master of science, Lehigh University, 1907; doctor of science, Wesleyan University, 1907; and doctor of science, Lehigh University, 1914.

From 1886 to 1891, he was employed as assistant electrician of the Westinghouse Electric and Manufacturing Company, and served as chief electrical engineer of that company from 1891 to 1897. He was an outstanding leader in the development of alternating current, and invented the "Stillwell regulator" for the adjustment

of voltage on outgoing
inventions which he mad
are more important, a
circuit breaker" and t
pilot-control switchboard

His contributions as
neer, to the general layou
first plant of the Nia
Company led to his ap
trical director of the
which position he held fr

Doctor Stillwell began
consulting engineer in N
1900, and has filled



Louis A. Ferguson

(A'01, M'04, F'12)

President 1908–09

THE life of Louis Aloysius Ferguson has been intimately connected with the tremendous growth of the electric light and power industry. When he entered the service of the Chicago Edison Company, now the Commonwealth Edison Company, Chicago, the original Adams Street station of this company with its 4 200-hp noncondensing engines and belted d-c generators was just nearing completion. Today, Mr. Ferguson is vice-president of the company, and its combined generating capacity is over 1,000,000 kw.

Mr. Ferguson was born in Dorchester, Mass., August 19, 1867. In 1888 he graduated from the electrical engineering course at Massachusetts Institute of Technology, Cambridge, with the degree of B.S. From there he went directly to the underground distribution department of the Chicago Edison Company.

In 1890 he was appointed electrical engineer in charge of all electrical engineering and electrical construction work of the company. Three years later he undertook, in addition, the supervision of all soliciting and contract work, in which field he was especially successful in conducting negotiations with large mercantile and industrial establishments. In 1897 he was appointed general superintendent of the Chicago Electric Company and a year later was given the same position in the Commonwealth Edison Company; supervision of the operating departments of the company was added to his duties. In 1902 he was elected second vice-president of both companies, in charge of contracts, operating, construction, and electrical departments. In 1907 he was elected second vice-president of the Commonwealth Edison Company, and since 1914 has been vice-president of this company.

Mr. Ferguson early recommended adoption of the 3-phase a-c system of transmission to substations, with rotary conversion to direct current for general distribution. He has made notable contributions to the development of low voltage distribution. He has kept in close touch with European engineering developments through frequent trips and has applied his findings to the Chicago system. Also, he has much to do with the development of rate structures as used in the United States.

Mr. Ferguson has served the Institute as manager, 1904–07, vice-president 1907–08, and as president. He also has been a member of the Edison Medal committee, board of award of the John Fritz medal, the committee of the Washington Award, and chairman of the executive committee. He is a past-president of the former National Electric Light Association and of the Association of Edison Illuminating Companies.

Lewis B. Stillwell

(A'92, M'92, F'12, member for life)

President 1909–10

Lamme Medalist 1933

THE INSTITUTE'S Lamme Medal for 1933 is to be presented at the 1934 summer convention to Dr. Lewis Buckley Stillwell "for his distinguished career in connection with the design, installation, and operation of electrical machinery and equipment." This distinguished career extends over a period of nearly 50 years, and includes not only the development of a number of pieces of electrical equipment used in the early days of the industry, but the supervision of an impressive list of modern installations, particularly in railway electrification.

Doctor Stillwell was born at Scranton, Pa., in 1863. He was a student in the Latin scientific course at Wesleyan University, Middletown, Conn., 1882–84, and took a special course in electrical engineering at Lehigh University, Bethlehem, Pa. In 1885 he received the degree of electrical engineer from Lehigh University. He also has received the honorary degrees of master of science, Lehigh University, 1907; doctor of science, Wesleyan University, 1907; and doctor of science, Lehigh University, 1914.

From 1886 to 1891, he was employed as assistant electrician of the Westinghouse Electric and Manufacturing Company, and served as chief electrical engineer of that company from 1891 to 1897. He was an outstanding leader in the development of alternating current, and invented the "Stillwell regulator" for the adjustment of voltage on outgoing lines. Two other inventions which he made and which today are more important, are the "time limit circuit breaker" and the "diagrammatic pilot-control switchboard."

His contributions, as Westinghouse engineer, to the general layout and design of the first plant of the Niagara Falls Power Company led to his appointment as electrical director of the latter company, which position he held from 1897 to 1900.

Doctor Stillwell began his practice as a consulting engineer in New York City in 1900, and has filled engagements with many companies on large and important engineering projects, including: the electrification of the elevated lines of the Manhattan Elevated Railway Company, 1900–06; Rapid Transit Subway Construction Company, 1900–09; Wilkes-Barre and Hazleton Railway, 1902–05; Hudson and Manhattan Railroad, 1905–13; Erie Railroad electrification, 1906; United Railways and Electric Company of Baltimore, Md., 1906–20; Interborough Rapid Transit Company, 1909–20; electrification of the Hoosac Tunnel of the New York, New Haven and Hartford Railway Company, 1910–11; New York, Westchester and Boston Railway Company, 1911–15; Lehigh Coal and Navigation Company, 1912–18; New York Municipal Railway Corporation, 1913–16; board of economics and engineering of the National Association of Owners of Railroad Securities, 1921–22; Holland vehicular tunnel, 1924–27; and Port of New York Authority since 1927.

Doctor Stillwell has served on many of the most important Institute committees, including the executive, code of principles of professional conduct, public policy (now Institute policy) Edison medal, standards, and board of examiners. He also has represented the Institute on the assembly of the American Engineering Council, the Engineering Foundation Board, John Fritz Medal board of award, and the coördination committee of engineering societies. He was a director of the Institute 1896–99, a vice-president 1899–1901, and the president 1909–10. He was vice-president of the American Engineering Council for 4 years, 1930–33, inclusive. He is the author of several important Institute papers. Doctor Stillwell has received a number of awards.

Dugald C. Jackson

(A'87, M'90, F'12, member for life)

President 1910–11

THROUGHOUT almost the entire history of the Institute, Dugald Caleb Jackson has been an active member of the profession, as an engineering educator and as consulting engineer.

He was born at Kennett Square, Pa., February 13, 1865. In 1885, one year after the founding of the Institute, he graduated from Pennsylvania State College with the degree of C.E. He then devoted 2 years to postgraduate study in electrical engineering at Cornell College, serving as instructor in physics in 1887.

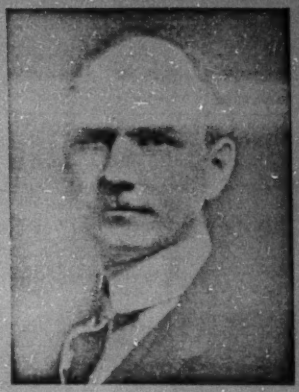
For the next 2 years he was vice-president and engineer for the Western Engineering Company at Lincoln, Neb., engaged in the design and construction of electric light and power plants and distribution systems in that part of the country. Throughout the years 1889–90 he served as assistant chief engineer with the Sprague Electric Railway and Motor Company, at New York, and for the following year was chief engineer of the central district of what was then the Edison General Electric Company. In these 2 positions he supervised the design and construction of many electric railway and power plants.

In 1891 he became a member of the firm of D. C. and Wm. B. Jackson, consulting engineers; also professor of electrical engineering at the University of Wisconsin. He remained at Wisconsin for 16 years, developing the department of electrical engineering, until, in 1907, he became professor of electrical engineering at the Massachusetts Institute of Technology, and head of its electrical engineering department. Professor Jackson still holds this position.

Professor Jackson continued as a member of the firm of D. C. and Wm. B. Jackson, until the firm of Jackson and Moreland was formed shortly after the War. He continued as the senior member until 1930. The firm has been particularly active in railway electrification.

Professor Jackson has given freely of his time to the Institute, having served on 16 of its committees, chairman of 3 of these, and a representative of the Institute on 3 other groups. He was vice-president 1897–99, and president.

During the World War, Professor Jackson served overseas as Lieut.-Col. of Engineers. He was a member of jury of electrical awards at the World's Columbian Exposition, Chicago, 1893, and at the Pan-American Exposition, Buffalo, 1901. In 1929 he was U.S. Government delegation to the World Engineering Congress. He is a chevalier of the French Legion of Honor. He is a past-president of the Society for Promotion of Engineering Education (recipient of its 1931 Lamme Medal), and of the Boston Society of Civil Engineers, as well as being a member or fellow of a number of other technical societies in this and other countries. He is the inventor of a number of electrical devices, as well as author of many technical papers and books on engineering subjects and on engineering education.



Gano Dunn

(A'91, M'94, F'12, Life Member)

President 1911–12

STRAIGHT thinking, combined with a sympathetic nature and a charming personality, has done much to account for the leadership of Gano Dunn. As an engineer he has made many original contributions to electrical design and application. As an executive he has led organizations with resourcefulness. In addition, he has given freely of his time to Institute activities in order that greater progress could be made by the entire profession.

Mr. Dunn was born in New York City, October 18, 1870. He attended the College of the City of New York, from which he graduated with the B.S. degree in 1889; he also received the degree of M.S. from that institution in 1897. In 1891 he received the E.E. degree from Columbia University, and the honorary M.S. degree from Columbia in 1914.

His professional work began in 1886, in the service of the Western Union Telegraph Company, where he remained 5 years. He then entered the service of the Crocker-Wheeler Company at Ampere, N. J., and from 1898 until 1911 was vice-president and chief engineer of that company. In the latter year he was elected vice-president in charge of engineering and construction of J. G. White & Company, and in 1913, when the J. G. White Engineering Company was organized to take over the engineering and construction work of the parent company, Mr. Dunn was made president, which position he still holds.

While with the Crocker-Wheeler Co., Mr. Dunn did much to build up this company from a small organization to a large manufacturing concern. Also, many patents were granted him on generators, motors, rheostats, switches, and on systems of operation, control, and regulation. Since joining J. G. White & Co. in 1911, he had been responsible for the design, construction, and operation of many public utility properties, including hydroelectric developments, central lighting and power stations, electric and steam railways, and other services throughout the world.

Mr. Dunn is the author of numerous papers on engineering subjects. He has served the Institute on 12 of its committees and has been the Institute's representative on 9 other bodies. He has also served as manager 1897–1900 and 1902–05; and as vice-president 1900–02 and 1905–07.

From 1900–02, Mr. Dunn was president of the New York Electrical Society. He was president of the United Engineering Societies from 1913 to 1916; of the John Fritz Medal Board of Award in 1914; the Engineering Foundation 1915–16, and vice-chairman of the National Research Council 1917, afterward becoming chairman.

He was secretary of electric lighting and distribution for the International Electrical Congress, St. Louis, 1904, and vice-president of the International Congress at Turin, 1911. In 1916–18 he was a member of the engineering committee of the Council of National Defence, and during the war was chairman of the State department committee on submarine cables.

Among the numerous engineering and scientific societies of which Mr. Dunn is a member are the Franklin Institute, American Society of Civil Engineers, The American Society of Mechanical Engineers, Institution of Electrical Engineers (Great Britain), and the Institute of Radio Engineers.

Ralph D. Mershon

(A '95, A '96, M '12, member for life)

President 1912–13

THE outstanding engineering contributions of Ralph Davenport Mershon have been in the field of high voltage transmission, of which he was one of the pioneers some 40 years ago. Since that time he has been responsible for the design and construction of many important generating stations, transmission lines, and substations in different parts of the world.

Mr. Mershon was born in Zanesville, Ohio, July 14, 1868. At the age of 17 he was engaged in railway location and construction for one year. Entering Ohio State University, he graduated in 1890 with the degree of M.E. He was student assistant in physics and electrical engineering during his senior year, and for one year following graduation was assistant instructor in electrical engineering.

During the period of 1891–1900, he was employed by the Westinghouse Electric and Manufacturing Company at East Pittsburgh, Pa., securing experience in all branches of electrical work. The transformers for which the Westinghouse Company received an award at the World's Columbian Exposition, Chicago, 1893, were of his design. In 1896–97 he was in charge of investigations of phenomena which occur between conductors at high voltages, for the Telluride (Colo.) Power Transmission Company and the Westinghouse Company. These original investigations of ionization and other atmospheric losses were of great importance at that time, and were carried up to 133,000 volts. On a leave of absence from the Westinghouse Company in 1897–98, he was chief engineer for the Colorado Electric Power Company. During 1898–1900, Mr. Mershon was engineer in the New York Office of the Westinghouse company, resigning in 1900 to enter the private practice of consulting electrical and mechanical engineer in New York City, in which capacity he is still active. He has designed and supervised many power plants and transmission systems in the United States, Canada, South Africa, and Japan.

Mr. Mershon has to his credit many inventions, which include the 6-phase rotary converter, the compounded rotary converter, systems of lightning protection for electrical apparatus, and a compensating voltmeter for which he was awarded the John Scott medal of the city of Philadelphia.

Prior to the war, Mr. Mershon was active in the creation of the reserve officers' training corps, and was made a major in this corps in 1917. During the war he was detailed to the Naval Consulting Board, and was Lieut.-Col. of Engineers at the time of his retirement from military service.

Mr. Mershon has served on a number of the Institute's committees, and was manager 1900–03, vice-president 1903–05, and later president. He is a member of other technical societies in the United States, Canada, and England, and is a past-president of the Inventors' Guild. Since 1895, he has been the author of a number of technical papers of importance to the industry. A paper presented in 1897 contained a chart for transmission line calculations, for which he has become widely known. In 1918 Tufts College presented him with the honorary degree of doctor of science.

C. O. Mailloux

(A '84, M '84, F '12, Life Member)

President 1913–14

CYPRIEN O'Dillon Mailloux, a charter member of the Institute and active in its affairs until his death, October 4, 1932, was among that group of pioneers in the industry which laid the foundations of electrical engineering practice and followed its development closely up to recent years.

Doctor Mailloux was born at Lowell, Mass., in 1860. At an early age he went to New York City where, in pursuit of professional learning, he was one of the leading pupils of Dr. M. I. Pupin, at that time a lecturer on advanced theory of electrical engineering at Columbia University.

Following graduation, Doctor Mailloux entered upon his career as a consulting electrical engineer, continuing in this capacity until his death. His application for transfer to the grade of Fellow in 1912 gives some idea of the remarkable range of his activities. This application states that in the preceding period of 25 years he had the direction of electrical work in over 800 jobs, ranging from 50 to 25,000 kw or more, including special design of apparatus and machinery in hundreds of cases, and that he had made at least 100 original inventions, over 30 of which had been patented. It also was stated that he had done expert work, and submitted testimony, reports, and arbitrations in over 1,000 cases, and had published several dozen original papers and articles.

In addition to having been president, Doctor Mailloux served the Institute as manager 1886–89, 1905–07, and 1899–1902. He also had served as vice-president 1898–99 and 1902–04. He had served on 5 of the Institute's committees, and been a representative of the Institute on 3 other bodies.

Doctor Mailloux was particularly active on the International Electrotechnical Commission, and on the U.S. national committee of this organization. For the U.S. national committee of the I.E.C. he had served as president 1914–24, chairman of the advisors on nomenclature, representative of the National Research Council on the division of foreign relations, and honorary president. For the I.E.C., he had been president 1919–23, director of the secretariat on nomenclature, and at the time of his death, honorary president. For the international conference on large electric high-tension systems, he had served as honorary president, acting also as United States delegate at recent biennial meetings.

Doctor Mailloux had been a chevalier of the French Legion of Honor. He also had received honors in this country, included in which was the degree of D.Sc., from Lehigh University in 1914.

Doctor Mailloux was a former editor of the *Electrical World*, having served during the early part of his career, and continued to be a liberal contributor to technical literature throughout his life. Largely through his efforts the electrical engineering nucleus of the present Engineering Society's library in New York had its origin. In 1903–04, he donated several volumes and subscriptions to technical periodicals to the library.

He had been for many years an advocate of the use of a universal language to standardize technical terms throughout the world.

Paul M. Lincoln

(A'95, M'98, F'12, member for life)

President 1914–15

ONE of the most prominent engineers and educators in the electrical engineering industry is Paul Martyn Lincoln, director of the school of electrical engineering at Cornell University.

He was born in Norwood, Mich., January 1, 1870, and was educated at Western Reserve and at Ohio State universities, receiving from the latter the M.E. degree in electrical engineering in 1892. He was employed first as testing electrician by the Brush Electric Company, doing some drafting later. The next year, in 1893, he went to the Pittsburgh plant of the Westinghouse Electric and Manufacturing Company, where he took the training course of the company. In 1895 he was chosen for the position of electrical superintendent in charge of water power development of Niagara Falls. Hydroelectric development was in the early stages then, and the amount of power generated, transmitted, and distributed by this first plant was so far in excess of anything accomplished up to that date that it was unique; Mr. Lincoln's responsibilities were considerable as he had charge of the operating department. In 1902 he returned to Westinghouse in Pittsburgh and was in charge of the power division of the engineering department for 6 years. He was appointed general engineer for the company in 1910, holding that position until 1919. At that time he resigned from his position with Westinghouse to join the firm of his older brother, the Lincoln Electric Company, as consulting engineer. From 1911 to 1915 he was head of the electrical school at the University of Pittsburgh, and from 1922 to date he has been director of the school of engineering at Cornell University.

In 1902 he received the John Scott medal award from the City of Philadelphia, upon the recommendation of the Franklin Institute, for his invention of the synchroscope, a device now in universal use wherever a-c machines are paralleled.

Mr. Lincoln has served the Institute as manager (1906–09) and as vice-president (1909–11). He has been very active on Institute committees, serving on the papers, and meetings and papers (now technical program) committees, on the executive, Sections and law committees, and on many technical committees, as, power stations, protective devices, transmission and distribution, electrical machinery, standards, instruments and measurements, etc. He has served on the board of award of the John Fritz medal, and at present is serving on the Edison and Lamme medal committees. He was a member of the board of management of the World's Congress of Engineers, 1923–25. He is a member of several scientific and engineering societies in the United States.

John J. Carty

(A'90, M'03, F'13, member for life)

President 1915–16
Honorary Member 1928
Edison Medalist 1917
John Fritz Medalist 1928

BECAUSE of his innumerable contributions to the art of telephony, John Joseph Carty ranked from the pioneer days of the telephone until his death in 1932 as one of the world's foremost telephone engineers. He was a prolific inventor and a skilful organizer of the inventive genius of others. Three of his early achievements are fundamental and necessary today: the invention of the "common battery," development of the high resistance bridging signal bell for subscribers' substations, and the discovery that the principal cause of cross interference between telephone circuits was electrostatic rather than electromagnetic unbalance. The accomplishments of his later life and for which he is best known in the field of electrical communication are those of a generalissimo—the organization and direction of long distance telephony over land, transoceanic radio telephony and coördination of the maze of factors which make telephony today so marvelously easy.

General Carty was born in Cambridge, Mass., April 14, 1861. He was obliged to forego a formal higher education because of a temporary impairment of vision. His tremendous knowledge he secured through original research, experience, scientific reading and, as he expressed it, "asking questions." In 1879, when he was 18 he entered the employ of the Telephone Dispatch Company of Boston. There he designed and installed the first metallic circuit multiple switchboard to be put into service.

In 1887 he was transferred to New York and placed in charge of cable manufacturing for the Western Electric Company in the East and later in charge of switchboard development and manufacture, making a number of improvements in the design and installation of cables and switchboards.

Two years later he went to the New York Telephone Company as electrician; later he became chief engineer. Under his direction the New York City telephone plant was converted from open wire to cable, and from the local battery switchboard system to the common battery system.

He was chief engineer of the American Telephone and Telegraph Company from 1906 to 1909, when he was elected vice-president. He consolidated all the laboratories and experimental work into a single organization known now as the Bell Telephone Laboratories. Under his leadership the transcontinental telephone line was completed in 1915; a successful demonstration of wireless telephony was made and the underground cable system from Washington to Boston was completed. In 1925 he became chairman of the board of directors of the organization, retiring in 1930, about 2 years before his death on December 27, 1932.

When the United States entered the war General Carty was a major in the signal corps reserve; he organized the research and inspection division for the chief signal officer of the American Expeditionary Forces. He was responsible for the maintenance of transatlantic communication between General Pershing and Washington and directed the construction of a long distance telephone system covering most of France. In 1918 he was promoted to colonel and ordered to France as chief signal officer. After the Armistice he was placed in charge of communications for the American Commission to Negotiate Peace. Later he was made Brigadier General and still later, General. He received the Cross of the Legion of Honor of France.

H. W. Buck

(A'95, M'01, F'12, member for life)

President 1916–17

THE engineering achievements of Harold Winthrop Buck have been principally in the field of construction of public utility properties. As an electrical engineer in charge of design and construction, in the earlier period of his career, and more recently as an executive of the corporation of Viele, Blackwell and Buck, consulting engineers, New York City, he has been identified with many important enterprises in the development of electric power.

Mr. Buck was born in New York City, May 7, 1873. In 1894 he graduated from Yale University with the degree of Ph.B., and received the degree of E.E. from Columbia School of Mines in 1895. The year 1895–96 was spent as a student in the shops of the General Electric Company at Schenectady, N. Y., most of this time being spent on experimental work on a-c apparatus for Dr. C. P. Steinmetz.

From 1896 to 1900, Mr. Buck was assistant to the chief engineer of the lighting department of the General Electric Company, Schenectady, in which capacity he had much to do with the introduction of high-voltage a-c distribution in many parts of the United States. During that same period, he also had charge of much experimental work leading to the development of the oil circuit breaker and other high-voltage devices.

In 1900 he was chosen chief electrical engineer of the Niagara Falls Power Company and allied interests at Niagara, having entire charge of electrical engineering in the design and construction of power house No. 2 on the American side of the Falls, and the Canadian Niagara Power Company's plant on the Canadian side; also the terminal stations at Buffalo, and engineering in connection with the distribution of power in Niagara, Tonawanda, and Buffalo.

In 1906, in coöperation with E. M. Hewett, at Niagara Falls, Mr. Buck carried on experimental work on high voltage insulators which had much to do with the development of the suspension insulators now in universal use.

Since 1908 Mr. Buck has been vice-president of Viele, Blackwell and Buck, engaged in the design and construction of hydroelectric and steam power plants and of transmission systems in the United States and Canada. In 1925 the International Commission made him consulting engineer on the investigation of the development of some 4,000,000 hp at various sites on the St. Lawrence River between Ogdensburg and Montreal.

Mr. Buck has presented a number of papers before the Institute and other organizations. In addition to serving the Institute as president, he was manager 1907–10, and vice-president 1910–12. He has served on 7 of the Institute committees, as well as having been its representative on 3 other organizations. His longest term of service was on the Institute's committee on public policy (now Institute policy) on which he served continuously from 1914 to 1929, with the exception of one year. Mr. Buck is a member of the Franklin Institute, the American Electrochemical Society, and the Engineering Institute of Canada.

E. W. Rice, Jr.

(A'87, M'88, F'13, member for life)

President 1917–18

Honorary Member 1933

Edison Medalist 1931

FOR "his contribution to the development of electrical systems and apparatus, and for his encouragement of scientific research in industry," the Institute's Edison Medal for 1931 was presented to Dr. Edwin Wilber Rice, Jr. Doctor Rice is one of the pioneers in electrical development in the United States, and has played a conspicuous part in the building up of the General Electric Company, of which he is now honorary chairman of the board.

He was born at La Crosse, Wis., May 6, 1862. As a school boy in Philadelphia, he came in contact in 1876 with Prof. Elihu Thomson, then a young teacher in the Boys' Central High School. When, in 1880, Professor Thomson gave up teaching to go into electrical manufacturing as scientist and inventor, young Rice gladly accepted the opportunity to become his assistant.

He went with Thomson to New Britain, Conn., in the old American Electric Company, and in 1883 went with the professor to Lynn, Mass., upon the organization of the Thomson-Houston Electric Company. At the age of 22 he was made plant superintendent and had full responsibility until the consolidation of the Thomson-Houston Electric Company and the Edison General Electric Company in 1892, under the name of the General Electric Company

In the new company, Doctor Rice was first made technical director, then vice-president in charge of manufacturing and engineering. He eventually became senior vice-president, and, in 1913, he succeeded Charles A. Coffin as president of the company. In 1922, after 9 years' service in that office, he was succeeded by Girard Swope. Doctor Rice at that time was made honorary chairman of the board, which position he still holds.

He has contributed much, through organization methods, improved factory routine, technical development, and engineering and scientific inventions, to the preëminence attained by the General Electric Company.

His degrees are: honorary A.M., Harvard, 1903; Sc.D., Union College, 1906; doctor of engineering, Rensselaer Polytechnic Institute, 1917; Sc.D., University of Pennsylvania, 1924. Doctor Rice is a chevalier of the Legion of Honor of France. In 1917 he was decorated by the Emperor of Japan with the Third Order of the Rising Sun with Cordon.

In addition to having been president, Doctor Rice has served the Institute on several committees, and been its representative on numerous other groups. He is now a member of the committee on economic status of the engineer, and a representative on the Hoover Medal board of award.

Doctor Rice has taken out over 100 patents, many of these being of great importance to the industry. He was one of the earliest to realize the advantages of scientific research, and it was primarily due to his foresight and guidance that the present research laboratories of the company were built up. In addition to his unusual engineering ability, his ability as a business executive is marked; having been in evidence even during the early years.

Comfort A. Adams

(A'94, M'05, F'13, member for life)

President 1918–19

AMONG the distinguished educators, research engineers, and technical writers on the practice and theory of electrical engineering of today, Comfort Avery Adams takes a prominent place. From his Chair at Harvard University, which he has occupied as Lawrence Professor of Engineering since 1914, he has always shown a keen interest in engineering education, emphasizing not the need for less theory, but for a thorough working foundation in theory. To his mind, the most important problem in the whole field of electrical engineering today is a more thorough understanding of dielectric phenomena in solid and semi-solid dielectrics. He has long been active in the electric welding field.

Professor Adams was born November 1, 1868, in Cleveland, Ohio, and was educated at the Case School of Applied Science His talent for teaching came to light early in his career, for he assisted Professor A. A. Michelson in the physical laboratory for 3 years during his course. In 1890 he was graduated with the B.S. degree. He was a member of the Reid expedition in Alaska during the summer and on his return to Cleveland in the fall he obtained a position as draftsman with the Brush Electric Company. Under Sidney S. Short he took part in the design of the first geerless railway motor. In 1891 he joined the teaching staff of Harvard with which he has been connected since, first as instructor, then as assistant professor (1896–06), professor (1906–16), Lawrence professor of engineering since 1914, dean of the engineering school (1919–21). In 1905 he took the E.E. degree from the graduate school and in 1925 the university bestowed upon him the honorary degree of doctor of engineering.

Professor Adams has carried on an extensive consulting practice, acting at present as consultant for the American Tool and Machine Company of Boston, Okonite Company, Okonite Callender Cable Company, Babcock and Wilcox, and General Electric. He has conducted numerous investigations on a-c commutating machines, leakage reactance of induction motors, etc.

He has served the Institute as manager (1912–15), vice-president (1915–17), and has participated in the activities of many important committees, as chairman and member at various times of the executive committee and the committees on public policy (now Institute policy), code of professional conduct, research, education, and electric machinery. He is now serving on the standards and electric welding committees. He has been active also in the coöperation movement of the engineering societies, taken part in the organization of what is now the American Standards Association, acting as its first chairman. He reorganized the engineering division of the National Research Council after the war, is a charter member of the American Engineering Council and took part in the organization of its predecessor, the Federated American Engineering Societies. He has represented the Institute as member and president of the John Fritz medal award board and served on Edison medal committee.

During the war Professor Adams served as chairman of the general engineering committee of the Edison Commission of the Council of National Defense; chairman of the welding committee of the Emergency Fleet Corporation, and chairman of the electrical engineering section of the National Research Council.

Calvert Townley

(A'01, M'07, F'12)

President 1919–20

AN UNUSUAL combination of engineering skill and managerial ability from the commercial standpoint made Calvert Townley one of the most conspicuous engineers in the railroad and utilities fields. He was a capable technical adviser, executive, and a very able engineer in the practical work of design, construction, and equipment.

He was born in Cincinnati, Ohio, October 18, 1864, and was graduated from the Sheffield Scientific School of Yale with the degree Ph.B. in 1886 and M.E. in 1888. For a short time Mr. Townley worked on the rebuilding of the central lighting station of the Brush Electric Company of Cincinnati. During most of the period from 1887 to the time of his retirement in 1931, he was connected with the Westinghouse interests in various positions. He was erecting engineer in office charge of the design of electric lighting distribution systems (1887), commercial executive (1888–95), manager for the Boston branch (1895–97; 1898–1900) and also associated with the Pittsburgh group of engineers in installation and equipment work throughout the New England states. During this period he was connected with the electrical equipment of the South Terminal of Boston and of the elevated railway system, and the installation of the polyphase transmission system and city lighting system of the Hartford Electric Light Company. He was general agent for the Westinghouse interests in New York (1901–04) in charge of large transportation interests in and about the city; he was concerned with the equipment of the Brooklyn Rapid Transit, Interborough Rapid Transit, and New York City railway systems.

From 1904 to 1911 he was associated with the New York, New Haven, and Hartford Railroad, in various executive capacities and as technical adviser. One of the important projects upon which he worked in both capacities was the electrification of the railroad's lines out of New York City. About this time the company began acquiring utility companies and Mr. Townley was appointed first vice-president of the holding company to manage their utilities as a side issue. The "side issue" reached such magnitude that after completing electrification plans and drawing specifications, Mr. Townley asked to be relieved of construction duties and became consulting engineer for the railroad in the management of utilities.

He returned to the Westinghouse Company in 1911 as assistant to the president, remaining in that position until 1931 when he retired. He died on November 27, 1933. He was also president of the Lackawanna and Wyoming Valley railroads, vice-president of the International Radio Telegraph Company and an officer and director of many other organizations. He was an active participant in Institute affairs, serving as manager (1905–8) and vice-president (1908–10) and as committeeman at various times.

Arthur W. Berresford

(A '94, M '05, F '14, member for life)

President 1920–21

IN THE field of electric motor control, Arthur William Berresford occupies an outstanding place. From observations made in early postgraduate days, Mr. Berresford became convinced that proper control devices would make possible extended use of electric motors and generators, and to the problems of construction and application he bent all his characteristic energy, inventiveness and ability to direct and coördinate the work of others.

He was born in 1872 in Brooklyn, and in 1892 graduated from Brooklyn Polytechnic College with the degree B.S. in electricity; the following year he received the degree M.E. in electricity from Cornell University. His first job was electrician for the Brooklyn City Railroad Co., overhauling motors and assisting in trolley line construction, etc. It was a small beginning, in his opinion, but very probably many of his ideas were forming which materialized later, as the next year, 1894, while employed in sales and installation work for the H. B. Coho Company, he carried on experimental work of a "private nature."

Then he was designer for the Riker Electric Company for about a year, going to the Ward-Leonard Electric Company in 1896 to take charge of the detail design of the apparatus and the testing of all material shipped. This company manufactured rheostats and electric controlling devices. In 1898 he organized his own manufacturing business with 2 associates, purchasing the defunct Iron Clad Rheostat Company and renaming it the Iron Clad Resistance Company. In 1900 he sold the concern to The Cutler-Hammer Manufacturing Co., entering the engineering department and becoming superintendent in 1901. Later he was made secretary and in 1905 general manager and vice-president.

In many problems, the rheostat as such plays merely an incidental part, and the knowledge, application, and devising of means for meeting the problems form by far the more important part, and in this phase of the work Mr. Berresford demonstrated his productiveness and ability as a shop manager and director as well as a designer. He was in charge of and responsible for the entire output of The Cutler-Hammer Co. and directly in touch with and responsible for the detail engineering and designing as well as manufacture of such intricate devices as have made possible hoisting and conveying machinery, electrically operated printing-presses, steel mill motors, elevators, etc.

During the war Mr. Berresford was chairman of the general war service committee of the electrical manufacturing industry. In 1926 he entered the field of electric refrigeration as vice-president of the Nizer Corporation of Detroit, which merged to form the Electric Refrigeration Corporation. Since 1929 he has been managing director of the National Electric Manufacturers' Association. He has given unstintingly of his time to Institute affairs, as manager (1909–12), vice-president (1912–14) and as committeeman. He is a member of other technical societies and the recipient of various medals and awards.

William McClellan

(A '04, M '09, F '12)

President 1921–22

A CASUAL glance over the record of the youth and young manhood of William McClellan would make it appear that he was destined for an academic life; as a matter of fact this academic experience formed an excellent basis for his later career as a prominent engineer and economist in the electric traction and public utilities fields.

He was born in Philadelphia in 1872 and graduated from high school at 17 years of age, taking a postgraduate course in electrical engineering the following year. He was an assistant in engineering for 1 year at Swarthmore college, and then taught mathematics and physics in the high schools of Philadelphia for 7 years. At the same time he studied at the University of Pennsylvania for the B.S. degree, which he received in 1900; in 1903 he received the Ph.D. degree. He was instructor in electricity and magnetism in the department of physics at the university from 1900 to 1905. A number of years later he returned to the university as dean of the Wharton School of Finance and Commerce, and in later years continued his connection with the university as director general of the alumni society and as trustee.

From 1900 to 1904 Doctor McClellan also worked in various capacities for the

Union Traction and Philadelphia Rapid Transit companies, some of his important assignments being the erection of a large car barn and the rebuilding of a large power house, including erection of engines, boilers, generators, motors, lighting switchboards, cables, etc. In 1905 he went to New York to do responsible design work for the Westinghouse Church, Kerr and Company on the lighting and power distribution for the Pennsylvania Railroad terminal. He also had charge of the layout and installation of a high-voltage substation and the car equipment for the Erie Railroad, and was design consultant of the Edison Illuminating plants at Brockton, Mass.

From 1907 to 1915 Doctor McClellan was vice-president of the Campion McClellan Company and was responsible for all the mechanical and electrical engineering, design, and construction handled. He drew up numerous reports on power plants and water power developments and took charge of the complete mechanical and electrical equipment and installations for various manufacturing plants. From 1915 to 1920 he was a member of the firm, Paine, McClellan and Campion. Between 1919 and 1921 he was vice-president of the Cleveland Electrical Illuminating Company. In 1922 he became a member of the firm of McClellan and Junkersfeld, remaining in this firm until, in 1929 he was elected vice-president of Stone and Webster Engineering Corporation. At present he is president of William McClellan and Company, Ltd., and of the Potomac Electric Power Company of Washington, D. C.

He was consulting engineer for the Public Service Commission of the 2nd district, New York State, from 1911–13 and a member of the President's commission on Muscle Shoals in 1925. During the war he was director of the intercollegiate intelligence bureau in Washington. He has served the Institute over a long period of years as officer and committeeman.

Frank B. Jewett

(A'03, M'10, F'12)

President 1922–23

Edison Medalist 1928

THE outstanding leader in the field of telephone research during the past 30 years is Dr. Frank Baldwin Jewett. Throughout this period he has been in active charge of the research work of the American Telephone and Telegraph Company and its affiliated organizations.

Doctor Jewett was born at Pasadena, Calif., September 5, 1879. In 1898 he graduated from Throop Polytechnic Institute (now the California Institute of Technology) at Pasadena, with the degree of B.A. In 1902 he received the degree of Ph.D. from the University of Chicago. Doctor Jewett then went to the Massachusetts Institute of Technology, Cambridge, where he continued study and was instructor in physics and electrical engineering.

In 1904, Doctor Jewett entered the employ of the American Telephone and Telegraph Company and was shortly thereafter given charge of its engineering research work. From 1908 to 1912, Doctor Jewett was transmission and protection engineer, responsible for the development of much equipment.

In 1912 he became assistant chief engineer of the Western Electric Company, and in 1916 was appointed chief engineer, having charge of the research laboratories of that company; 6 years later he became vice-president. During Doctor Jewett's association with this company, many of the most important advances in the field of communications were made.

In 1925 Doctor Jewett became vice-president of the American Telephone and Telegraph Company, in direct charge of the department of development and research (now combined with the Bell Telephone Laboratories, Inc.) and at the same time was elected president and a member of the board of directors of the Bell Telephone Laboratories, Inc., conducting the laboratory and research work formerly done by the engineering department of the Western Electric Company. He now holds these positions.

In 1917 Doctor Jewett was commissioned major in the Signal Corps, U.S. Reserves, and was later that year promoted to lieutenant-colonel in the Signal Corps of the regular Army. For his service during the war, he received the Distinguished Service Medal.

During 1915–18 Doctor Jewett was a manager of the Institute, a vice-president 1918–19, and president 1922–23. He has served on some 15 of the Institute's committees, and as its representative on 8 other bodies. He has presented many papers and articles before the Institute and other organizations. He has been active in The Engineering Foundation and the National Research Council.

Doctor Jewett is a term member of the Massachusetts Institute of Technology Corporation, and a member of the committee on Carnegie Institute of Technology. He has received several honorary degrees. The Fourth Order of the Rising Sun has been bestowed upon him by the Japanese Government.

Harris J. Ryan

(A'87, M'95, F'23, member for life

President 1923–24

Edison Medalist 1925

IN 1889, Dr. Harris Joseph Ryan presented before the Institute a paper on transformers, which was immediately recognized as a remarkable one, reaching into the future and exploring the unknown field of high-voltage phenomena. It is the continued exploration of high-voltage phenomena over a period of some 40 years that distinguishes the work of Doctor Ryan.

He was born at Powells Valley, Pa., January 8, 1866. When an electrical engineering course was first inaugurated at Cornell University in 1883, he entered, graduating in 1887 with the degree of M.E. in E.E. For the next 2 years he was associated with J. G. White & D. C. Jackson in general engineering practice at Lincoln, Neb., under the firm name of the Western Engineering Company. In 1889 he returned to Cornell to take charge of the electrical machinery laboratory, and since that time has been concerned principally with scientific research, although he has always been interested primarily in practical applications.

He then started the investigation of high voltages in the laboratory at Cornell, constructing under his supervision much of the equipment necessary. In 1890 he was chosen assistant professor in electrical engineering, and in 1895, when only 29 years of age, he was appointed professor in full charge of electrical engineering. For a number of years following 1900, he conducted important experiments on the cathode ray oscillograph.

In 1905 Doctor Ryan became head of the electrical engineering department at Stanford University, Calif. Doctor Ryan held this position continuously until 1931, when he retired from active teaching and executive duties. He is now professor emeritus of electrical engineering at Stanford, and honorary director of the Ryan research laboratory.

In the high-voltage laboratory built for him by Stanford University in 1913, much research was carried on which contributed to the present-day success of high-voltage transmission. The Harris J. Ryan high-tension laboratory at Stanford University built in 1926, stands as a fitting monument to the untiring energy and ability of the man whose name it bears.

Doctor Ryan has served the Institute on 11 of its committees, and has been its representative on other bodies. He was manager 1893–96, vice-president 1896–98, as well as president. He also has given his time to several other technical societies.

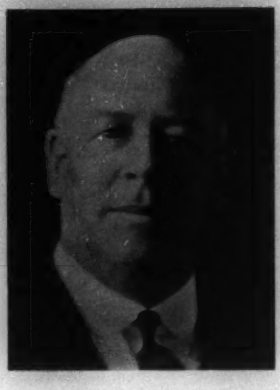
Doctor Ryan was director of the supersonics laboratory of the National Research Council, Pasadena, Calif., 1918–19. During 1909–23 he served as consulting engineer for the Los Angeles Aqueduct Power Bureau.

In 1925 the degree of LL.D. was conferred upon him by the University of California. He was judge, board of awards, at the World's Fair, Chicago, 1893; U.S. delegate to the International Electrical Congress, St. Louis, 1904; and member of the jury, Panama Pacific International Exposition, San Francisco, 1915.

Farley Osgood

(A'05, M'11, F'12)

President 1924–25



THE professional activities of Farley Osgood may be divided into 2 parts, the first of which, 14 years in length, was concerned with the telephone industry, and the second, 25 years in length, was concerned with the electric light and power industry.

Doctor Osgood was born at Chelsea, Mass., in 1874. In 1897, he graduated from a 6-year course at Massachusetts Institute of Technology, part of the time between 1894 and 1897 being spent in the engineering department of the American Bell Telephone Company at Boston.

Between 1897 and 1898, he was traveling engineer for the new England Telephone and Telegraph Company, covering their territory in Massachusetts, Maine, and New Hampshire, making inspections and installations. In 1898, he went to New Jersey with the New York and New Jersey Telephone Company, acting as chief clerk in the operating department, as special plant engineer, as confidential man to the vice-president, and as division manager, until 1904. In the latter year he became chief engineer and general manager of the new Milford (Conn.) Power Company. Here he had charge of the construction work for the company, and organized its operating forces.

The second phase of Doctor Osgood's career began in 1908, when he joined the organization of the Public Service Electric Corporation of New Jersey (now Public Service Electric and Gas Company) as general superintendent. In 1917, he became vice-president and general manager of this company, remaining in this position until 1924, when he retired to undertake private practice in New York as a consulting engineer. Doctor Osgood maintained this latter activity until his death October 6, 1933.

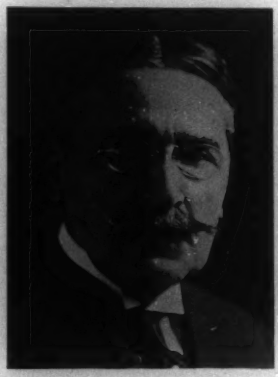
Doctor Osgood has served the Institute in many capacities, having been manager 1911–14, vice-president 1914–16, as well as president. He was chairman of the New York Section 1921–22, and has been a member of the following committees: Edison Medal, executive, finance, safety codes, standards, coördination of Institute activities, education, meetings and papers (now technical program), and Institute policy. He had also been the Institute's representative on many bodies, including the electrical committee of the National Fire Protection Association, the national joint committee on overhead and underground line construction, joint power factor committee, Charles A. Coffin fellowship and research fund committee, American Engineering Council, John Fritz Medal board of award, and the U.S. national committee of the International Electrotechnical Commission. He was a member of the New York Electrical Society and the former National Electric Light Association.

In 1925 he received the honorary degree of doctor of engineering from Rensselaer Polytechnic Institute.

M. I. Pupin

(A'90, F'15, member for life)

President 1925–26
Honorary Member 1928
Edison Medalist 1920
John Fritz Medalist 1932



THE career of Michael Idvorsky Pupin is one of the most unusual in the history of science, and it is indeed fortunate that because of his unusual ability as a writer, the story of this career has become known to thousands through his autobiography, "From Immigrant to Inventor."

Doctor Pupin was born at Idvor, Banat, Hungary, October 4, 1858. Displaying unusual talent at an early age, he was sent to Prague, Czecho-Slovakia, to prepare for higher education, but being attracted by America, ran away from Prague and came to New York in 1874. After having struggled to save sufficient funds, he entered Columbia College, graduating in 1883 with the degree of B.A. He afterward studied physics and mathematics at the University of Cambridge, England, and the University of Berlin, Germany, obtaining from the latter his Ph.D. in 1889.

Returning to America in the latter year, he became instructor of mathematical physics at Columbia University. In 1892, he became adjunct professor of mechanics, and in 1901 was appointed professor of electromechanics. He was appointed director of the Phoenix Research Laboratory of Columbia University in 1903, and retained this position as well as his professorship until 1929, when he retired from active service with the title of professor emeritus in active residence. Doctor Pupin now holds this latter position.

Doctor Pupin is widely known for his important inventions; his significant contributions to knowledge in a-c theory, the passage of electricity through gases, long distance communication, and many other scientific subjects; and his many publications.

Many of Doctor Pupin's inventions have proved to be commercially successful. Following several years' study, a patent for electrical tuning circuits was granted him, and sold to the Marconi Company in 1902. He was the first to produce an X-ray photograph in this country as a guide to surgical operations, and at that time, in 1896, he also invented a method of rapid X-ray photography. He also made the important discovery of secondary X-ray radiation.

One of his most outstanding contributions was the mathematical solution of electrical transmission over telephone wires with induction coils periodically recurring at specific points; this led to the construction of the so-called loaded telephone conductor now used for long-distance telephone communication. He made fundamental contributions in the rectification of waves.

His ability as a teacher is widely recognized, and many men who later became prominent were among his pupils.

In 1892–95, Doctor Pupin was a manager of the Institute, and a vice-president 1895–97, and 1901–03, and later president. He has served on many of its committees. He is a past-president of the Institute of Radio Engineers, past-chairman of The Engineering Foundation, and a member of many other societies. He has received the medal of honor of the Institute of Radio Engineers, 1924; Cresson Medal of the Franklin Institute, 1902; Prix Herbert, French Academy, 1916; Social Science Medal, 1920; Washington Award, 1928; as well as the John Fritz medal 1932, and the Institute's Edison medal, 1920. He has received some 18 honorary degrees.

C. C. Chesney

(A'94, M'99, F'13, member for life)

President 1926–27

Edison Medalist 1921

CUMMINGS C. Chesney is well known as a pioneer in designing a-c generators for high voltages and many other developments in a-c machinery and high power transmission. He has built up an enviable record as a designer, operating engineer and organizer, first receiving wide recognition as one of the developers of the S. K. C. (Stanley, Kelly, Chesney) apparatus. In 1921 he was awarded the Edison Medal for his early contributions to the development of a-c transmission.

He was born in Selingsgrove, Pa., October 28, 1863. He was graduated from Pennsylvania State College in 1885, and for 3 years taught mathematics and chemistry at the Doylestown (Pa.) Seminary. In 1888 he joined William Stanley's laboratory force at Great Barrington, Mass., working on experimental chemistry and electrodynamics, and the following year entered the services of the United States Electric Lighting Company in Newark.

In 1890 he moved to Pittsfield, Mass., and became a member of the Stanley Laboratory Company; in 1893 when the Stanley Electric Manufacturing Company was organized, he assumed the formal title of chief supervising and designing engineer and the position of first vice-president. In these capacities he was largely responsible for the design, manufacture, and installation of switchboard instruments, high-voltage arc breaking devices, frequency indicators, indicating wattmeters, lightning protection for high- and low-voltage currents, condensers, belt-driven alternators, the first revolving field type of alternator, etc. Shortly after Mr. Chesney and his colleagues developed the well-known S. K. C. system, the first polyphase transmission plant equipped with the system was installed and put into successful operation, in 1893, at Housatonic and Great Barrington, Mass. In 1895 a 12,000-volt plant was installed for service from Lowell to Grand Rapids, Mich. Many other installations followed. Two-phase a-c induction motors, electrostatic condensers at 500 volts and transformers of 100-light capacity were developed. In developing the transformer all spaces in the coils were filled with gilsonite to provide better heat dissipation and insulation. This and the development of cloth treated with oxidized linseed oil occurred as early as 1892.

In 1906 the General Electric Company acquired the Stanley company and Mr. Chesney became Pittsfield works manager and chief engineer, holding this position until 1927. Under his supervision particular progress was made in the development of apparatus for commercial service up to 220,000 volts, and successful tests of 1,000,000 volts for transmission purposes were completed. He is now an honorary vice-president of the General Electric Company.

He has taken an active interest in the affairs of the Institute, serving as manager (1905–08), as vice-president (1908–10) and as committeeman over a long period of years.

Bancroft Gherardi

(A'95, M'04, F'12, member for life)

President 1927–28

Edison Medalist 1932

SINCE the early days of the telephone Bancroft Gherardi has been an outstanding figure. His initiative and skill in the development of engineering and operating organizations and in the development of the art generally have contributed enormously to the growth and success of present-day communication.

Mr. Gherardi was born April 6, 1873, in San Francisco, Calif., and received his education at the Polytechnic Institute of Brooklyn, N. Y., taking the degree B.S. in 1891. In 1893 he received the M.E. degree from Cornell, and in 1894 the master's degree in mechanical engineering. The following year he entered the employ of the New York Telephone Company (then the Metropolitan Telephone and Telegraph Company) where he worked under John J. Carty for 4 years, quickly winning promotion because of his work in improving the cable practice of the company. He was engaged on various problems, planning the scientific arrangement of control stations; he had charge of the planning and supervising of the underground systems and conductor arrangements installed for the city of New Rochelle, N. Y. He also made a study of the efficiency of telephone transmission on underground cables of various types and aerial circuits of various sizes of wire.

In December 1899 Mr. Gherardi became engineer of the traffic department of the company and was responsible for recommendations for new switchboards and additions to switchboards required. In 1901 he became chief engineer of the New York and New Jersey Telephone Company, in responsible charge of the planning and construction of all central office buildings. He made a study of the conditions of telephone development in the New Jersey territory, which involved laying comprehensive underground and aerial lines, based upon the estimated development of the future. He gave special attention to the commercial application of the Pupin loading coils to the underground cable system.

He was assistant chief engineer of the New York Telephone Company, 1906–07. He became engineer of plant of the American Telephone and Telegraph Company, 1907–18, acting chief engineer and chief engineer, 1918–20, and since 1920 he has been vice-president and chief engineer. He is a director of the Michigan Bell Telephone, Cuban American Telephone and Telegraph Companies, the 195 Broadway Corporation, and the Bell Telephone Laboratories, Inc.

Mr. Gherardi has been an active participant in Institute affairs, having served as manager, 1905–08 and 1914–17, and as vice-president, 1908–10. At various times he has been a member of Institute committees, including executive, finance, and research. He is now serving on the committee on Institute policy. He has represented the Institute on the board of trustees of the United Engineering Trustees, Inc., the national committee of the International Electrochemical Commission, the National Research Council and on other bodies. He is a member of several important technical societies in the United States.

R. F. Schuchardt

(A'03, M'09, F'12)

President 1928–29

RUDOLPH Frederick Schuchardt was one of the outstanding leaders in central station engineering, and a man who served the Institute enthusiastically and effectively in many of its activities. In addition to his splendid qualifications as an electrical engineer, he maintained adherence to principles of the highest type, and had a keen interest in the development of individual engineers.

Mr. Schuchardt was born in Milwaukee, Wis., December 14, 1875, and in 1897 graduated from the electrical engineering course of the University of Wisconsin. Following graduation he spent a short period with the Janesville (Wis.) Electric Light and Power Company, later in that year joining the staff of Meysenberg and Badt, Chicago, as engineering salesman. In July 1898, he entered the employ of the Chicago Edison Company (later the Commonwealth Electric Company and Commonwealth Edison Company) remaining in this organization until the time of his death, October 25, 1932.

Starting in this company, first as a substation operator for a few weeks and then in charge of the company's exhibit at the Trans-Mississippi Exposition, Omaha, Nebraska, he spent one year in the statistical department of the company. During the period 1899–1906 he was in the testing department, going through all phases from assisting to acting head. In 1906 he became engineer of electrical construction, having charge of this work for all stations and substations. In 1909 he was appointed electrical engineer of the company, subsequently having the title of chief electrical engineer. From 1909 until his death in 1932 he was intimately connected with the development of the company.

Mr. Schuchardt made many contributions to electrical literature since the presentation before the Institute in 1897 of his first paper "Electricity Meters of Today" which attracted considerable attention. He has long been active in the Institute. He served on many committees including the education, power generation, power transmission and distribution, protective devices, standards, Technical Program, executive, electrical machinery, law, Edison Medal, and public policy committees, as well as on the committee on code of principles of professional conduct. He has also been the Institute's representative on 5 other bodies. In addition to the presidency, Mr. Schuchardt served as vice-president of the Institute 1922–24.

Mr. Schuchardt also was chairman of the Chicago section of the Illuminating Engineering Society, chairman of the technical national section of the former National Electric Light Association, and member of the Western Society of Engineers (chairman electrical section 1913), the Society for the Promotion of Engineering Education, and the Institution of Electrical Engineers, of Great Britain. He has been chairman of the public affairs committee of the American Engineering Council, and in 1929 was a delegate to the World's Engineering Conference in Japan. He also has been active in civic affairs.

In 1907, Mr. Schuchardt was awarded the Chanute Medal of the Western Society of Engineers.

Harold B. Smith

A'91, M'01, F'13, member for life)

President 1929–30

THE career of Harold Babbitt Smith was fundamentally that of an educator, supplemented by engineering research in the field of high voltage, and with consulting engineering practice. He was head of the department of electrical engineering at Worcester Polytechnic Institute throughout practically its entire existence up to the time he retired in June 1931. He also contributed freely of his time and support to the technical societies.

Professor Smith was born at Barre, Mass., May 23, 1869. In 1891 he graduated from Cornell University with the degree of M.E. in electrical engineering, remaining there as a graduate student several months thereafter.

In January 1892 he was appointed professor of electrical engineering in charge of the department at the University of Arkansas. Resigning from this position in December of that year, he became head designer and electrical engineer for the Elektron Manufacturing Company, Springfield, Mass. During the period 1893–96 he was director of the department of electrical engineering at Purdue University. It was in 1896 that he became professor of electrical engineering and director of the department at Worcester Polytechnic Institute, which position he held until his retirement in 1931. His death occurred February 9, 1932, at Worcester, Mass.

Professor Smith retained his connection with the Elektron Manufacturing Company as consulting engineer until 1902, and did consulting work for several other organizations at various times. From 1905 until 1931, he had served as a consulting engineer for the Westinghouse Electric and Manufacturing Company.

Professor Smith was one of the pioneers in the development of high-voltage power transmission systems and equipment, and carried on many researches involving dielectric phenomena and stress distribution. He held numerous patents on his inventions, and had contributed many papers to the various engineering societies of which he was a member.

He was chairman of the international group, jury of awards in electrical engineering at the St. Louis Exposition, 1904. During 1917–19, he was an associate member of the Naval Consulting Board and consultant of the special board of the Navy on anti-submarine work.

Professor Smith had served the Institute as manager 1920–24, vice-president 1924–26, and as president. He had served on 13 of the Institute's committees, being particularly interested in the Sections and Student Branches committees, and the educational committee. He had been the Institute's representative on 4 other groups. Professor Smith was a member of the American Society of Mechanical Engineers, Institution of Electrical Engineers (Great Britain), Society for the Promotion of Engineering Education, and the American Association for the Advancement of Science.

Two honorary degrees were conferred upon him in 1929; these were doctor of engineering from Purdue University and from Worcester Polytechnic Institute.

W. S. Lee

(A'04, M'05, F'13)

President 1930–31

THE development of the electric power industry in the southeastern part of the United States was the constant endeavor throughout the engineering and business career of William States Lee. Mr. Lee was one of the outstanding figures in the industry at the time of his recent death, March 24, 1934.

Mr. Lee was born in Lancaster, S. C., January 28, 1872. He received the degree of C.E. from The Citadel, the Military College of South Carolina, in 1894. He received the honorary degree of doctor of laws from this institution in 1932, and that of doctor of science from Davidson College, N. C., in 1929.

Following graduation, he was obliged to teach 2 years, in return for the free scholarship to the Citadel, which he had won in a competitive examination.

In 1897 he was appointed resident engineer at the Anderson (S. C.) Light and Power Company. In 1898 he became resident engineer of the Columbus (Ga.) Power Company, becoming chief engineer of this company in 1902. He next went with the Catawba Power Company, Charlotte, N. C., being appointed chief engineer in March 1903, and vice-president and chief engineer in October of that year. This company was a subsidiary of the Southern Power Company, and in 1905 he became chief engineer of the latter company. He later received the appointment of vice-president and chief engineer, which position he held for about 15 years. At the time of his death in March of the present year, Mr. Lee was vice-president and chief engineer of the Duke Power Company, Charlotte, N. C., and president of W. S. Lee Engineering Corporation of New York and Charlotte.

Mr. Lee held a number of other offices, being president and chief engineer of the Piedmont and Northern Railway Company, vice-president and chief engineer and director of the Wateree Power Company, Western Carolina Power Company, and Catawba Power Company.

Mr. Lee was long associated with the late James B. Duke, and together they were active in the construction of many power systems and the development of hydroelectric resources in the south. Probably Mr. Lee's most notable achievement was the designing and building of the Duke Power Company system, consisting of some 32 hydroelectric stations and 7 steam electric stations, with a generating capacity of more than 1,000,000 kva. He also designed and supervised the building of the Duke-Price Power Company's Isle Maligne station on the Saguenay River, Quebec, Canada. He was consulting engineer for the Alcoa Power Company, and designed the Beauharnois Plant which is now being constructed on the St. Lawrence River, near Montreal; when completed it will probably be the largest hydroelectric plant in the world.

Mr. Lee has given freely of his time to the Institute, having been a manager 1911–14, and a director 1929–30, in addition to having been president. He has served on 8 of the Institute committees and been its representative on several other bodies. He was particularly active in American Engineering Council, having been its president for the 2 years 1932–33. He was a member of several other societies.

C. E. Skinner

(A'99, M'03, F'12)

President 1931–32

AN UNUSUAL record of service has been made by Charles Edward Skinner, who not only spent over 42 years participating in the engineering development of one industrial concern, but who has worked for the advancement of the entire profession for a period of many years. His record with the Institute is striking, in that he has served on 17 of its committees, having been chairman of several of these, and has been its representative on 10 other bodies. As an officer, in addition to having been president, he was manager 1915–19, and vice-president 1919–20.

Doctor Skinner was born near Redfield, Ohio, May 30, 1865. He studied at Ohio University and Ohio State University, graduating from the latter in 1890 with the degree of M.E. On August 16, 1890, he joined the organization of the Westinghouse Electric and Manufacturing Company and remained with that company continuously until his retirement from the company January 1, 1933. Living at Wilkinsburg, Pa., he has continued his support of the Institute's affairs, and has taken part in many other endeavors.

His first position with the Westinghouse Company was as a machinist in charge of the manufacture of railway controllers. In 1891 he was put in charge of all insulation design as well as testing, and in 1892, in addition, took up magnetic testing and the development of magnetic materials. He remained in charge of this latter work for many years.

In 1906 Doctor Skinner organized the research division of the engineering department of the Company, and was responsible for the organization and equipment of the chemical, physical, and process laboratories, as well as the high voltage test laboratories. Through his efforts a laboratory for more fundamental research was determined upon in 1915, and he had charge of the building, equipping, and organization of the personnel of this laboratory. In 1920 he was made manager of the research department, having direct charge for the next 2 years. In 1922 he was made assistant director of engineering, holding this position until his retirement at the beginning of 1933.

Doctor Skinner has for many years been particularly active in the field of standardization and has been chairman of American and international standards associations. He has many times been a delegate to international congresses and commissions at meetings in various cities in Europe, and in Japan, and was chairman of the American delegation at 2 of the meetings of the International Electrotechnical Commission.

Doctor Skinner is a member of a very large number of technical societies, and has published many writings on insulation, testing, magnetics, research, standardization, and education. In 1927 he received the honorary degree of doctor of science from Ohio University. In 1931 Doctor Skinner was awarded the Lamme Medal of Ohio State University, one of the 3 medals established by the late Benjamin G. Lamme.

Harry P. Charlesworth

(Member 1922, Fellow 1928)

President 1932–33

HARRY Prescott Charlesworth ranks among the outstanding engineers in the field of telephone plant engineering having handled with repeated success large responsibilities in the Bell system, which required an executive ability of the highest order and a thorough understanding of engineering principles and practice.

He was born in Haverhill, Mass., April 7, 1882, and after attending the public school and Wheeler's Academy there, he entered Phillips-Exeter Academy in Exeter, N. H., where he prepared for college. He received the B.S. degree from the Massachusetts Institute of Technology in 1905 and immediately joined the staff of the American Telephone and Telegraph Company, then located in Boston.

For the first 2 years he worked in the circuit development division of the engineering department. Then in 1907 he was transferred to the toll traffic division.

During the period 1907 to 1919 he was assigned to special problem work. Among the more important of these assignments were the development of alternating high-voltage telegraph systems and the development of systems for use with small gauge long cable circuits. He also acted as advisory engineer to the Chesapeake and Potomac Company in important matters having to do with the Government telephone requirements in Washington, from 1917 to 1919 during the course of the War.

In 1919 he became equipment and transmission engineer of the engineering department of the American Telephone and Telegraph Company, and a year later he was appointed plant engineer, taking responsible charge of the design of the telephone properties and having general supervision over the entire plant engineering work of the Bell system. He has acted as consulting engineer for the chief engineers and executive managers of the associated Bell companies throughout the country.

In 1928 he was elected vice-president of the Bell Telephone Laboratories, Inc., where he directed development, research and related activities pertaining to the art of telephonic communication. In 1933 he resigned to accept his present position as assistant chief engineer of the American Telephone and Telegraph Company in New York.

Mr. Charlesworth has been especially generous in giving his time to Institute activities. He was a manager (1924–27), chairman of the meetings and papers (now technical program) committee (1927–29) and chairman of the New York Section (1929). In 1930 he became vice-president (representing district No. 3) and a member of the board of directors. He has participated as member and chairman of many committees. At present he is serving on the executive, Institute policy, and Edison medal committees, the special committee on model registration law, and represents the Institute on the John Fritz medal award committee. He is a member of the board of United Engineering Trustees, Inc., and a member of National Research Council, division of engineering and industrial research. He is a member of the corporation of the Polytechnic Institute of Brooklyn.

John B. Whitehead

(A'00, M'08, F'12, Life Member)

President 1933–34

JOHN Boswell Whitehead, now serving the Institute as president for the 1933–34 term, has long been prominent in the academic field for his work as a teacher and for his outstanding researches on the problems of dielectrics and corona phenomena. He is also well known as a consulting engineer in these latter fields.

He was born at Norfolk, Va., August 18, 1872, and studied at Johns Hopkins University, receiving the degrees E.E. (1893), B.A. (1898) and Ph.D. (1902). His first position was with the Westinghouse Electric and Manufacturing Company, working in the shop, laboratory and engineering department for one year and designing for 2 years. In 1897 he was plant engineer for the Niagara Falls Power Company and in charge of the plant of the Pittsburgh Reduction Company. From 1898 to 1904 he was instructor in electrical engineering at Johns Hopkins, becoming associate professor of applied electricity in 1905. In 1919 he became professor, and since 1919 has been dean of the school of engineering.

In addition to teaching Doctor Whitehead has carried on an extensive consulting practice. From 1899 to 1900 he worked for the Rowland Multiplex Telegraph System. In 1902 he undertook research work with the Bureau of Standards, and from 1902 to 1905 he was research assistant at the Carnegie Institution. From 1900 to 1908 he had charge of the power plant of the university. Over a period of 12 years, from 1900 to 1912, he was consulting engineer for the Maryland Railways Company. A noteworthy piece of work he did for the company was the design and supervision of the installation of the single-phase equipment for the Baltimore-Annapolis Short Line (1906–08). In later years his work on high-voltage insulation has been outstanding. He has been consultant and director for various projects in this field supported by the former National Electric Light Association, Utilities Research Commission of Illinois and the Engineering Foundation.

Doctor Whitehead has been active in Institute affairs for many years. He founded the Baltimore section and was its chairman for 19 years. He has served as a member of the board of directors (1924–28), chairman of the electrophysics committee (1912–16), and research committee (1922–27). From its inception he has been identified with the work of the latter. In 1927 he organized the committee on electrical insulation of the National Research Council's division of engineering and industrial research, serving continuously as chairman. He also is serving on the executive and Edison medal committees of the Institute and is the Institute's representative on American Engineering Council, the John Fritz medal award committee, and the Charles A. Coffin fellowship and research fund committee.

He served as major in the engineering division of the Reserve Officers Corps during the War. In 1926 he was exchange professor in engineering and applied science to France. Honors awarded him include the Edward Longstreth Medal and the Elliott Cresson Gold Medal of the Franklin Institute, the Montefiore award, and the Medaille d'Honneur of the University of Nancy, France, 1927.

Honorary Members and Medalists

Other Than Those Who Served Terms as Presidents

Biographical sketches of Honorary Members of the Institute and the recipients of its medals are given on the following pages, excepting only those Honorary Members and medalists who also served terms as presidents of the Institute. Biographical sketches of this latter group have been given on the preceding 23 pages.

Sir William Preece

Honorary Member 1884

THE first regular meetings of the Iustitute following organization meetings were held on October 7 and 8, 1884. A few days later, on October 21, Sir William Henry Preece, pioneer in the electrical industry in Great Britain, was elected as the first Honorary Member of the Institute. He had much to do with the laying of the foundations of applied electricity, in telegraph engineering in particular. He was born in England on February 15, 1834. After leaving King's College, London, where he was educated, he spent a short time in the telegraph engineering offices of Edwin and Latimer Clarke, and in 1853 joined the Electric and International Telegraph Company. After a number of years' experience in the telegraph companies, he became a divisional engineer under the British post office, when, in 1870, the various telegraph companies were transferred to the State. He subsequently became electrician and later engineer-in-chief to the post office, retiring in 1899, when he took up a consulting practice. Sir William Preece's official duties did not deter him from taking a very active part in the affairs of the engineering profession. He was a member of many scientific societies, and contributed largely to their proceedings. For the Institution of Civil Engineers and for the Institution of Electrical Engineers (both of Great Britain) he served as president and he was at one time chairman of the council of the Royal Society of Arts. He was a Fellow of the Royal Society.

Mr. Preece's name is connected with many improvements and inventions in telegraph work. At the age of 21 he patented a system of duplex telegraphy; he subsequently took out a number of patents on railway signaling apparatus, although most of his inventions concern telegraph apparatus directly. He also invented a new telephone in 1878, and was proud in later years of having, in 1892, originated a system of signaling across space by induction telegraph with the aid of 2 parallel telegraph lines. Upon the introduction of wireless telegraphy, Mr. Preece became an active supporter of this new method of communication, and maintained an active interest in the progress of science until he died, November 6, 1913.

Moses G. Farmer

(Associate 1884)

Honorary Member 1890

THE THIRD individual to be awarded honorary membership in the Institute was Prof. Moses Gerrish Farmer, a charter member, whose election on October 21, 1890, followed that of Dr. Norvin Green (see p. 788 this issue).

Professor Farmer was born February 9, 1820, at Boscawen, N. H. He studied at Dartmouth College 1840–43. After having charge of a private school, he gave up this work in 1847 to devote his entire time to scientific pursuits. In this year he invented an electromagnetic engine, and in an exhibition at Dover, N. H., on July 26 of that year, transported passengers on a miniature electric railroad. After lecturing on this invention a number of times, he opened a telegraph office at South Framingham, Mass., and there devised an electrical fire alarm system. This was shown by him in Boston in 1849, and afterward perfected in conjunction with Dr. W. F. Channing. The system was first placed in operation in 1852. Professor Farmer subsequently devised many machines and much equipment of importance in the very early days of the electrical industry. In 1852, he devised a system of 2 or more closed circuit repeaters, and in 1853 patented apparatus for simultaneous transmission of 4 messages on one wire. He then became interested in dial telegraphy, duplex and multiple transmission, and the manufacture of rubber insulation. Becoming interested in electric lighting, in 1859 he invented an automatic regulator for controlling current to electric lamps, and illuminated his own house by electricity that year. Among his many other activities, he is reported to have been the first to construct a self-excited magneto-electric machine. Professor Farmer was connected with many scientific associations of the day. He died at Chicago, Ill., May 25, 1893, where he had gone to prepare an exhibition of his early inventions for the Columbian Exposition.

Cyrus W. Field

Honorary Member 1892

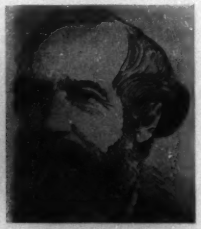
CYRUS West Field, promotor of submarine telegraphy, was elected an Honorary Member of the Institute May 17, 1892. Like many of those connected with the early history of the Institute, his principal activity was in the telegraph industry.

He was born November 30, 1819, in Stockbridge, Mass. At the age of 15 he entered a mercantile house in New York, but when about 20, went into business for himself and soon became prosperous. In 1853 he partially retired and spent several months in travel. Meeting a Canadian engineer, who had attempted to lay a subterranean telegraph line across Newfoundland, Mr. Field's imagination was immediately fired with the idea of laying a submarine cable across the Atlantic ocean. From this time, January 1854, until the transatlantic cable was successfully completed July 27, 1866, Mr. Field worked unceasingly in the accomplishment of this endeavor. He put a large part of his own funds into the enterprise, and succeeded in interesting many others in the venture. The first cable was received from England and was to be laid across the Gulf of St Lawrence, but during a gale the cable was cut in order to save the ship after 40 miles had been laid. Additional financing, which became necessary, was secured in England, and by an appropriation of the U.S. Congress. Starting from the shore of England, 335 miles of cable were laid, when the cable parted on August 11, 1857. In 1858, a cable was started from each shore, and after considerable difficulty, was spliced on July 29. While celebration of this event was going on, the cable parted, and it was not until 1865 that the work of laying the cable was again begun. The now famous steamship "Great Eastern" was used in this endeavor, and after unsuccessful attempts, the laying was completed in 1866. Many honors were bestowed upon Mr. Field in the United States, England, France, and Italy, for his success. Mr. Field subsequently became interested in the development of elevated railways in New York City, and in other submarine cables. His death occurred July 11, 1892.

Mr. Field shared with Professor Farmer the distinction of being the only American elected to honorary membership until the election of Thomas A. Edison in 1928.

SIR WILLIAM PREECE

M. G. FARMER



CYRUS W. FIELD

Lord Kelvin

Honorary Member 1892
John Fritz Medalist 1905

WILLIAM THOMSON, first Lord Kelvin, the noted British scientist, past-president of the Institution of Electrical Engineers, Great Britain, was elected an Honorary Member of the Institute, May 17, 1892. Lord Kelvin was born in Belfast, Ireland, June 25, 1824. He graduated from St. Peter's College, Cambridge, in 1845, where he won notable honors. At the age of 22, he became professor of natural history at the University of Glasgow, and remained with that institution the rest of his life. He was elected a chancellor of the university in 1904. He was knighted in 1866, as one who had done more than any other scientific man to develop submarine telegraphy. In addition to many inventions in telegraphy, he originated the quadrant electrometer, improvements on the compass, and several other inventions. In 1892, he was made a peer by Queen Victoria, and subsequently received a great many honors. Lord Kelvin made many contributions to fundamental theory of electricity. He had a passion for the investigation of natural phenomena, and had acquired a mastery of mathematics that served him as a valuable instrument of research and partly accounted for his remarkable precision of thought. His participation in the activities of scientific and engineering organizations, long after their power to confer distinction upon him had ceased, deserves emulation. His death occurred December 17, 1907.

E. W. von Siemens

Honorary Member 1892

DR. Ernst Werner von Siemens, inventor, promoter of the telegraph and other early electrical apparatus, and a founder of the German firm of Siemens and Halske, was elected to honorary membership in the Institute July 17, 1892. Doctor Siemens was born in Germany in 1816, the eldest of 7 brothers, all of whom achieved distinction in the pursuit of science. His early life was spent in acquiring an education at the Gymnasium of Lubeck, and afterward in the study of military practice and theory. At the age of 28, he was appointed superintendent of artillery workshops and devoted his attention to the application of mechanical, electrical, and chemical science to the defences of his country. About 1848, Doctor Siemens proposed the use of subterranean instead of overhead telegraph lines, and invented a machine for applying seamless gutta-percha to the conductor. Shortly after this he retired from the army, and commenced to devote his whole energy to investigations of theoretical and applied science. His numerous achievements in practical electricity include dial and printing telegraphs, development of the duplex telegraph circuit, apparatus for localizing faults in electric cables, the polarized relay, an electrical range-finder, and the development of the self-excited dynamo, and methods of armature winding. In 1879, he exhibited an electric railway in Berlin. One of the earliest forms of self-regulating arc lamps also is attributed to this prolific inventor. He received from the University of Berlin, in 1860, the honorary degree of Ph.D. Among other honors, a patent of nobility was conferred upon him by the Emperor Frederick III, and he had received the highest scientific order of his country, the Prussian order, "for merit." Doctor Siemens died December 6, 1892.

André Blondel

(Associate 1905)

Honorary Member 1912

ANDRÉ E. Blondel, who is now professor of applied electricity at l'Ecole Nationale des Ponts et Chaussées, Paris, France, was elected an Honorary Member of the Institute January 12, 1912. He was born at Chaumont, France, in 1863. Graduating from the universities of Paris and Dijon in 1889, he was then appointed engineer in the Department of Ponts et Chaussées (civil engineering). From 1890 to 1927 he was engaged in the lighthouse service of that department, successively with the titles of engineer-in-chief and inspector-general. Since 1904 he has held his present position of professor of applied electricity. During his long service, he has been instrumental in introducing many important changes in signaling on the coasts of France, principally by wireless. In 1897 he conducted an exhaustive series of experiments on the electric arc. These led him to study the measurement of electrical quantities and to develop the art of photometry, upon which he has long been a leading authority. His investigations have been extended to the advancement of electrical theory and practice in relation to many types of equipment, including generators, motors, and transmission equipment, and he has to his credit many inventions. His published contributions to the science of electrical engineering have been extensive. He has presided over committees and commissions, national and international, and has received many honors.

C. E. L. Brown

Honorary Member 1912

CHARLES Eugene Lancelot Brown, famous Swiss engineer and organizer of Brown, Boveri and Company, was elected on January 12, 1912, to be an Honorary Member of the Institute. He was born in Switzerland in 1863, the son of an engineer of exceptional ability. After a year's apprenticeship, he organized an electrical department in the locomotive plant at Basle, and in 1874, at the age of 20, he entered the service of the Oerlikon Engineering Works, for which, 2 years later, he became director of the electrical department. In 1885, he conceived a type of armature winding for rotating machines now commonly used. The following year he undertook d-c high-voltage transmission, developing several unusual features of equipment. Turning to a-c machinery, in 1889, he designed some of the first oil-insulated transformers, and produced generators suitable to the new requirements. In 1891 he organized his own concern of Brown, Boveri and Company, at Beden, Switzerland, where he took up the development of the revolving-field type of alternator. The following year the concern undertook the commercial production of induction motors. Among the many developments which Mr. Brown pioneered, the introduction of slow-speed machines was one most frequently connected with his name. He did much original work in the design of switch and control gear, and in the development of the steam turbine. In 1900 he became president of the board of directors of Brown, Boveri and Company, retaining this position until 1911 when he retired. In 1912 a honorary doctor's degree was conferred upon him by the technical college of Karlsruhe. His death occurred May 2, 1924.

LORD KELVIN

E. W. VON SIEMENS

ANDRÉ BLONDEL

C. E. L. BROWN

Emil A. Budde

Honorary Member 1912

DR. Emil Arnold Budde, prominent German scientist and electrical engineer, was elected an Honorary Member of the Institute January 12, 1912. Doctor Budde was born July 28, 1842. He was educated at the gymnasiums of Arnsberg and Dusseldorf and at the University of Bonn, where after graduation he became assistant in mathematics and physics. During the Franco-German war he was a war correspondent for the *Koln Zeitung*, later becoming editor and then foreign correspondent. In 1887 he opened a private laboratory in Berlin and in 1892 was appointed physicist with the Siemens and Halske Company, of which organization he was director from 1893 on, for many years. He contributed largely to German scientific publications. Doctor Budde was official delegate for Germany with Helmholtz at the International Electrical Congress at Chicago in 1893. He was one of the founders of the Verband Deutscher-Electrotechniker of which he served as secretary and later president. He was president of the International Electrotechnical Commission succeeding Dr. Elihu Thomson. Doctor Budde died August 19, 1921.

S. Z. de Ferranti

(Associate 1903, Member 1906)

Honorary Member 1912

SEBASTIAN Ziani de Ferranti was one of the pioneers in the field of electric power distribution in Great Britain, and in recent years had made many contributions in radio development. He was born at Liverpool, England, April 9, 1864, and was educated at St. Augustine's College, Ramsgate, and University College, London. At any early age he displayed unusual ability in machine design, and when between 10 and 12 years old he had produced original drawings demonstrating his extraordinary grasp of detail. Continuing to direct his attention to the development of electrical devices throughout his life, he had to his credit inventions in various lines which are among the most notable contributions to the electrical art. When 22 years of age he began his work of supplying London with electricity from a plant remote from the city, and in 1891 the scheme was perfected and the regular transmission of current at 10,000 volts to the city was initiated. The large Ferranti power plant at Hollinwood was started in 1895. In the construction of this and other early power plants, Mr. Ferranti showed great ingenuity in overcoming the difficulties which were constantly arising. In recent years Doctor Ferranti had been interested chiefly in radio developments and devoted exhaustive study to audio-frequency transformers, which he brought to a high degree of perfection. His contributions to the profession have been marked. In 1910 Doctor Ferranti was elected president of the Institution of Electrical Engineers, of Great Britain, and in 1926 was elected to honorary membership in this institution. On January 12, 1912, Doctor Ferranti was elected an Honorary Member of the A.I.E.E. His death occurred January 13, 1930. He received the honorary degree of Sc.D. from the University of Manchester in 1911; in 1924 he received the Faraday medal of the Institution of Electrical Engineers, and in 1927 he was elected a fellow of the Royal Society.

Antonio Pacinotti

Honorary Member 1912

PROFESSOR Antonio Pacinotti, original inventor of the d-c dynamo with its commutator, and of the ring and toothed types of armature, was born at Pisa, Italy, June 17, 1841; his death occurred in that city on March 24, 1912, only a few weeks after his election on January 12, 1912, as an Honorary Member of the Institute. Under the direction of his father he early began the study of electromagnetism, and by the time he was 17 years of age had the principles of the d-c generator well in mind, constructing in 1860 the celebrated machine which 10 years later was reinvented by Gramme. After 3 years of experimentation with his models, Professor Pacinotti published an illustrated description of his dynamo in the *Nuovo Cimento* in 1864, but this received little attention at the time. The machine described by the young Italian embodied for the first time the ring armature with its symmetrically grouped coils closed upon themselves and connected to the bars of a commutator, the brushes of which delivered practically non-fluctuating current. Early in his work the Italian inventor discovered the reversibility of the dynamo of his creation, having noted that if the machine were supplied with energy from an outside source it would run as a motor. In 1862 he was appointed to the assistant professorship of astronomy at Florence, and, having to renounce carrying out his electrical experiments on the enlarged scale he had planned, then prepared the *Nuovo Cimento* description of his generator already mentioned. In 1864 he received the professorship of applied physics at Bologna and in 1873 was appointed professor of physics at Cagliara. At the Vienna exposition in 1873 he exhibited his dynamo model made in 1860, and for the first time received wide credit. A medal of progress was granted Professor Pacinotti at Vienna, and other medals of honor were given him in 1881 at Paris. At the time of his death he was professor of technological physics at the University of Pisa and senator of the kingdom of Italy.

S. P. Thompson

(Associate 1897)

Honorary Member 1914

SILVANUS Phillips Thompson, noted physicist and electrical engineer of Great Britain, and celebrated as a teacher and writer on electricity and magnetism, was elected an Honorary Member of the Institute March 13, 1914. He was born at York, England, June 19, 1851. Upon graduation from London University in 1869, he took up the study of chemistry and physics at the Royal School of Mines, also studying at foreign universities. In 1875 he received the degree of B.S. from the University of London, and in 1878 that of Sc.D. from the same university. He became professor of experimental physics at Bristol University College in the latter year. Here he began a series of investigations covering a wide range of problems in physics and electricity, becoming an authority on the subject of dynamo-electric machines. In 1885 he became principal and professor of physics at the City and Guilds Technical College at Finsbury, London. At the time of his death June 13, 1916, he was principal and professor of electrical engineering at this college. He was a fellow of the Royal Society, and was a past-president of the Institution of Electrical Engineers, of Great Britain. Doctor Thompson had also made many contributions to the history of science and philosophy.

EMIL A. BUDDE

S. Z. de FERRANTI

ANTONIO PACINOTTI

S. P. THOMPSON

Guglielmo Marconi

Honorary Member 1917
John Fritz Medalist 1923

GUGLIELMO Marconi, Italian inventor, famous for establishing wireless telegraphy on a commercial basis, was elected an Honorary Member of the Institute on August 14, 1917. He was born in Italy on April 25, 1874, and was educated privately. In 1895 the idea became firmly rooted in his mind that a system of telegraphy through space, could be provided by means of electromagnetic waves, the existence of which had already been determined. Marconi was the first to devise practical means by which these waves could provide a new method of communication. In 1896 he went to England, taking out during that year the first patent ever granted on wireless telegraphy. An extensive series of experiments followed, and his first commercial company was organized in 1897. During the next few years, he took out many patents on new devices in wireless telegraphy, and had much to do with the remarkable growth of this industry in many countries of the world. He also was one of the pioneers in the use of short-wave for radio communication. During the World War, Marconi served in both the Italian Army and Navy; and also visited America as a member of the Italian War Commission to the U.S. Government. He was appointed a delegate to the Peace Conference in Paris in 1919. Among the many honors he has received are the Nobel Prize for physics in 1909, the Albert Medal of the Royal Society of Arts, of Great Britain, and the 1932 Kelvin Medal of the Institution of Civil Engineers, of Great Britain. He has been decorated with the Italian order of St. Maurice and St. Lazarus, and with the Grand Cross of the Crown of Italy. In 1915 he was nominated senator of the Kingdom of Italy. In the United States, he has received the Franklin and John Fritz medals and Medal of Honor of the Institute of Radio Engineers. He is president of the Marconi Wireless Telegraph Company, Ltd., at London, England.

Oliver Heaviside

Honorary Member 1918

OLIVER Heaviside, English scientist, who has been recognized as one of the most eminent exponents of electrical science, particularly for his development of the electromagnetic theory, was elected to honorary membership in the Institute on February 14, 1918. Mr. Heaviside was born in England in 1848, and lived there until his death in 1925. His retiring character and desire to avoid society, partly due to almost complete deafness since childhood, has resulted in his name being unknown to the general public, but those who have come in contact with his work regard him as an illustrious successor to Wheatstone, Maxwell, and Kelvin. He lived alone in a cottage at Lower Warberry, Torquay, England, in poverty, a pension of £200 a year having practically been forced upon him. While he wrote papers of great value for the Philosophical Magazine of the Royal Society of London and for the *London Electrician*, for which he received but scant remuneration, these papers were difficult to read and little known. No pictures of him exist and few of his admirers ever met him. His writings, however, had considerable practical value, particularly his mathematical theory of the value of distributed self-induction in long distance telephony, a theory which was later used for practical application and to telephony, establishing a new epoch in this field. The Royal Society, of England, had elected him to fellowship.

Ferdinand Foch

Honorary Member 1921

FERDINAND Foch, Marshal of France from August 9, 1917, until his death, March 20, 1929, was made an Honorary Member of the 4 national societies of civil, mining and metallurgical, mechanical, and electrical engineers, at an impressive ceremony held in the Engineering Societies' Building, New York City, on February 13, 1921. This award was made to "the world's greatest soldier in recognition of his unparalleled service to mankind." In Marshal Foch's brief speech of response he paid tribute to the engineering profession in the following words: "It was due largely to engineering and the engineering industry that the war was brought to a successful conclusion. To the engineering profession also we are indebted for many great lessons which will be vital to mankind in the future. The armies could not have done a great deal without the effort of the engineer. Success was made possible to a great extent by the industry of the people at home but when it became a question of decision, when the decisive moments arrived, the engineer stood out as an essential factor in complete triumph. What would have become of the armies without the technical training, without the professional knowledge which you have exercised for the Allies and which enabled us to lead our armies in the field, to feed them, to protect them, and to facilitate their advance quickly and decisively? It is for these reasons that I am pleased to find you here today, to receive from you so splendid a welcome and to express my gratitude and the gratitude of France, as well as the recognition of my countrymen for the tremendous sacrifices made by you and the men of your calling. I am grateful to you for including me in your ranks as a member of the 4 great engineering societies of the United States."

Thomas A. Edison

(A'84, M '84, member for life)

Honorary Member 1928
John Fritz Medalist 1908

THOMAS Alva Edison, the outstanding inventor in the history of the electrical industry, was born at Milan, Ohio, February 11, 1847. The following minute, adopted by the Institute's board of directors shortly after Mr. Edison's death, indicates briefly the tremendous scope of his activity: "The physical life of Thomas Alva Edison, world benefactor, ended on Sunday, October 18, 1931. The spiritual benefits of his contributions to humanity continue to live. His genius, vision, patience, persistence, industry, and widely diversified talents, which brought to fruition many of his conceptions, have contributed greatly to the comfort, convenience, and happiness of mankind, and his achievements constitute a great incentive and inspiration to those who follow. In particular, his invention of the incandescent electric lamp and his conception, more than 50 years ago, of the combination of a central generating station with a suitable distributing system for electrical energy, firmly establish him as the founder of the electric lighting industry of the world. He was the outstanding world leader in the group of inventors, scientists, and engineers whose achievements in technology have produced great social and economic benefits, including the employment, in useful occupations throughout the civilized world, of tens of thousands of men and women. He was respected and admired by his associates who cherish their memory of his ability, simplicity, and other personal characteristics. Mr. Edison was, in 1884, one of the signers of the call for the organization meeting of the American Institute of Electrical Engineers, and he was elected a vice-president at the first election of officers; later he was elected an Honorary Member. His achievements caused a group of his associates and friends to establish the Edison Medal, which is now awarded annually by this Institute."

GUGLIELMO MARCONI

FERDINAND FOCH

THOMAS A. EDISON

AMBROSE SWASEY

HERBERT HOOVER

CHARLES F. BRUSH

MOTOJI SHIBUSAWA

Ambrose Swasey

Honorary Member 1928
John Fritz Medalist 1924

THE devotion of Ambrose Swasey, famous manufacturer of precision instruments and mechanisms, to the engineering profession, is evidenced by his founding of the Engineering Foundation in 1914. Doctor Swasey has contributed gifts totaling $750,000 to the Foundation, research agency of the 4 national societies of civil, mining and metallurgical, mechanical, and electrical engineers. Doctor Swasey was born at Exeter, N. H., December 19, 1846. During the period 1869–80 he was with the Pratt and Whitney Company, Hartford, Conn., paying special attention to gearing. In 1880, he went into partnership with W. R. Warner (incorporated in 1900 as The Warner and Swasey Company) for the manufacture of machine tools and astronomical instruments. The firm was first established in Chicago, but soon was transferred to Cleveland, where it has since remained. Since the death of Mr. Warner, Doctor Swasey has been chairman of the board. Many remarkable telescopes have been built by this firm, and during the war it solved many important problems. In 1924, the John Fritz Gold Medal was awarded Doctor Swasey; he has also received the Franklin Medal, highest award of the Franklin Institute. In addition to honorary membership in the A.I.E.E., which was awarded him June 27, 1928, he is an honorary member of The American Society of Mechanical Engineers (president 1904), American Society of Civil Engineers, Institution of Mechanical Engineers (Great Britain), Institution of Mining Engineers (Great Britain), and the Society of Civil Engineers. He is a chevalier and officer of the French Legion of Honor, and has received several honorary degrees in the United States.

Herbert Hoover

Honorary Member 1929
John Fritz Medalist 1929

HERBERT Clark Hoover, famous engineer and president of the United States 1929–33, was elected to honorary membership in the Institute, June 25, 1929. During the same year, Mr. Hoover was awarded the John Fritz Medal. He received many other medals in the U.S. and other countries, and is a past-president of the American Institute of Mining and Metallurgical Engineers and of American Engineering Council. Mr. Hoover was born at West Branch, Iowa, August 10, 1874. In 1895 he received the degree of B.A. in mining engineering from Stanford University, Calif. Subsequently he has received many honorary degrees. During the period of 1895–1913 he was engaged in professional work in mines, railways, and metallurgical work throughout the world. In 1913–14 he represented the Panama-Pacific International Exposition in Europe. During 1914–15 he was in London, England, as chairman of the American relief commission, and in 1915–19, was chairman of the commission for relief in Belgium. During the period of 1917–19 he was also U.S. Food Administrator. He also served on several war boards and councils, and was director of various economic measures in Europe during the armistice. In 1919 he also was chairman of the American relief administration engaged in children's relief in Europe. In 1921 he was appointed U.S. Secretary of Commerce by President Harding, and was reappointed by President Coolidge. Mr. Hoover has served on many commissions in the United States.

Charles F. Brush

(A'84, M'84, member for life)

Honorary Memder 1929
Edison Medalist 1913

OVER a period of almost 60 years of activity, Charles Francis Brush was in the forefront as a pioneer in electrical development. He was born at Euclid, Ohio, March 17, 1849. While still at school, he became intensely interested in electrical apparatus. In 1869 he graduated in mining engineering from the University of Michigan, later securing the degree of M.S. at this university, followed by a Ph.D. from the Western Reserve University, Cleveland. One of the first to realize the value of the work of Gramme, in 1876, he designed and built a dynamo. The following year he introduced the compound field winding for obtaining constant voltage. It was at an exhibit in 1878 that he displayed the earliest form of what afterward became the world-famous Brush arc light machine. His, too, was the invention of the differential arc lamp, which made it possible to operate lamps in series, and of many other devices. In 1881 the Brush Electric Company was incorporated and capitalized at $3,000,000, being absorbed 10 years later by the General Electric Company, when the works were removed to Schenectady. Doctor Brush continued to develop much other apparatus, and contributed great improvement in the manufacture of storage batteries. He was a charter member of the Institute; he served in 1884–87 as one of the Institute's first managers, and was a member of the Edison Medal committee at the time of his death. On that date, June 15, 1929, his name was being voted upon for honorary membership in the Institute, and this distinction was conferred upon him by the board of directors 10 days after his death.

Motoji Shibusawa

(Associate 1905)

Honorary Member 1929

MOTOJI Shibusawa, dean of the faculty of engineering and professor of electrical engineering at the Tokyo (Japan) Imperial University, and also engineer of the Department of Communication, Japan, was elected an Honorary Member of the Institute on August 6, 1929. He was born, October 25, 1876, in Japan, and graduated in electrical engineering at Tokyo Imperial University in 1900. Following one year in the army service, he spent the period between 1901 and 1906 in study at different universities and in gaining practical experience at industrial plants, in several European countries and in the United States. Returning to Japan, he was appointed engineer of the department of communication in 1906, serving at the electrotechnical laboratory. In 1909 he was appointed to the additional post of engineer of the Imperial Railway Board. In 1911 he obtained the academic degree of doctor of engineering at the Tokyo Imperial University. In 1919 he was appointed engineer-in-chief, bureau of electricity, ministry of communication, and in that year he took the additional post of professor of the Tokyo Imperial University, to which later post he was definitely transferred in 1924. He was appointed dean of the faculty of engineering in 1929. Subsequently, he received promotions in both academic and business posts, and served the government on several special bureaus. In 1924 he was elected president of the Institute of Electrical Engineers, of Japan, and has been president of the Japan Electric Technical Committee, and has received many other honors.

W. L. R. Emmet

(A'93, M'94, member for life)

Honorary Member 1933
Edison Medalist 1919

AT THE time William LeRoy Emmet began his career in the electrical industry some 50 years ago, he was noted for his desire to explore new fields of engineering, rather than to work in those in which considerable development work had been done. This characteristic has continued throughout his life. Doctor Emmet was born in Pelham, N. Y., July 10, 1859. In 1881 he graduated from the U.S. Naval Academy, remaining in the Navy for 2 years thereafter. In 1887 he joined the Sprague Electric Company, then engaged in the historic electric railway developments at Richmond, Va., and at other cities. After short periods with the Westinghouse Electric and Manufacturing Company and the Buffalo (N. Y.) Railway Company he went to Chicago as district engineer for the newly formed Edison General Electric Company. In 1892 he was transferred to the New York office of the company, which later became the General Electric Company. In 1900 Doctor Emmet started his work on the Curtis steam turbine, and he continued its development until recent years, when his attention turned to the mercury vapor power process in which activity he has again been singularly successful. He is now a consulting engineer of the General Electric Company. Doctor Emmet was elected an Honorary Member of the Institute May 22, 1933, and in 1919 received the Edison Medal. Other medals have been awarded him. He has served the Institute on several of its committees, and was vice-president 1900–02. He is also a past vice-president of the American Society of Mechanical Engineers.

G. A. Hamilton

(A'84, M'84, F'13, member for life)

Honorary Member 1933

GEORGE ANSON HAMILTON, one of the 6 living charter members of the Institute, vice-president 1884–86, and national treasurer for the 35-year period 1895–1930, was elected an Honorary Member of the Institute May 22, 1933. In addition to this unusual record of service, Mr. Hamilton served on the Edison Medal and executive committees for a great many years, and on the first editing committee and the committee on permanent quarters. He is the only surviving member of the original committee of 5 on organization. He is now retired, living at Elizabeth, N. J. Mr. Hamilton was born at Cleveland, Ohio, December 30, 1843. Between 1860 and 1873, he was in telegraph and railway signaling service. During 1873–75 he was assistant to Prof. Moses G. Farmer, an Honorary Member of the Institute, and a pioneer electrical inventor. Here Mr. Hamilton received much valuable experience. In 1875 he became assistant electrician of the Western Union Telegraph Company, New York, N. Y., being appointed chief electrician of the repair expedition of the Key West-Havana Cable the following year. In 1889 he became engineer for the Western Electric Company, New York, N. Y., supervising the production of fine electrical instruments. He retained this position until his retirement in 1909. Mr. Hamilton is a member of the Institution of Electrical Engineers (Great Britain), Société Française des Électriciens, Société Française de Physique, and Société Belge d'Astronomie.

R. A. Millikan

(Member 1922)

Honorary Member 1933
Edison Medalist 1922

ONE of the outstanding teachers and physicists of the present time was elected to honorary membership in the Institute when Dr. Robert Andrews Millikan was chosen May 22, 1933. Doctor Millikan was born at Morrison, Ill., March 22, 1868, and received the B.A. degree from Oberlin College in 1891, and that of Ph.D. from Columbia University in 1895. During the next year he attended the universities of Berlin and Göttingen. He has received many honorary degrees from universities in the United States and other countries. From 1891 to 1893 he tutored in physics at Oberlin College, and in 1896 became assistant in physics at the University of Chicago, becoming assistant professor in 1902; from 1906 to 1910 he was associate professor, becoming professor in the latter year. Since 1921 he has been director of the Norman Bridge Laboratory of Physics and chairman of the executive council of the California Institute of Technology, Pasadena. Doctor Millikan has conducted many fundamental experiments in physics which have been important contributions to present knowledge. He has recently become well known for his experiments on the so-called "cosmic" or Millikan ray, although his earlier experiments have been of much greater value to electrical engineers. In his work of instruction, he has evidenced rare ability to impart his own extraordinary scientific knowledge to others. He is a member of a large number of societies in the United States and other countries, having served as president of some of these.

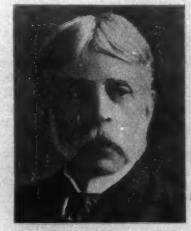
George Westinghouse

(Associate 1902)

Edison Medalist 1911
John Fritz Medalist 1906

WHILE the fame of George Westinghouse rests largely upon his invention of the air brake and on the organization of tremendous manufacturing companies in the electric and related industries, he was responsible for the development of railway switch and signaling apparatus, the a-c system for lighting and power, a method for carrying natural gas over long distances, and many other devices. Not the least of his contributions was the environment which he created for many of the most outstanding electrical engineers and inventors of his day. His personal interest in their work and the inspiration and commercial impetus he gave to the development of such important advances in the art as Stanley's system of distribution of alternating current by transformers, Tesla's polyphase induction motor, the Shallenberger meter, and the Stillwell regulator resulted in epoch-making steps in the progress of civilization. Mr. Westinghouse was born in Central Bridge, N. Y., October 6, 1846. He attended Union College and served for 2 years on the North side of the Civil War. When, at 21, he announced to the authorities of the Pennsylvania Railroad at Pittsburgh, that he had invented an apparatus which would enable a locomotive engineer to completely control a train, he was laughed at, and it was several years before he could interest the company in the invention. Within a few years he founded the first of the various Westinghouse organizations with which he was actively associated until shortly before his death on March 12, 1914.

W. L. R. EMMET



G. A. HAMILTON

R. A. MILLIKAN

GEORGE WESTINGHOUSE

WILLIAM STANLEY

NIKOLA TESLA

B. G. LAMME

JOHN W. HOWELL

William Stanley

(A'87, M'98, F'13)

Edison Medalist 1912

WILLIAM STANLEY was very prominent among the electrical inventors and engineers who made possible long-distance light and power transmission; his inventions on the transformer and early work in the development of the a-c system contributed greatly to the advancement of the electrical art. During the earlier period of his career he was responsible for several incandescent lamp inventions, while in the employ of the United States Electric Company (1879–81) and the Swan Electric Company (1882–83). From 1883 to 1884 he experimented on storage batteries and other apparatus in a private laboratory at Englewood, N. J. He then became associated with the Westinghouse organization, and installed and equipped an incandescent lamp factory at Swissvale, Pa. In 1885, when because of illness he removed from Pittsburgh to Great Barrington, Mass., he set up a plant incorporating his ideas on long-distance light and power transmission, which distributed to the town 500 volts through transformers connected in multiple. The Westinghouse Company then took over the manufacturing details and installed the Stanley apparatus at Niagara Falls. In 1890 Mr. Stanley organized the Stanley Electric Manufacturing Company, which made the first of a long series of installations of the multiphase transmission system in 1894 at Housatonic, Mass., operating at 2,000 volts. In 1898 he organized the Stanley Instrument Company. He also carried on an extensive consulting practice, until his death on May 14, 1916. He served the Institute on the Edison medal committee, from 1914 to 1916. He was born November 22, 1858, in Brooklyn, N. Y.

Nikola Tesla

(A'88, F'17, member for life)

Edison Medalist 1916

IN THE days when a commercial rivalry existed between the supporters of the a-c and d-c systems, Nikola Tesla invented independently the polyphase a-c system and built the first small polyphase motor, inaugurating a new epoch in the electrical industry. His other discoveries and inventions are many, principally connected with apparatus for the use and transmission of power, such as the polyphase generator and transformer, oscillation transformer, revolving field generator, and split-phase motor, as well as high-frequency machines and coils, Tesla tubes, lamp and other high-potential high-frequency apparatus. Mr. Tesla was born in Smiljan, Lika, a borderland region of Austria-Hungary, and was educated at the Polytechnical School in Gratz and at the University of Prague. His electrical career began in 1881 when he was 24, at Budapest, where he made his first electrical invention, a telephone repeater, and conceived his idea of the rotating magnetic field. He came to the United States in 1884 and became a naturalized citizen. At first he was employed at the Edison works, and later by the Westinghouse Company, which purchased his patents on the polyphase a-c system and manufactured the motor. In 1890 he left the Westinghouse organization and began experimenting with high-potential, high-frequency alternating currents. In the last few years he has been working on a method to derive power in large amounts without regard to location.

Benjamin G. Lamme

(Associate 1903, Member 1903)

Edison Medalist 1918

FOR more than 30 years Benjamin Garver Lamme was an acknowledged leader in the invention and mathematical design of electrical apparatus particularly in the a-c field. Chief among his inventions of which the patents numbered more than 150, were the "umbrella" generators first used at Niagara Falls, the synchronous converter and the series commutator-type motor, which is now in use in street and other electric transit systems. Beginning in the testing department of the Westinghouse Electric and Manufacturing Company in 1889, he rose to distinction early through his remarkable ability to apply complex mathematical theorems to electrical apparatus: in 1890 he prepared specifications purely from calculation for a double-reduction railway motor. In 1900 he was made assistant chief engineer and from 1903 until his death July 8, 1924, he was chief engineer. Mr. Lamme was greatly interested in high-power generators and shortly before his death designed a 65,000-kw generator, the largest built to that date. He was born January 12, 1864, at Springfield, Ohio, and graduated in 1888 from Ohio State University with the degree of mechanical engineer. He served the Institute on many committees and represented it on the national committee of the International Electrical Congress (1919–21) and acted as chairman of the committee on inventions of the Naval Consulting Board in 1917. The Lamme medal was established by his bequest.

John W. Howell

(A'87, M'88, F'12, member for life)

Edison Medalist 1924

ONE OF the most distinguished pioneers in the incandescent lamp field of electrical engineering is John White Howell, whose inventions and extensive research work have contributed greatly to the improvements and enlargement of incandescent lamp production. Among his important achievements are the development of a successful portable voltmeter, a wheatstone bridge type of potential indicator, and the comparative indicator. He determined for the first time the relation between the life and candle-power of incandescent lamps (1886); introduced a carbonaceous clamp which decreased clamping and filament costs and increased the quality of the lamp (1887) and later made certain changes to increase the speed of exhaust. He improved the Thomson-Houston method of treating carbon filaments and developed a treating machine which revolutionized the treating process, and introduced the squirted cellulose filament. He assisted in the design of the first stem-making machine and in the development of metalized filaments. He was born in New Brunswick, N. J., December 22, 1857. In 1881 he finished a special course in electrical engineering at Stevens Institute, receiving the honorary E.E. degree in 1899. He became identified with the Edison Lamp Company, beginning as electrician in 1881 and becoming technical advisor to the manager of works in 1890; in 1912, when the company was merged with the General Electric Company, he was made engineer and assistant manager of the lamp works. When he retired in 1931 his title was chief engineer of the lamp works. He is a member of The American Society of Mechanical Engineers, the Franklin Institute, and other technical societies.

W. D. COOLIDGE

FRANK CONRAD

EDWARD D. ADAMS

ELMER A. SPERRY

W. D. Coolidge

(A'10, M'34)

Edison Medalist 1927

AMONG electrical engineers engaged in the electrochemical and X ray fields, William David Coolidge holds an outstanding place. He is well known for his invention and application of ductile tungsten and for his development of a vacuum tube that has simplified and revolutionized the production of X rays. He is also the inventor of a submarine detecting device and of the Coolidge X ray tube. Doctor Coolidge was born at Hudson, Mass., October 23, 1873, and was graduated with the B.S. degree from Massachusetts Institute of Technology (1896), and Ph.D. from the University of Leipzig (1899). For 5 years he taught at the Massachusetts Institute of Technology as assistant in physics, instructor in physical chemistry and assistant professor of physicochemical research. In 1905 he joined the research laboratory of the General Electric Company, becoming assistant director in 1908, associate director in 1928, and director in 1932, which position he now occupies. Doctor Coolidge served the Institute as a member of the electrophysics committee from 1927 to 1929. He is a member of the American Electrochemical Society, American Physical Society; American Roentgen Ray Society, American Radium Society, Radiological Society of North America; Roentgen Society (England) and many others. He has been the recipient of several distinctive awards, notably the Washington award in 1932.

Frank Conrad

(Associate 1902)

Edison Medalist 1930

EVEN if he were not widely known for his contributions to radio broadcasting and short-wave radio transmission, Frank Conrad would be an outstanding figure in the electrical engineering world for his invention of numerous important electrical devices. He was born in Pittsburgh, Pa., May 4, 1874. At 16 he entered the employ of the Westinghouse Electric and Manufacturing Company in Pittsburgh as a shop assistant. On the strength of his first idea concerning a feeding mechanism for arc lamps, although rejected, he was taken into the experimental laboratory where he obtained an excellent foundation in physics and electricity. Within a short time he was busy on a long succession of inventions, including the "round type" arc lamp, long-scale induction indicating instrument, "round type" watthour meter, magnetic shunt and other switches, lightning arresters, and circuit breakers for use in a-c work, which are covered by more than 200 patents. He was closely associated with, and later in entire charge of, the arc-lamp design department. In 1904 he was appointed general engineer; since 1921 he has been assistant chief engineer. Doctor Conrad's connection with radio began with his interest as an amateur in the reception of time signals, and later in radio-telephone transmission. One of the few radio devices which saw war service was his 1,000-cycle 200-volt self-exciting generator for airplanes, weighing 11 pounds, encased with radio equipment and driven by a propeller. From 1919 to 1921 Doctor Conrad served the Institute as a member of the joint power factor committee. In 1928 the University of Pittsburgh awarded him the honorary degree of D.Sc. He is a fellow of the Institute of Radio Engineers and a member of the Society of Automotive Engineers and the American Society for the Advancement of Science.

Edward D. Adams

(Associate 1910)

John Fritz Medalist 1926

EDWARD Dean Adams is well known in the electrical field for his life-long connection with important engineering works and as an officer and director of corporations engaged in the construction and operation of water works, power plants, railroads, etc. He first became identified with the electrical industry by lending financial support to Edison's proposal to introduce electric lighting for streets and buildings in New York, about 1878. Next he became interested in the development of hydroelectric power at Niagara Falls. When electrical transmission was decided upon, Mr. Adams organized and became president of the Cataract Construction Company, which completed the project in 1895. He then turned his attention to the development, reorganization, and financing of numerous railroads, such as the St. Paul and Northern Pacific, Missouri Pacific, Northern Pacific, and West Shore. At various times he served as an officer of these and the many other utility, power and manufacturing organizations with which he was associated. Mr. Adams was born in Boston, April 9, 1846, and was educated at Norwich University, Vermont, receiving the B.S. degree (1864), M.S. (1897), LL.D. (1906) and M.A. (1908). He served the Institute on the Edison medal committee, 1919–24; and from 1916 until his death May 20, 1931, he represented the Institute on the Engineering Societies' library board and in the United Engineering Trustees, Inc. He was a member of the National Research Council, engineering and industrial research division, the American Society of Civil Engineers, and a vice-president of The American Society of Mechanical Engineers.

Elmer A. Sperry

(A'84, M'93, member for life)

John Fritz Medalist 1927

WHILE he had to his credit more than 400 patents, Elmer Ambrose Sperry is perhaps best known for his gyro-compass and ship stabilizer. Other inventions included his arc lamp, automatic current regulator, arc dynamo, motors, storage battery, high-intensity arc light, and searchlight. He was the originator of the first electric mining machinery and many new developments in the transportation line. Mr. Sperry was born at Cortland, N. Y., October 12, 1860. He was graduated from the State Normal School at Cortland and attended lectures at Cornell. The honorary degree of doctor of engineering was conferred upon him by Stevens Institute of Technology and Lehigh University, and doctor of science by Northwestern University. When he was only 19, he perfected one of the first electric arc lights and secured its practical adoption. Beginning in 1880, he organized numerous companies bearing his name to perfect and manufacture his inventions, one of the last being the Sperry Development Corporation, which he sold in 1929 to the Curtiss air interests. At the time of his death, June 16, 1930, he was the proprietor of Sperry Products, Inc. He was a charter member of the Institute and served as a member of the marine, research, Edison medal, and Lamme medal committees at various times. He was a member of a number of other societies, including the Electrochemical Society, of which he was a charter member, and The American Society of Mechanical Engineers, and was the recipient of several prizes and distinctions, both national and foreign.

Allan B. Field
(A'03, M'09, F'13, Life Member)

Lamme Medalist 1928

THE first Lamme Medal to be presented by the A.I.E.E. was awarded Allan Bertram Field in 1928 "for the mathematical and experimental investigation of eddy current losses in large slot-wound conductors in electrical machinery." Mr. Field was born in New Barnet, England, December 28, 1875. He studied at Finsbury Technical College, London, 1890–93. After being engaged in shopwork and drafting, he studied at St. Johns College, Cambridge, 1896–99, and was awarded the Honours B.A. degree, and later the M.A. and Honours B.Sc. degrees. During 1900–02, he was engaged in engineering work for the British Thomson-Houston Company in London. He came to the United States in 1902, spending more than a year in the testing department of the General Electric Company at Schenectady, N. Y., afterward being engaged in transformer design. During 1905–08, he was with the Bullock Electric Manufacturing Company, and the Allis-Chalmers Company in the design of a-c generators and motors. In 1909 he joined the Westinghouse Electric and Manufacturing Company, being appointed engineer-in-charge of turbine generator design in 1911. In 1914 Mr. Field returned to England, becoming consulting engineer and professor of mechanical engineering at the University of Manchester, retaining this position until 1917 when he went with Vickers, Ltd., London. In 1920 he became and still is consulting engineer for the Metropolitan-Vickers Electrical Company, Ltd., Manchester, England.

R. E. Hellmund
(A'05, M'09, F'13)

Lamme Medalist 1929

THE second individual to be awarded the Lamme Medal of the Institute was Rudolf Emil Hellmund. Mr. Hellmund is widely known for his inventive genius, some 300 patents in the United States and other countries having been granted him. He was born at Gotha, Germany, February 2, 1879. He graduated from the Technical Institute of Ilmenau, Germany, worked 3 years, then continued his studies at Charlottenburg University, Berlin, graduating in 1899 with the degree of electrical engineer. After being engaged in the development work in Germany, he came to the United States in 1903. After doing other engineering work, he was associated in 1905 with William Stanley at Great Barrington, Mass. During 1905–07, he was in the engineering department of the Western Electric Company at Hawthorne, Ill., in charge of all a-c motor design for the company. Since October 1907, he has been with the Westinghouse Electric and Manufacturing Company. After being in charge of the development of various kinds of induction motors, he was placed in charge of all designs of d-c and a-c railway motors. In 1907 he was assigned miscellaneous consulting duties, and in 1921 was appointed engineering supervisor of development. In 1926 he was made chief electrical engineer and in 1933 was given the position of chief engineer of the company. Mr. Hellmund has presented many papers before the Institute and has been a member of the standards committee since 1930. In the past 2 years he has devoted much attention to the development of air conditioning equipment.

William J. Foster
(Associate 1907, Fellow 1916)

Lamme Medalist 1930

THE Institute's Lamme Medal for 1930 was presented to William James Foster "for his contributions to the design of rotating a-c machinery." Doctor Foster has a long record of service in the design of motors and generators and has been responsible for a great many inventions in this field. He was born at Argyle, N. Y., September 17, 1860. After receiving the A.B. degree from Williams College in 1884, he remained a year for advance work in mathematics. During the next 5 years, he taught high school subjects, and made an intensive study of physics. In 1891 the degree of M.S. was conferred upon him by Cornell University. In the summer of that year Doctor Foster began his engineering career in the Thomson-Houston works at Lynn, Mass., being engaged in the design of d-c machines and synchronous converters. In 1892 he was made assistant engineer. In 1894 he became designing engineer for the General Electric Company at Schenectady, in general charge of electrical design of a-c machines. For about 25 years thereafter he was in charge of practically all the designs and calculations on a-c machines, he himself designing many of the most important generators that were built by the company. Through Doctor Steinmetz, with whom he worked closely for many years, he prepared many of the standards adopted by the A.I.E.E. Doctor Foster is now consulting engineer (retired) for the General Electric Company, and lives at Schenectady. He was a member of the Institute's committee on electrical machinery 1920–30 (chairman 1928–29), and of the meetings and papers (now technical program) committee 1928–29.

Guiseppe Faccioli
(A'04, M'11, F'12)

Lamme Medalist 1931

"FOR his contributions to the development and standardization of high-voltage oil-filled bushings, capacitors, lightning arresters, and numerous other features in high-voltage transformers and power transmission," Guiseppe Faccioli was presented the 1931 Lamme Medal of the A.I.E.E. He was born at Milan, Italy, April 7, 1877. Graduating from the University of Milano in 1899 with the highest scholarship, he was engaged for one year in the electrification of a locomotive factory, spent one year in the testing room and in charge of the design of induction motors and alternators for the Tenomasio Brown Boveri of Milano, was engaged as a consulting engineer for one year, and then in 1902 came to the United States. Between 1902 and 1906 he had a varied experience, being with the Interborough Rapid Transit Company, New York, the Crocker-Wheeler Company, and an assistant to William Stanley at Great Barrington, Mass. In 1906 he began his long term of service with the General Electric Company. He continued at the Great Barrington laboratory until 1908, when he was transferred to the railway department at Schenectady, later the same year being transferred to the transformer department, and in 1911 appointed assistant engineer of the transformer department. Later he was transferred to the Pittsfield works, and in 1913 was appointed work's engineer of this plant. In 1927 he also became associate manager, retiring in 1930. His death occurred January 13, 1934. Mr. Faccioli had served the Institute as manager 1918–22, and as vice-president 1922–24. He had also served on many committees of the Institute.

ALLAN B. FIELD

R. E. HELLMUND

W. J. FOSTER

GUISEPPE FACCIOLI

The Institute's National Secretaries

N. S. Keith

(Associate 1884, Member 1894)

Secretary 1884–85

THE FIRST secretary of the Institute was Doctor Nathaniel Shepard Keith, one of the most active of the small group of individuals who founded the Institute. Doctor Keith served as secretary during 1884 and 1885. It was he who circulated the "call" for the first meeting of what was to be the American Institute of Electrical Engineers.

Doctor Keith was born at Boston, Mass., July 14, 1838. He was educated as a chemist in his father's chemical laboratory in New York City, and maintained practice as an electrometallurgical engineer the larger part of his life. The early years of his life were spent as a mining and metallurgical engineer in Colorado. For many years following 1870, he was engaged in electrical work as an investigator, inventor, writer, and electrical engineer. For some time following 1885 he was engaged in the manufacture and installation of electric light and power apparatus in San Francisco. He was at one time secretary-treasurer of the American Venture and Mines Corporation. For many years preceding his death, January 27, 1925, Doctor Keith had been in business in Philadelphia as a consulting engineer.

During the first 2 years of the Institute's history Doctor Keith was a member of the editorial staff of the *Electrical World*, along with C. O. Mailloux and T. C. Martin, both of whom subsequently became presidents of the Institute. Doctor Keith was one of the conferees of the Electrical Conference in Philadelphia, in 1884, and a judge of the Philadelphia Electrical Exhibition in that year.

T. COMMERFORD MARTIN,
ACTING SECRETARY 1884–85

DURING the period 1884–85, while Dr. N. S. Keith was serving the Institute as secretary, Thomas Commerford Martin (president of the Institute 1887–1888) served as acting secretary. A biographical sketch of Mr. Martin is given in connection with the group of presidents in this issue.

Ralph W. Pope

(A'04, member for life)

Secretary 1885–1911

OVER a period of nearly 27 years, Ralph Wainwright Pope served the Institute as its secretary. He was first elected in 1885, and served each year consecutively from that time until 1911, when he was appointed honorary secretary for life. Mr. Pope was a younger brother of Franklin L. Pope, second president of the Institute.

Ralph W. Pope was born at Great Barrington, Mass., August 16, 1844. He was educated at Amherst Academy. Early in life he developed a marked taste for mechanics. After early experience in the local telegraph office, he entered the service of the Housatonic Railroad in 1859, becoming a telegrapher. After being in various telegraph offices of this road, he entered the service of the American Telegraph Company in 1864, being in the New York office. In 1865 he joined the Collins Overland Telegraph Expedition in an attempt to establish a through service to Europe by way of Alaska and Siberia. It was this expedition of which Franklin L. Pope was chief of the geographical department; the success of the Atlantic cable prevented the establishing of this connection. Ralph W. Pope was for 10 years thereafter in the service of the Gold and Stock Telegraph Company, resigning his position as deputy superintendent in 1883. From that date until 1888 he was actively engaged in the editing and publishing of technical electrical papers in New York City. He was associate editor of *The Telegrapher* and *The Electrical Engineer*, and editor of *Electric Power*, which he founded.

During his tactful administration, the growth of the Institute was rapid. In 1887, he consented to devote practically all of his time to its interests alone. He made a constant study of its needs, and did not hesitate to recommend the adoption of all that appealed to him as desirable in the methods and activities of other technical organizations. His clear conception of detail, his genius for taking pains, and the orderly methods of his office, all were extremely valuable in his position as secretary.

F. L. Hutchinson

(A'94, M'13, member for life)

Secretary 1911–32

UPON the resignation of Ralph W. Pope in August 1911, Frederick Lane Hutchinson was appointed acting secretary, being later appointed secretary as of January 1, 1912.

Mr. Hutchinson was born at Elizabeth, N. J., April 2, 1866. He began his business experience with several years' service with the Pennsylvania Railroad Company in New York City, later entering Cornell University in 1889. In 1893 he graduated from the electrical engineering course, and immediately entered the employ of the Westinghouse Electric and Manufacturing Company. After several years' experience in the manufacturing, testing, engineering, and sales departments in Newark, N. J., New York City, and Pittsburgh, Pa., he was transferred to the publication department.

In 1901 he became manager of the publication department of the C. W. Hunt Company, New York, and in the following year became advertising manager of the National Electric Company of Milwaukee, Wis. A year later he was made manager of electrical sales for the same company.

Mr. Hutchinson returned to New York in 1904 to undertake some special work on the TRANSACTIONS of the Institute. This work gradually increased in scope until in February 1908 he was appointed assistant secretary, becoming the national secretary at the beginning of 1912. Mr. Hutchinson served in this capacity continuously until his death, February 26, 1932.

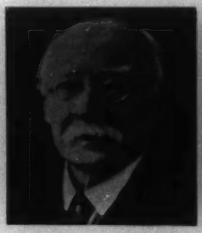
Mr. Hutchinson was thoroughly familiar with the history and policies of the Institute, the scope and duties of its numerous committees and representatives, and the relations of the Institute to other engineering and similar organizations, both in this country and abroad. He was one of the delegates to the World Power Conference, London, 1924, and to the World Engineering Congress, Tokyo, 1929. He had served on various Institute committees, both before and after becoming secretary. Immediately prior to his death he was a member of the committees on publications, coördination of Institute activities, award of Edison Medal, and maintenance of Institute headquarters. He was also a representative of the Institute on several other bodies. During Mr. Hutchinson's term as secretary, the Institute's membership increased $2^1/_2$ times.

H. H. Henline

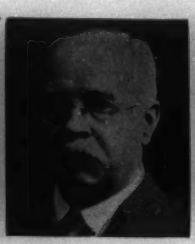
(Associate 1919, Member 1926)

Secretary 1932–

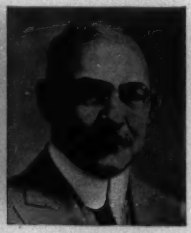
THE PRESENT national secretary of the Institute is Henry Harrison Henline. Mr. Henline became assistant na-



N. S. KEITH



RALPH W. POPE



F. L. HUTCHINSON

tional secretary in 1927, and upon the death of F. L. Hutchinson in 1932, he became acting national secretary. Effective January 1, 1933, he was appointed national secretary, taking over all the executive duties that had been performed by Mr. Hutchinson for 20 years.

For many years Mr. Henline has been active in Institute work, and prior to his affiliation with the national headquarters staff, he made numerous contributions to its published technical work. These included papers on engineering education, a standard frequency radio station, and high voltage power transmission. He has served as chairman of the San Francisco section (1922–23); faculty counselor for the Student Branch at Stanford University, Calif. (1926); chairman of the committee on student activities for the Pacific district (1926); and as a member of the Sections committee (1923–27). Since joining the headquarter's staff in 1927, Mr. Henline has served as a member of 6 of the Institute's committees, and has been a representative of the Institute on 6 other bodies. He is at present active on most of these.

As assistant secretary, Mr. Henline participated in many phases of the Institute's work, but devoted his principal attention to the work of its many Sections and Branches.

Mr. Henline was born at Colfax, Illinois, March 12, 1889, graduating in 1914 from the University of Illinois, with the degree of B.S. in E.E. After serving for a year as instructor in science and mathematics in the Oktaha (Okla.) High School and as director of athletics for the public schools there, he entered the Chicago Central Station Institute of the Commonwealth Edison Company. In 1916 he entered the commercial Engineering department of the Illinois Maintenance Company of Chicago.

Joining the faculty of Stanford University in 1917 as an instructor, Mr. Henline later was promoted to assistant professor (1920) and to associate professor (1924) in the department of electrical engineering. In his work of instruction Mr. Henline gave at various times many courses in electrical engineering subjects, and was in charge of the machinery laboratory for 5 years, and in charge of communication engineering for 3 years. He also was associated with Dr. Harris J. Ryan in some of the high voltage research that has been carried on so energetically at Stanford University.

The Institute's National Treasurers

Rowland R. Hazard

(Associate 1884)

Treasurer 1884–86

THE INSTITUTE'S first treasurer was Rowland Robinson Hazard. Mr. Hazard was a charter member of the Institute, and at the time of its formation was president of the Gramme Electric Company, of New York City. He presented a paper, "The Scientific Street," at the Institute's first technical meeting, October 7–8, 1884. About 5 years ago Mr. Hazard died at his home on the Island of Jersey, England, where he had lived many years. He was over 90 years of age.

George M. Phelps

(Associate 1884)

Treasurer 1887–95

THE SECOND treasurer of the Institute was George May Phelps, who served continuously from the time of his first election to that office on May 17, 1887, until his death on April 11, 1895.

Mr. Phelps was born at Troy, N. Y., in 1843. He was educated in the public schools and high school of that city. From 1861 until his death he was continuously engaged in electrical interests, excepting for an interval of 5 years. He was first employed in the shop of the American Telegraph Company, of which his father was superintendent. He afterward served in the auditing department of the American Telegraph Company from 1863 to 1866. From 1871 to 1879, he was assistant to his father in the management of the factory of the Western Union Telegraph Company in New York City. In April 1879, the Western Union disposed of its manufacturing interests to the Western Electric Company, and Mr. Phelps was appointed superintendent of the factory by the latter organization, which position he held until December 1885. In 1886, he joined Franklin L. Pope, who was then president of the Institute, in conducting *The Electrician and Electrical Engineer*, at that time published monthly, acquiring a proprietary interest in that journal shortly after. The title was subsequently changed to *The Electrical Engineer*, and, beginning in 1890, was issued weekly, with Mr. Phelps as president.

Mr. Phelps was a charter member of the Institute and was elected as one of its managers on May 19, 1885. He served on the council in this capacity until his election as treasurer. He also had served on various standing and special committees, and had at all times given readily of his time and services to the interests of the Institute.

George A. Hamilton

(A'84, M'84, F'13, HM'33, member for life)

Treasurer 1895–1930

THE THIRD treasurer of the Institute was George Anson Hamilton, a charter member of the Institute. A biographical sketch of Mr. Hamilton is given on p. 816 of this issue, in connection with his election as an Honorary Member, and a recent statement of his is given on p. 823.

W. I. Slichter

(A'00, M'03, F'12)

Treasurer 1930–

THE FOURTH and present treasurer of the Institute is Walter Irvine Slichter, who has served since 1930. He is now professor of electrical engineering and head of the department at Columbia University.

Professor Slichter was born in St. Paul, Minn., May 7, 1873, and graduated from Columbia University in 1896, with an E.E. degree. He entered the employ of the General Electric Company as a student in that year, being transferred to the office of Dr. C. P. Steinmetz the following year. During the next 2 years he was engaged in designing induction motors, alternators, rotary converters, transformers, and special experimental apparatus. For a number of years thereafter he devoted most of his time to the design of electrical machinery, and, more particularly, the equipment of electric railways. In 1910 he was appointed to his present position as professor of electrical engineering and head of the department at Columbia. During the war, he was civilian director of the air service school for radio officers at Columbia.

Professor Slichter was a member of the Institute's board of directors 1918–22, vice-president 1922–24, and has been an active worker upon several of the important committees of the Institute. He has been chairman of the meetings and papers committee, of the editing committee, and a member of the finance committee. He is a member of several other engineering and scientific societies, and in 1903 was president of the General Electric Engineering Society, and was instrumental in reorganizing it into the Schenectady Section of the Institute.

H. H. HENLINE

GEORGE M. PHELPS

W. I. SLICHTER

Formation of the Institute and the Enrolling of Its Charter Members

"WE LEARN that a movement has been inaugurated for the formation of a national electrical society, and that several distinguished men connected with the science and with electrical enterprises have promised it their warmest support. The idea is admirable, and cannot but succeed. It is said that details will shortly be made public." This simple statement, presaging the founding of the Institute, appeared in the *Electrical World* for March 29, 1884.

The first definite steps toward the formation of a society were taken in April 1884, when Dr. N. S. Keith, electrical engineer, New York City, circulated a "call" for the purpose of establishing a national electrical society to which it was suggested to give the name of the "American Institute of Electrical Engineers." This "call" outlined the principal reasons for the formation of a society, and outlined the activities which it was proposed to undertake. The activities mentioned in this early document are almost identical with those on which the Institute today is engaged. The pioneers in the electrical industry who organized the Institute had a remarkably clear vision as to what it might accomplish for the benefit of its members and of society in general.

Although the "call" had proposed that an organization meeting be held on May 13, 1884, the document was so quickly signed by a large number of electrical engineers, then commonly known as "electricians," capitalists, and others connected with electrical enterprises or interested in the advancement of electrical science, that it was deemed advisable to hold a meeting on April 15, 1884. The signers of this document, and a number of other individuals who had expressed interest, were requested to meet on that date at the rooms of the American Society of Civil Engineers, New York, as founders of the proposed society.

Meeting of April 15, 1884

The meeting of April 15, 1884, was called to order by Dr. N. S. Keith, who nominated Joseph P. Davis, vice-president of the Metropolitan Telegraph and Telephone Company, as chairman of the meeting. After Mr. Davis took the chair, Dr. Keith was elected temporary secretary.

A series of resolutions as to name, object, membership, dues, management, committees, etc., was then offered, and after some debate, the resolutions and the whole scheme of organization were referred to a committee of 5, with instructions to call a meeting to hear and act upon its report. The chair afterward appointed the committee, consisting of the following:

W. A. Hovey, president, Merchants' Electric Light Company, Boston.
N. S. Keith, electrical engineer.
G. A. Hamilton, electrician, Western Union Telegraph Company.
William H. Eckert, general superintendent of the Metropolitan Telephone and Telegraph Company.
George L. Beetle, Western Electric Company.

After a vote of thanks to the American Society of Civil Engineers for the use of its rooms, the meeting adjourned.

Meeting of May 13, 1884

The organization meeting of the Institute, held May 13, 1884, was presided over by Joseph P. Davis. Following a reading and approval of the minutes of the April 15 meeting, the committee on organization reported that it had completed a proposed set of rules for the government of the Institute and had nominated a sufficient number of persons to fill the offices created. The rules were then read and adopted, the election was held, and the results announced. The Institute then had a permanent organization, with a complete set of officers.

With the organization completed, the first piece of business was undertaken, which consisted of the reading of a communication from the examiner in the electricity division of the U.S. patent office, pointing out various evils in patent procedure; a resolution urging that the work of the patent office be put on a more efficient basis was then passed, and a committee of 3 was authorized to promote this endeavor.

Following a discussion of the state of electric lighting on the Pacific Coast, resolutions thanking the American Society of Civil Engineers for the use of the rooms and thanking the organization committee, were passed, and the meeting adjourned.

Philadelphia Meeting, 1884

One of the factors which precipitated the founding of the Institute in 1884 was the International Electrical Exhibition to be held in the fall of that year in Philadelphia under the auspices of the Franklin Institute. In conjunction with this exhibition, the U.S. Congress had authorized a National Conference of Electricians. Representatives of many foreign electrical societies were to attend the exhibition, and it was felt essential that there be some organization of electrical engineers in the United States to officially receive these delegates.

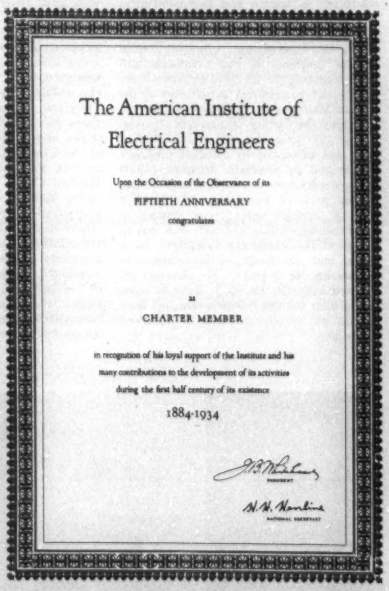
The directors of the International Electrical Exhibition tendered to the Institute the use of rooms in the exhibition building, these rooms being open to Institute members from September 2 to October 11. On October 7 and 8, 1884, the first meeting of the Institute for the reading and discussion of professional papers was held at the Continental Hotel and in the exhibition rooms. Eleven papers were read at these meetings, several of which have since become historic documents.

Annual meetings were then held in May 1885 and in May 1886, when the development of a system of more frequent meetings was begun. Subsequent developments have, of course, included the holding of several national meetings each year, with Section and Branch meetings held many times a year in all sections of the United States.

The Institute's Charter Members

Analysis of the records of the Institute definitely indicates that at least 71 charter members were enrolled at the meeting of April 15, 1884. In addition to these, it is possible that there were a few more charter members, as accurate records were not always kept at that time.

Of these 71 charter members, 6 are still


The American Institute of
Electrical Engineers

Upon the Occasion of the Observance of its
FIFTIETH ANNIVERSARY
congratulates

as
CHARTER MEMBER

in recognition of his loyal support of the Institute and his
many contributions to the development of its activities
during the first half century of its existence

1884-1934

PRESIDENT

NATIONAL SECRETARY

Certificate to be awarded the 6 living charter members of the Institute during the 1934 summer convention, June 25–29, at Hot Springs, Va.

on the rolls of the Institute. These are: Charles L. Clarke, Schenectady, N. Y.; E. N. Dickerson, Jr., New York, N. Y.; George A. Hamilton, Elizabeth, N. J.; Frank B. Rae, Berkeley, Calif; Elihu Thomson, Lynn, Mass.; and Edward Weston, Newark, N. J. Biographical sketches of Mr. Hamilton, Professor Thomson, and Doctor Weston, have been given in connection with the items on Presidents and Honorary Members on preceding pages of this issue. Brief items on the other 3 living charter members follow, together with statements prepared by Mr. Clarke and Mr. Hamilton.

Charles L. Clarke

Charles Lorenzo Clarke (A'84, M'85, F'12, member for life) a charter member of the Institute, and now a consulting engineer living at Schenectady, N. Y., was born at Portland, Maine, April 16, 1853. In 1870 he began civil and railroad engineering, becoming first assistant engineer on the old Boston and Maine Railroad, but gave up this position to enter Bowdoin College, from which he received the degrees B.S., 1875; M.S., 1879; and C.E., 1880. During part of this period he was designer and draftsman in various steel manufacturing plants. In 1880 he entered the laboratory of Thomas A. Edison, at the time Mr. Edison invented the incandescent electric lamp, as mathematical assistant. However, Mr. Clarke quickly engaged in experimental, testing, and research work and then designing of electrical generators and other apparatus for Mr. Edison's first commercial system of lighting. In 1881, he was chief engineer of the parent Edison Electric Light Company, and had engineering charge of the pioneer development and installation of the first system for central station and isolated plant lighting, organized and managed the engineering staff and research and testing departments, and was consulting engineer of the allied operating companies. Between 1884 and 1887 he was engineer for the Telemeter Company, New York, and for the next 2 years was with the Gibson Electric Company, engaged in the development of storage batteries. Between 1889 and 1901 he was in consulting engineering practice and on patent work. In 1901 he became consulting engineer and patent expert in the board of patent control of the General Electric Company and the Westinghouse Electric and Manufacturing Company, and in 1913 became consulting engineer on the staff of the General Electric Company at Schenectady. Mr. Clarke held this position until his retirement in 1931. Mr. Clarke's position as one of the outstanding pioneers of the electric industry is justified by his work on the design of the famous Jumbo machine installed on early Edison systems, and his supervision of the installation of the Jumbo machines and other equipment in the also famous Pearl Street station in New York.

A Statement From Mr. Clarke

Mr. Clarke has contributed a statement for this anniversary issue of Electrical Engineering, in which he expresses briefly his feelings in respect to the past and present of the Institute, and the true status of the so-called machine age in which Institute members are so vitally concerned. Mr. Clarke's statement follows:

"On this 50th anniversary in the life of the American Institute of Electrical Engineers, a charter member is naturally in reminiscent mood to compare the early with the present status of the organization, which at the end of 3 years after its founding counted only about 30 members, with no assets now worth mentioning, and has phenomenally prospered, with a present membership of 15,200, with assets amounting to some $800,000. This material growth symbolically bespeaks the value of the past accomplishments of the Institute for

CHARLES L. CLARKE

the welfare of electrical engineers, and in turn, the obviously great worth of their service to society at large. The outcome of that service is seen and in use on every hand, both day and night, on a scale which in the aggregate is so immense as to be almost beyond reckoning, it may quite truly be said.

"Included in major activities of members of the Institute have been the creating and applying of electric machines largely for operating in conjunction with other machines, to lessen labor, or increase and lessen cost of production, or both. The members are historically acquainted with the long-ago periodical, unthinking agitations against and sometimes forceful opposition to, the use of these machines for these purposes. This objection to machines had died down, and was practically non-existent when the Institute was founded.

"But in the last 50 years, charter members, and other members in more recent years, have seen a phenomenal increase in use of such so-called labor saving machines, which has given opprobrious rise to the term 'machine age,' and much comparatively recent misdirected agitation against this alleged condition, on the ground that labor has become the slave of the machine, which is patently an incorrect conception of the true situation.

"Machines have neither souls nor hearts, thus can neither be soulless nor heartless, like some human beings. Nor can they make slaves of men, as can other men, who sometimes do so. Machines are but inert material tools in the hand of man, for him to use for a good purpose, or possibly for bad, if such be his disposition and intent. In this sense, no more and no less, they are exactly like the generally simple tools of man in early centuries. So it comes to this: that the welfare of society depends upon the acts of man toward man, fair or foul, just or unjust, machine or no machine. There can be no such condition as a machine age in a sense invidious to the machine. It may be made to do a great good, but of itself can harm no one.

"Let not any member of the Institute be misled into discouragement by revival of the old agitation against machines; but let him keep on improving the old and adding to the number of new machines—all useful when under wise management, that has a heart and soul, and a moral interest in the just welfare of all men in all stations of life."

E. N. Dickerson

Edward Nicholl Dickerson (A'84, member for life), electrical engineer and patent attorney, was born at Newport, R. I., August 23, 1852. He is a son of E. N. Dickerson, Sr., who in the period of about 1850 and 1860, was probably the outstanding patent attorney in the United States. E. N. Dickerson, Jr., the charter member of the Institute, graduated from Trinity College with the degree of A.B. in 1874, and from Columbia Law School with the degree of LL.B. in 1876. His principal activity has been the practice of patent law, which he has maintained in New York. During the early days of the Institute while it was active in an attempt to secure improved patent procedure, Mr. Dickerson suggested methods of providing reforms. He is a member of many clubs and associations in New York, several of them connected with the legal profession.

Mr. Hamilton's Statement

A brief statement prepared by George A. Hamilton for this anniversary issue of Electrical Engineering follows. A biographical sketch of Mr. Hamilton, who served the Institute as its national treasurer over a 35-year period, and who was elected an Honorary Member of the Institute in 1933, is given on a preceding page of this issue.

"The Institute is now celebrating its 50th anniversary. The occasion naturally turns our attention to its earlier days, and the following brief references thereto may not be without interest.

"In the early eighties there was much activity in electrical matters, new industries were coming to the front, and old ones expanding. In this connection the growing desire for some authoritative body to deal with the technical side of questions was felt, and on the initiative of N. S. Keith a meeting of those interested was called to consider the matter. The final outcome resulted in the organization of the Institute, with Dr. Norvin Green as president.

"Under the favorable conditions the new body grew and prospered, slowly at first, and more rapidly later. By 1920 its rolls listed 10,000 members and by 1930 over 18,000.

"Members sometimes met at dinner for discussion and informal talks.

"The first 3 or 4 years few papers were published but since there has been no dearth of papers as attested by the well-filled volumes of the PROCEEDINGS.

"I have enjoyed my membership in the Institute as well for the social pleasures as for the technical information it has brought me, for the new acquaintances formed, and for the more frequent opportunities of meeting old ones, numbers of whom, alas, are no longer with us."

Frank B. Rae

FRANK BENJAMIN RAE (A'84, M'20, member for life) another of the 6 living charter members, was born at Elmira, N. Y., July 25, 1854. Mr. Rae is self-educated. During the period of 1870 to 1881, he was in the telegraph service as messenger, operator, and manager of the Atlantic and Pacific Telegraph Company and the Western Union Telegraph Company. In 1881 he resigned from the position of electrician at San Francisco for the latter company and became engineer for what was then the Brush Electric Light Company, San Francisco, and manager of the San José (Calif.) Brush Electric Company. In 1883 he became engineer for the Commercial Telegram Company (stock quotations) at New York. During the period of 1885–87 he was a consulting engineer at New York, as a member of the firm of Mailloux and Rae. In 1887 he was consulting engineer for the Barker Syndicate in China, and during 1887–92 was engineer for the Detroit (Mich.) Electrical Works, engaged on the Rae Electric Railway System. Since 1892 he has been a consulting electrical engineer, being at Detroit, Mich., 1892–95; Chicago, Ill., 1895–1900; New York, N. Y., 1900–05; Detroit, 1905–10; New York, 1910–13; Cleveland, Ohio, 1913–19; and San Francisco, 1919–23. In 1923 he became electrical engineer for the city of Berkeley, Calif., resigning in 1930. Mr. Rae holds a total of about 100 patents.

List of Charter Members

In addition to the 6 living charter members just mentioned, there were 65 other charter members who are no longer living. Biographical sketches of 13 individuals in this latter group are given in associated pages of this issue. Six of these served the Institute as presidents, 3 were elected to honorary membership, 1 was awarded the John Fritz medal, while 1 charter member served the Institute as secretary, and 2 as treasurers.

A list of all who have been definitely determined to have been charter members of the Institute follows. For those who are mentioned in biographical sketches in this issue, reference to the page number where the sketch appears is given after the name.

Adams, H. C., New York Agent, Fort Wayne Jenney Elec. Lt. Co., New York, N. Y.

Bates, D. H., Pres., B. & O. Tel. Co., New York, N. Y.

Bell, Prof. A. Graham, Washington, D. C. (p. 791)

Berliner, Emile, Inventor, Washington, D. C.

Bosch, Adam, Supt., Fire Alarm Telegraph, Newark, N. J.

Brush, Chas. F., Elec. Engr., Cleveland, Ohio. (p. 815)

Buckingham, Chas. L., Counsel, Western Union Tel. Co., New York, N. Y.

Cheever, Chas. A., New York, N. Y.

Chinnock, C. E., Edison Elec. Illuminating Co., New York, N. Y.

Clarke, Charles L., Elec. Engr., Gibson Electric Co., New York, N. Y. (p. 823)

Cleveland, Wm. B., Elec. Engr., Cleveland, Ohio.

Cross, Chas. R., Thayer Prof. of Physics, and Director of the Rogers Lab., Mass. Inst. of Tech., Boston, Mass.

Curtis, Chas. G., New York, N. Y.

Dana, R. K., Agent, Washburn and Moen Mfg. Co., New York, N. Y.

Davis, Jos. P., Vice-Pres., Met. Tel. and Tel. Co., New York, N. Y.

Delaney, P. B., Synchronous Multiplex Telegraph, New York.

Dickerson, E. N., Jr., Electrician and Counsel in Patent Causes, New York, N. Y. (p. 823)

Diehl, Philip, Inventor, Singer Sewing Machine Co., Elizabeth, N. J.

Durant, Geo. F., Vice-Pres. of Bell Tel. Co. of Mo., St. Louis, Mo.

Edison, Thomas A., Inventor, Orange, N. J. (p. 814)

Emmet, Herman L. R., Publisher and Printer, New York, N. Y.

Farmer, Prof. Moses G., Electrician and Inventor, Eliot, Me. (p. 811)

Field, Stephen D., Electrician, Commercial Tel. Co., New York, N. Y.

Gilliland, E. T., Vice-Pres., Empire City Elec. Co., New York, N. Y.

Green, Norvin, Pres., Western Union Tel. Co., New York, N. Y. (p. 788)

Hall, Clayton C., Civil Engr., Baltimore, Md.

Hamilton, George A., Electrician, Western Union Tel. Co., New York, N. Y. (p. 816)

Haskins, Charles D., Elec. Engr., Western Elec. Co., New York, N. Y.

Hazard, Rowland R., Pres., Gramme Elec. Co., New York, N. Y. (p. 821)

Healy, Clarence L., Supt. and Electrician, Commercial Telegraph Co., New York, N. Y.

Hebard, George W., Pres., United States Elec. Lt. Co., New York, N. Y.

Hochhausen, William, Pres., Excelsior Elec. Co., Brooklyn, N. Y.

Houston, Prof. Edwin J., Electrician, Thomson-Houston Co., Lynn, Mass. (p. 792)

Johnston, W. J., Publisher of *The Electrical World*, New York, N. Y.

Jones, F. W., Electrician, Bankers and Merchants Tel. Co., New York, N. Y.

Keith, N. S., Elec. Engr., New York, N. Y. (p. 820)

Leland, H. W., Mgr., Telephone Exchange, Jersey City, N. J.

Lockwood, Thomas D., Electrician, Am. Bell Tel. Co., New York, N. Y.

Madden, O. E., Pres., Empire City Elec. Co., New York, N. Y.

Mailloux, C. O., Elec. Engr., New York, N. Y. (p. 800)

Martin, T. Comerford, *The Electrical World*, New York, N. Y. (p. 789)

Maynard, Geo. C., Electrician, Washington, D. C.

McKinistry, J. P., Cleveland, Ohio.

Morrison, J. Frank, Baltimore, Md.

Phelps, Geo. M., Elec. Engr. and Editor, New York, N. Y. (p. 821)

Plush, Dr. S. M., Electrician, Philadelphia, Pa.

Pope, Franklin L., Solicitor of Patents, New York, N. Y. (p. 788)

Rae, Frank B., Supt., Commercial Tel. Co., New York, N. Y. (p. 824)

Reilly, J. C., Supt., N. Y. & N. J. Tel. Co., Brooklyn, N. Y.

Roome, H. C., New York, N. Y.

Royce, Fred W., Electrician and Patent Solicitor, Washington, D. C.

Sargent, W. D., Gen. Mgr., N. Y. & N. J. Tel. Co., Brooklyn, N. Y.

Seely, J. A., Electrician, Metropolitan Tel. and Tel. Co., New York, N. Y.

Slater, Henry B., Elec. Engr. and Electrometallurgist, Leadville, Colo.

Smith, Gerritt, Circuit Electrician, Western Union Tel. Co., New York, N. Y.

Smith, J. Elliot, Supt., Fire Alarm Telegraph, New York, N. Y.

Smith, Jesse M., Cons. Elec. Engr. and Expert in Patent Cases, Detroit, Mich.

Sperry, E. A., Elec. Engr., Chicago, Ill. (p. 818)

Stockly, Geo. W., Vice-Pres. and Mgr., Brush Elec. Co., Cleveland, Ohio.

Thompson, Edward P., Cons. Electrician and Patent Atty. in Elec. Cases, New York, N. Y.

Thomson, Prof. Elihu, Electrician, Thomson-Houston E. Co., Lynn, Mass. (p. 790)

Trowbridge, Prof. W. P., Columbia College, New York, N. Y.

Vail, Theo. N., Pres., Metropolitan Tel. and Tel. Co., New York, N. Y.

Vansize, William B., Solicitor of Patents, New York, N. Y.

Wallace, William, Wire Mfg., Ansonia, Conn.

Waring, Richard, Pittsburgh, Pa.

Weston, Edward, Electrician, United States Elec. Lighting Co., New York, N. Y. (p. 789)

Wetzler, Joseph, Editor, "The Electrical World," New York, N. Y.

White, H. C., Mgr., Phoenix Iron Works Co., New York, N. Y.

Williams, Charles, Jr., Electrician, Boston, Mass.

Worthington, Geo., *Electrical Review*, New York.

Among Long-Standing Members

ALTHOUGH the American Institute of Electrical Engineers often is referred to by some of its most ardent supporters as an "organization of young men," and correctly so on the basis of membership analysis, here is a list of members that have been on the Institute's rolls for a total of some 35 to 50 years each, with an average tenure of membership for the 317 of them amounting to more than 40 years! Although the bulk of the burden of leadership and development may fall upon the younger members, the wealth of experience represented in the professional careers of these and other long-time members of the Institute is one of the Institute's greatest assets.

1884 (7)

Clarke, Chas. L. . Schenectady, N. Y.
Dickerson, E. N. . New York, N. Y.
Hamilton, Geo. A. . Elizabeth, N. J.
Millis, John . Cleveland, Ohio
Rae, Frank B. . Berkeley, Calif.
Thomson, Elihu . Lynn, Mass.
Weston, Edward . Newark, N. J.

1886 (4)

Davis, M. M. . North Chatham, Mass.
Hunter, R. M. . Philadelphia, Pa.
Insull, Samuel . Chicago, Ill.
Turner, W. S. . Portland, Ore.

1887 (16)

Ahearn, Thomas . Ottawa, Ontario, Canada
Bates, J. H. S. . Olympia, Wash.
Howell, J. W. . Newark, N. J.
Howson, Hubert . New York, N. Y.
Jackson, D. C. . Cambridge, Mass.
Nichols, E. L. . Ithaca, N. Y.
O'Dea, M. T. . Elmhurst, Ill.
Porter, J. F. . Kansas City, Mo.
Rice, E. W. Jr. . Schenectady, N. Y.
Robinson, Almon . Lewiston, Me.
Rohrer, A. L. . Maplewood, N. J.
Ryan, H. J. . Stanford Univ., Calif.
Sprague, F. J. . New York, N. Y.
Terry, C. A. . New York, N. Y.
Weeks, E. R. . Kansas City, Mo.
Welles, F. R. . Altadena, Calif.

1888 (7)

Goldmark, C. J. . New Haven, Conn.
Kennelly, A. E. . Cambridge, Mass.
Lang, P. A. . London, England
Tesla, Nikola . New York, N. Y.
Townsend, H. C. . New York, N. Y.
Waddell, Montgomery . New York, N. Y.
Wilson, Fremont . New York, N. Y.

1889 (15)

Baylis, R. N. . Bloomfield, N. J.
Bogue, C. J. . Hoboken, N. J.
Colby, E. A. . Newark, N. J.
Davis, D. L. . Salem, Ohio
Doane, S. E. . New York, N. Y.
Dunlap, W. K. . East Pittsburgh, Pa.
Hayes, H. V. . Boston, Mass.
Henshaw, F. V. . New York, N. Y.
Lemp, Hermann . New York, N. Y.
Mosscrop, W. A. . Hempstead, N. Y.
Parsell, H. V. A. . New York, N. Y.
Randall, J. E. . Cleveland, Ohio
Stebbins, Theodore . New York, N. Y.
White, J. G. . New York, N. Y.
Winslow, I. E. . Nice, France

1890 (20)

Bennett, J. C. . Montclair, N. J.
Black, C. N. . San Francisco, Calif.
Brooks, Morgan . Urbana, Illinois
Cornell, C. L. . Plainfield, N. J.
Davis, C. H. . Cape Cod, Mass.
Donner, W. H. . Lansdowne, Pa.
Elmer, William . Philadelphia, Pa.
Entz, J. B. . New Rochelle, N. Y.
Freedman, W. H. . Nyack, N. Y.
Hutchinson, C. T. . New York, N. Y.
Lee, J. C. . Wellesley, Mass.
Lundell, Robert . Vreten, Sweden
Marks, L. B. . New York, N. Y.
Pupin, M. I. . New York, N. Y.
Reist, H. G. . Schenectady, N. Y.
Rosenberg, E. M. . Brooklyn, N. Y.
Uebelacker, C. F. . New York, N. Y.
Waters, E. G. . Schenectady, N. Y.
White, W. F. . New York, N. Y.
Whitmore, W. G. . St. Petersburg, Fla.

1891 (18)

Bedell, Frederick . Ithaca, N. Y.
Bourne, Frank . London, England
Caldwell, Edward . New York, N. Y.
Dunn, Gano . New York, N. Y.
Gordon, Reginald . Newburgh, N. Y.
Hewlett, E. M. . Schenectady, N. Y.
Land, Frank . Nyack, N. Y.
Lovejoy, J. R. . Schenectady, N. Y.
Mordey, W. M. . London, England
Pattison, F. A. . New York, N. Y.
Pike, C. W. . Philadelphia, Pa.
Rosebrugh, T. R. . Toronto, Ontario, Canada
Simpson, A. B. . Brooklyn, N. Y.
Stone, C. A. . New York, N. Y.
Strong, F. G. . Wethersfield, Conn.
Vanwyck, P. V. R. . New York, N. Y.
Webster, E. S. . Boston, Mass.
Wilson, C. H. . Mountain Lakes, N. J.

1892 (16)

Aldrich, W. S. . Syracuse, N. Y.
Arnold, B. J. . Chicago, Ill.
Cory, C. L. . Berkeley, Calif.
Crehore, A. C. . E. Cleveland, Ohio
Edwards, J. P. . Cave Spring, Ga.
Gale, H. B. . Natick, Mass.
Hunting, F. S. . Fort Wayne, Ind.
Jackson, J. P. . New York, N. Y.
Meyer, Julius . New York, N. Y.
Page, A. D. . Clayton, N. J.
Ray, W. D. . Chicago, Ill.
Ross, R. A. . Montreal, Quebec, Canada
Sachs, Joseph . Hartford, Conn.
Scott, C. F. . New Haven, Conn.
Smith, F. S. . Allentown, Pa.
Stillwell, L. B. . Princeton, N. J.

1893 (35)

Adams, A. D. . Boston, Mass.
Barbour, F. F. . Oakland, Calif.
Barnes, E. A. . Fort Wayne, Ind.
Boggs, L. S. . E. Pittsburgh, Pa.
Brenner, W. H. . Atlanta, Ga.
Burke, James . Erie, Pa.
Burnett, Douglas . Baltimore, Md.
Burton, W. C. . New York, N. Y.
Carpenter, C. E. . Hopewell Junction, N. Y.
Comstock, L. K. . New York, N. Y.
Corey, F. B. . Barberton, Ohio
Corson, W. R. C. . Hartford, Conn.
Creaghead, T. J. . Covington, Ky.
Dodge, O. G. . Washington, D. C.
Dow, Alex. . Detroit, Mich.
Emmet, W. L. R. . Schenectady, N. Y.
Ely, W. G. . Schenectady, N. Y.
Fitzmaurice, J. S. . Adelaide, Australia
Gerry, M. H., Jr. . San Francisco, Calif.
Goldsborough, W. E. . New York, N. Y.
Iwadare, Kunihiko . Tokyo, Japan
Keller, E. E. . New York, N. Y.
Meredith, Wynn . San Francisco, Calif.
Moore, D. McF. . Harrison, N. J.
Osborne, L. A. . New York, N. Y.
Puffer, W. L. . Boston, Mass.
Roper, D. W. . Chicago, Ill.
Sands, H. S. . Wheeling, W. Va.
Scheffler, F. A. . New York, N. Y.
See, A. B. . New York, N. Y.
Storrs, H. A. . Oakland, Calif.
Wait, H. H. . Chesterton, Ind.
Waterman, F. N. . New York, N. Y.
Worswick, A. E. . London, England
Wray, J. G. . Chicago, Ill.

1894 (35)

Adams, C. A. . Cambridge, Mass.
Agnew, C. R. . New York, N. Y.
Archbold, W. K. . Syracuse, N. Y.
Barstow, W. S. . New York, N. Y.
Berg, E. J. . Schenectady, N. Y.
Berresford, A. W. . New York, N. Y.
Billberg, C. O. C. . Philadelphia, Pa.
Bliss, W. L. . Niagara Falls, N. Y.
Boileau, W. E. . Bath, N. Y.
Caldwell, F. C. . Columbus, Ohio
Carichoff, R. R. . Schenectady, N. Y.
Chesney, C. C. . Pittsfield, Mass.
Cobb, H. B. . New York, N. Y.
Dommerque, F. J. . Lakewood, N. J.
Dunn, K. G. . Berkeley, Calif.
Gossler, F. G. . New York, N. Y.
Hadaway, W. S., Jr. . New Rochelle, N. Y.
Hadley, A. L. . Fort Wayne, Ind.
Hewitt, W. R. . New York, N. Y.
Hobart, H. M. . Schenectady, N. Y.
Hubley, G. W. . Louisville, Ky.
Kirkland, J. W. . Johannesburg, S. Africa
Knox, F. H. . Mt. Pleasant, S. C.
Lardner, H. A. . New York, N. Y.
Moses, P. H. . New York, N. Y.
Neiler, S. G. . Chicago, Ill.
Olivetti, Camillo . Ivrea, Italy
Phillips, L. A. . New York, N. Y.
Price, C. W. . New York, N. Y.
Reed, H. D. . New York, N. Y.
Rouquette, W. F. B. . Brooklyn, N. Y.
Sever, G. F. . Kingston, Mass.
Smith, F. R. . San Francisco, Calif.
Smith, J. B. . Manchester, N. H.
Tait, F. M. . Dayton, Ohio

1895 (38)

Bancroft, C. F. . St. Petersburg, Fla.
Berg, Eskil . Schenectady, N. Y.
Boyer, E. E. . East Lyne, Mass.
Buck, H. W. . New York, N. Y.
Burton, P. G. . Washington, D. C.
Cabot, F. E. . East Milton, Mass.
Coles, E. P. . Charlotte, N. C.
Coster, Maurice . New York, N. Y.
Crawford, D. F. . Pittsburgh, Pa.
Davis, W. J., Jr. . Schenectady, N. Y.
Degen, Lewis . Burlingame, Calif.
Fisher, H. W. . St. Petersburg, Fla.
Fortenbaugh, S. B. . Schenectady, N. Y.
Garrels, W. L. . Kirkwood, Mo.
Gherardi, Bancroft . New York, N. Y.
Gherky, W. D. . Philadelphia, Pa.
Harvey, R. R. . Wilkes-Barre, Pa.
Hewitt, C. E. . Walpole, N. H.
Hubbard, A. S. . Bethel, Conn.
Klinck, J. H. . E. Pittsburgh, Pa.
Lincoln, P. M. . Ithaca, N. Y.
McMeen, S. G. . Pasadena, Calif.
Mershon, R. D. . New York, N. Y.
Merz, C. H. . London, England
Nunn, P. N. . Salt Lake City, Utah
Parry, Evan . London, England
Pinkerton, Andrew . Pittsburgh, Pa.
Powell, P. H. . Wallingford, Conn.
Price, E. F. . New York, N. Y.
Robinson, O. F. . Philadelphia, Pa.
Roller, F. W. . New York, N. Y.
Rushmore, D. B. . New York, N. Y.
Storer, N. W. . E. Pittsburgh, Pa.
Swenson, E. V. . New York, N. Y.
Torchio, Philip . New York, N. Y.
Warren, A. K. . New York, N. Y.
Webb, H. S. . Scranton, Pa.
Wilcox, N. T. . Melvin Village, N. H.

1896 (33)

Appleyard, A. E. . Ashland, Wis.
Betts, Philander . Newark, N. J.
Biddle, J. G. . Philadelphia, Pa.
Brinckerhoff, H. M. . New York, N. Y.
Chapman, A. W. . New York, N. Y.
Clark, C. M. . New York, N. Y.
Collett, S. D. . Brooklyn, N. Y.
Crain, J. J. . Waterbury, Conn.
Cunningham, E. R. . Portland, Ore.
Foster, S. L. . San Francisco, Calif.
Goddard, C. M. . Boston, Mass.
Gorrissen, Charles . Hamburg, Germany
Greenleaf, L. S. . Pittsburgh, Pa.
Griffes, E. V. . Hollywood, Calif.
Hadley, F. W. . Atlanta, Ga.
Hammer, E. W. . New York, N. Y.
Hathaway, J. D. . Montreal, Quebec, Canada
Hill, Nicholas, Jr. . New York, N. Y.
Humphrey, H. H. . St. Louis, Mo.
Iijima, Zentaro . Tokyo, Japan
Little, C. W. G. . London, England
Maxwell, Eugene . Scottsbluff, Neb.
Moore, W. E. . Pittsburgh, Pa.
Porter, H. H. . New York, N. Y.
Reid, E. S. . New York, N. Y.
Sampson, F. D. . Charlotte, N. C.
Schwabe, W. P. . Thompsonville, Conn.
Speed, Buckner . New York, N. Y.
Stewart, R. S. . La Jolla, Calif.
Straus, I. E. . Baltimore, Md.
Wagner, E. A. . Pittsfield, Mass.
Whitaker, S. R. . Bronxville, N. Y.
Wise, J. S., Jr. . Allentown, Pa.

1897 (32)

Brackett, B. B. . Vermillion, S. D.
Clement, E. E. . Washington, D. C.
Copeland, C. A. . Los Angeles, Calif.
Edmands, I. R. . Brookline, Mass.
Frankenfield, Budd . Los Angeles, Calif.
Hommel, Ludwig . Pittsburgh, Pa.
Hopewell, C. F. . Watertown, Mass.
Hosmer, Sidney . Boston, Mass.
Jackson, W. M. . New York, N. Y.
Kenan, W. R., Jr. . New York, N. Y.
Kinsley, Carl . Kearny, N. J.
Klaudet, R. H. . Philadelphia, Pa.
MacGregor, W. H. . Bayside, N. Y.
Mather, E. H. . Boston, Mass.
Mole, H. E. . Summit, N. J.
Pillsbury, C. L. . Minneapolis, Minn.
Rice, C. W. . New York, N. Y.
Richey, A. S. . Worcester, Mass.
Scott, W. M. . Philadelphia, Pa.
Shaw, H. B. . Raleigh, N. C.
Williams, Arthur . New York, N. Y.
Willis, E. J. . Richmond, Va.

1898 (37)

Allen, W. C. . San Francisco, Calif.
Armstrong, A. H. . Schenectady, N. Y.
Beebe, M. C. . Waterbury, Conn.
Carter, F. W. . Rugby, England
Crowell, Robinson . Oakland, Calif.
Damon, G. A. . Pasadena, Calif.
Dates, H. B. . Cleveland, Ohio
Davis, A. G. . New York, N. Y.
Doherty, H. L. . New York, N. Y.
Downing, P. M. . San Francisco, Calif.
Gallatin, A. E. . New York, N. Y.
Garfield, A. S. . Paris, France
Gaytes Herbert . San Francisco, Calif.
Gladson, W. E. . Fayetteville, Ark.
Hoffmann, Bernhard . New York, N. Y.
James, H. D. . E. Pittsburgh, Pa.
Leitch, H. W. . New York, N. Y.
Livingston, J. . New York, N. Y.
Lohman, R. W. . Los Angeles, Calif.
Muschenheim, F. A. . New York, N. Y.
Sharp, C. H. . White Plains, N. Y.
Thompson, J. W. . Puebla Pen, Mexico
Tripier, Henri . Paris, France
Vreeland, F. K. . New York, N. Y.
Wagner, H. A. . Baltimore, Md.
Winfield, J. H. . Halifax, Nova Scotia
Woodbridge, J. E. . San Francisco, Calif.

1899 (35)

Bogen, L. E. . Milwaukee, Wis.
Burkett, C. W. . San Francisco, Calif.
Chappell, W. E. . Sheffield, England
Dyer, B. . Piedmont, Calif.
Edwards, C. V. . New York, N. Y.
Grant, L. T. . San Francisco, Calif.
Hallberg, J. H. . New York, N. Y.
Hardy, C. E. . Oakland, Calif.
Hewlett, E. F. J. H. . Mansfield, England
Hill, R. R. . New York, N. Y.
Insull, M. J. . Chicago, Ill.
Lawrence, W. H. . New York, N. Y.
Layman, W. A. . Chicago, Ill.
Lyford, O. S. . Bronxville, N. Y.
McCollum, R. D. . New York, N. Y.
Moody, V. D. . New York, N. Y.
Peck, J. S. . Manchester, England
Rendell, C. W. . Chicago, Ill.
Schweitzer, E. O. . Chicago, Ill.
Scudder, H. . Schenectady, N. Y.
Skinner, C. E. . Wilkensburg, Pa.
Swope, G. . New York, N. Y.
Wells, W. F. . Brooklyn, N. Y.
Wilson, H. S. . Brooklyn, N. Y.
Wolff, F. A. . Washington, D. C.

Groups on Which the Institute Is Represented

Organizations	1903–04	1904–05	1905–06	1906–07	1907–08	1908–09	1909–10	1910–11	1911–12	1912–13	1913–14	1914–15	1915–16	1916–17	1917–18	1918–19	1919–20	1920–21	1921–22	1922–23	1923–24	1924–25	1925–26	1926–27	1927–28	1928–29	1929–30	1930–31	1931–32	1932–33	1933–34
Nat'l Bureau of Eng'g Registration	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕
Coörd. Comm. of Eng'g Societies	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕
International Edison Foundation	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕
Research Procedure Comm., Eng'g Foundation	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕
Engr's Coun. for Gen'l Devlpt	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕
Electric St'ds Comm., A.S.A.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕
Amer. Comm. Marking Obstructions to Air Navigation	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕
Eng'g Soc. Comm. Century of Progress Exp.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	·
Adv. Comm. on Aeronautic Radio Research	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	·
Eng'g Societies Monographs Comm.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕
Educ. Research Com., The Eng'g Foundation	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕
Hoover Medal Board of Award	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕
Alfred Noble Prize Comm.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕
Eng'g Index Advisory Board	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕
Comm. on Heat Transmission, N.R.C.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕
American Standards Ass'n	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕
Bd. Trustees Nat'l Museum Eng'g & Ind.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	·	·	·	·	·	·	·	·
The Newcomen Society	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	·	·	·	·	·
Radio Adv. Comm., Bureau of St'ds	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Nat'l Safety Coun., A.S.S.E. Eng'g Sect.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Gilbreth Int'l Comm. on Elim. Fatigue, S.I.E.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	·	·
American Marine Standards Comm.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Soc. Pro. Eng'g Educ., Bd. Invest & Coörd.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	·	·	·	·
Joint Conference Comm. of Founder Societies	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	·	·	·
Nat'l Fire Waste Council	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Apparatus Maker & Users. Comm. of N.R.C.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Chas. A. Coffin Fellowship & Research Fund Comm.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Joint Comm. on Synch. Motors for Refrig. Mach.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	·	·	·	·	·	·	·	·	·
U.S. Nat'l Comm. Int'l Electrotechnical Com.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Joint Comm. on Welded Rail Joints	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	·	·
American Eng'g Council Assembly	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Franco-American Eng'g Comm.	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·
American Bureau of Welding	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Spec. Joint Comm. Determination of Power Factor Polyphase	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·
Joint Comm. on St'd Threads-Insulators & Pins	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Nat'l Research Coun., Eng'g & Indust. Research	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Comm. Gen'l Eng'g Adv. Com. Coun. Nat'l Defense	·	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Joseph A. Holmes Safety Ass'n	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·
Commission of Washington Award	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
American Eng'g Standards Comm.	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	·	·	·	·	·	·	·
Joint Comm. on Metric System	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Pan-American Eng'g Comm.	·	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Engineering Foundation Board	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Joint Comm. on Eng'rs Officers Research Corps	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Joint Comm. Classification Tech. Literature	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Naval Consulting Board	·	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·
Nat'l Joint Comm. Overh'd & Undergr'd Line Constr.	·	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·
American Comm. on Electrolysis	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	·	·
U.S. Nat'l Comm. of Int'l Illumination Com.	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Joint Comm. on Legislation Relative Licensing Engrs.	·	·	·	·	·	·	·	·	·	·	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Panama-Pacific Int'l Congress (1915) Bd. Managers	·	·	·	·	·	·	·	·	·	·	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Nat'l Conservation Congress, Adv. Bd.	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Library Board, United Eng'g Trustees Inc.	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Amer. Elect. Railway Ass'n Joint Use of Poles	·	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Joint Confer. Comm. of the Eng'g Soc.	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·
American Year Book Adv. Bd.	·	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Resuscitation Commission	·	·	·	·	·	·	·	·	·	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Nat'l Fire Protection Ass'n, Electr. Comm.	·	·	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Gov't Adv. Bd. Fuels & Struct. Mats.	·	·	·	·	·	·	·	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
American Ass'n Adv. of Science Council	·	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Joint Comm. on Eng'g Education	·	·	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·
United Eng'g Trustees Inc.	·	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Joint Comm. Union Eng'g Bldg.	·	·	⊕	⊕	⊕	⊕	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
John Fritz Medal Board of Award	·	·	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕

THIS CHART shows the representation of the Institute on joint projects, since 1903, at which time joint participation was placed upon a more definite basis than previously existed. This chart is arranged to illustrate the expansion of interest in the later years.

The abbreviations used in the titles are as follows:

Adv.	Advisory
Bd.	Board
Com.	Commission
Comm.	Committee

In addition to these organizations on which the Institute has official representatives, there are of course a number of congresses and special commissions to which the Institute has sent delegates. These include the most important congresses held throughout the world since the organization of the Institute.

Note: The U.S. National Committee of the International Electrotechnical Commission Representatives, shown on this chart, is successor to the General committee which was dissolved in 1921, as shown on the chart of committees.

Chart of Institute Committees

Committee	Class	1887–88	1888–89	1889–90	1890–91	1891–92	1892–93	1893–94	1894–95	1895–96	1896–97	1897–98	1898–99	1899–00	1900–01	1901–02	1902–03	1903–04	1904–05	1905–06	1906–07	1907–08	1908–09	1909–10	1910–11	1911–12	1912–13	1913–14	1914–15	1915–16	1916–17	1917–18	1918–19	1919–20	1920–21	1921–22	1922–23	1923–24	1924–25	1925–26	1926–27	1927–28	1928–29	1929–30	1930–31	1931–32	1932–33	1933–34
Transfers	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕
Iwadare Foundation	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕
Economic Status of the Engineer	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕
Popular Science Award	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕
Lamme Medal	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕
Electric Welding	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Automatic Stations	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Advisory Comm. to N. Y. Museum S. & I.	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Technical Activities	S	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	.	.	.	.	.	.	.	.
Legislation Affecting the Eng'g Profession	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Columbia University Scholarships	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Award of Institute Prizes	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Research	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Coördination of Institute Activities	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Instruments & Measurements	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Electrical Machinery	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Headquarters	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Student Branches	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Development of Water Power	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Applications to Iron & Steel Production	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Economics of Electric Service	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Protective Devices	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Applications to Marine Work	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Applications to Mining Work	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Patents	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Organization of Technical Committees	S	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Constitutional Revision	S	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	.	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Institute Policy	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Electrophysics	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Relations of Consulting Engineers	S	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Indexing Transactions	S	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Historical Museum	S	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Power Generation	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Electrochemistry & Electrometallurgy	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Production & Application of Light	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
General Power Applications	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Additional Grade of Membership	S	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
U. S. Nat'l Com. International Electrotech. Coms.	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Transportation	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Education	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Code of Principles of Professional Conduct	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Bibliography	S	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Conservation of Natural Resources	S	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Edison Medal	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Constitution & By-Laws	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Communication	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Power Transmission & Distribution	T	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Safety Codes	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Sections	G	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Building Fund	S	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	.	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
New York Reception Comm.	S	.	.	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	.	.	.	.	.	.	.	.	.	.	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Standards	G	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Coöperative Research	G	.	.	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Executive	G	.	.	.	.	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Units & Standards	G	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Membership	G	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	.	.	.	⊕	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Technical Program	G	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Library	G	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Publication	G	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	.	.	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Finance	G	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	.	.	.	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕
Board of Examiners	G	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕

THIS CHART illustrates the growth of Institute activities as reflected by the number and diversity of committees. Only those committees acting for 2 years or more are shown. In every case the title is that by which it was last known, although it may have developed from another committee of different name but similar purpose.

The committees are designated as General, Technical, or Special by the letter in the first column following the title. Committees once known as "Standing" are classed as General, as are those of the earlier years when no differentiation was made.

Early Committees

Although the records of committee activities preceding 1887 are not complete, the following standing committees and their chairman appointed by the council of the Institute at its second meeting June 3, 1884, gives a very good idea of the recognized division of electrical engineering at that date:

Dynamo Electric Machines—Edward Weston
Telephones—Alexander Graham Bell
Telegraphs—George A. Hamilton
Arc Lamps—Edwin J. Houston
Incandescent Lamps—Thomas A. Edison
Prime Motor and Transmission of Power—Edward Weston
Electric Railways and Signals—Stephen D. Field
Underground and Submarine Cable Work—George A. Hamilton
Electrochemistry and Metallurgy—Nathaniel S. Keith
Voltaic Batteries, Galvanometers, and Measurements—Charles H. Haskins
Secondary Batteries—Edward J. Houston

In the first 4 volumes of the Institute's yearly TRANSACTIONS, references are made to various committees, most of which served only for a short time to meet some particular need. There was, of course, the committee on organization mentioned in the article "Formation of the Institute and the Enrolling of Its Charter Members" appearing on p. 822–4 of this issue.

Chairmen of the Institute's Committees

A CUMULATIVE listing of the chairmen of the Institute's general, technical, and special committees is given in the pages immediately following. These committees correspond with those shown in the charts on the preceding page. In the following listing, the dates of organization of the committees are given, together with the names and terms of service of all chairmen of these committees.

Executive Committee. Organized in 1896 to function as required between regular meetings of the board of directors.

Louis Duncan, Baltimore, Md. 1896–97
F. B. Crocker, New York, N. Y. 1897–98
A. E. Kennelly, Philadelphia, Pa. 1898–00
Carl Hering, Philadelphia, Pa. 1900–01
C. P. Steinmetz, Schenectady, N. Y. 1901–02
C. F. Scott, Pittsburgh, Pa. 1902–03
B. J. Arnold, Chicago, Ill. 1903–04
J. W. Lieb, Jr., New York, N. Y. 1904–05
S. S. Wheeler, Ampere, N. J. 1905–06
Samuel Sheldon, Brooklyn, N. Y. 1906–07
H. G. Stott, New York, N. Y. 1907–08
L. A. Ferguson, Chicago, Ill. 1908–09
L. B. Stillwell, New York, N. Y. 1909–10
D. C. Jackson, Boston, Mass. 1910–11
Gano Dunn, New York, N. Y. 1911–12
R. D. Mershon, New York, N. Y. 1912–13
C. O. Mailloux, New York, N. Y. 1913–14
P. M. Lincoln, East Pittsburgh, Pa. 1914–15
J. J. Carty, New York, N. Y. 1915–16
H. W. Buck, New York, N. Y. 1916–17
E. W. Rice, Jr., Schenectady, N. Y. 1917–18
C. A. Adams, New York, N. Y. 1918–19
Calvert Townley, New York, N. Y. 1919–20
A. W. Berresford, Milwaukee, Wis. 1920–21
William McClellan, Philadelphia, Pa. 1921–22
F. B. Jewett, New York, N. Y. 1922–23
H. J. Ryan, Stanford Univ., Calif. 1923–24
Farley Osgood, Newark, N. J. 1924–25
M. I. Pupin, New York, N. Y. 1925–26
C. C. Chesney, Pittsfield, Mass. 1926–27
Bancroft Gherardi, New York, N. Y. 1927–28
R. F. Schuchardt, Chicago, Ill. 1928–29
H. B. Smith, Worcester, Mass. 1929–30
W. S. Lee, New York, N. Y. 1930–31
C. E. Skinner, East Pittsburgh, Pa. 1931–32
H. P. Charlesworth, New York, N. Y. 1932–33
J. B. Whitehead, Baltimore, Md. 1933–34

Board of Examiners. Organized in 1887 to study and recommend as to acceptability the qualifications of applicants for membership or applicants for transfer to a higher grade of membership.

W. B. Vansize, New York, N. Y. 1887–94
G. A. Hamilton, New York, N. Y. 1894–95
C. E. Emery, New York, N. Y. 1895–98
William Maver, Jr., New York, N. Y. 1898–07
H. W. Buck, New York, N. Y. 1907–10
W. G. Carlton, New York, N. Y. 1910–12
H. St. Clair Putnam, New York, N. Y. 1912–13
Maurice Coster, New York, N. Y. 1913–15
A. S. McAllister, New York, N. Y. 1915–18
F. L. Rhodes, New York, N. Y. 1918–20
C. H. Sharp, New York, N. Y. 1920–21
H. H. Norris, Upper Montclair, N. J. 1921–25
Erich Hausmann, Brooklyn, N. Y. 1925–27
E. H. Everit, New Haven, Conn. 1927–30
H. W. Drake, New York, N. Y. 1930–31
H. Goodwin, Jr., Wyncotte, Pa. 1931–34

Coördination of Institute Activities, Committee on. Organized in 1920 to study and advise concerning matters affecting 2 or more committees or other subdivisions of the Institute's organization.

L. T. Robinson, Schenectady, N. Y. 1920–21
W. I. Slichter, New York, N. Y. 1921–24
F. B. Jewett, New York, N. Y. 1924–25
Farley Osgood, New York, N. Y. 1925–27
G. L. Knight, Brooklyn, N. Y. 1927–28
H. A. Kidder, New York, N. Y. 1928–30
H. P. Charlesworth, New York, N. Y. 1930–32
E. B. Meyer, Newark, N. J. 1932–34

Bibliography, Committee on. Organized in 1906; discontinued in 1908.

W. D. Weaver, New York, N. Y. 1906–08

Building Fund Committee. Organized in 1902 as the building committee; name changed in 1903 to the building fund committee; discontinued in 1908.

C. W. Rice, New York, N. Y. 1902–04
T. C. Martin, New York, N. Y. 1905–08

Columbia University Scholarships, Committee on. Organized in 1923.

Francis Blossom, New York, N. Y. 1923–25
W. I. Slichter, New York, N. Y. 1925–34

Conservation of Natural Resources, Committee on. Organized in 1905 as the committee on forest preservation; name changed in 1908 to the committee on conservation of natural resources; discontinued in 1911.

F. A. C. Perrine, New York, N. Y. 1905–07
C. H. Porter, Boston, Mass. 1907–08
H. G. Stott, New York, N. Y. 1908–10
L. B. Stillwell, New York, N. Y. 1910–11

Constitution and By-Laws Committee. Organized in 1903 as the committee on by-laws; reorganized in 1905 as the law committee; name changed in 1932 to the committee on constitution and by-laws.

R. W. Pope, New York, N. Y. 1903–04
C. O. Mailloux, New York, N. Y. 1905–08
H. G. Stott, New York, N. Y. 1908–11
Charles A. Terry, New York, N. Y. 1911–14
G. H. Stockbridge, New York, N. Y. 1914–16
Samuel Sheldon, Brooklyn, N. Y. 1918–20
H. H. Barnes, Jr., New York, N. Y. 1920–24
L. F. Morehouse, New York, N. Y. 1924–25
W. I. Slichter, New York, N. Y. 1925–27
C. O. Bickelhaupt, Atlanta, Ga. 1927–29
L. F. Morehouse, New York, N. Y. 1929–30
E. B. Meyer, Newark, N. J. 1930–31
W. S. Gorsuch, New York, N. Y. 1931–34

Constitutional Revision, Committee on. Organized in 1912; discontinued in 1916.

W. S. Murray, New Haven, Conn. 1912–13
Bancroft Gherardi, New York, N. Y. 1913–14
Bancroft Gherardi, New York, N. Y. 1915–16

Consulting Engineers, Committee on Relations of. Organized in 1910; discontinued in 1916.

Frank J. Sprague, New York, N. Y. 1910–11
Francis Blossom, New York, N. Y. 1911–12
L. B. Stillwell, New York, N. Y. 1912–16

Economic Status of the Engineer, Committee on. Organized in 1931.

C. O. Bickelhaupt, New York, N. Y. 1931–34

Edison Medal Committee. Organized in 1905

J. W. Howell, Harrison, N. J. 1905–07
C. L. Clarke, New York, N. Y. 1908–10
Elihu Thomson, Swampscott, Mass. 1910–13
S. S. Wheeler, Ampere, N. J. 1913–16
A. E. Kennelly, Boston, Mass. 1916–17
Carl Hering, Philadelphia, Pa. 1917–20
C. A. Adams, Cambridge, Mass. 1920–22
E. D. Adams, New York, N. Y. 1922–24
Gano Dunn, New York, N. Y. 1924–27
M. I. Pupin, New York, N. Y. 1927–28
Samuel Insull, Chicago, Ill. 1928–30
D. C. Jackson, Cambridge, Mass. 1930–33
C. E. Stephens, New York, N. Y. 1933–34

Finance Committee. Organized in 1887 as the committee on permanent quarters; name subsequently changed to committee on finance, building and permanent quarters, 1889; and in 1896 to finance committee.

G. M. Phelps, New York, N. Y. 1887–95
F. B. Herzog, New York, N. Y. 1895–96
W. B. Vansize, New York, N. Y. 1896–97
J. J. Carty, New York, N. Y. 1901–07
Calvert Townley, New Haven, Conn. 1907–10
A. W. Berresford, Milwaukee, Wis. 1910–12
C. W. Stone, Schenectady, N. Y. 1912–13
J. F. Stevens, Philadelphia, Pa. 1913–17
N. A. Carle, Newark, N. J. 1917–20
Charles Robbins, East Pittsburgh, Pa. 1920–21
L. F. Morehouse, New York, N. Y. 1921–23
G. L. Knight, Brooklyn, N. Y. 1923–26
H. A. Kidder, New York, N. Y. 1926–28
E. B. Meyer, Newark, N. J. 1928–30
C. E. Stephens, New York, N. Y. 1930–33
E. B. Meyer, Newark, N. J. 1933–34

Headquarters Committee. Organized in 1917.

N. A. Carle, Newark, N. J. 1917–20
W. A. Del Mar, Yonkers, N. Y. 1920–22
E. B. Craft, New York, N. Y. 1922–25
H. A. Kidder, New York, N. Y. 1925–26
G. L. Knight, Brooklyn, N. Y. 1926–28
R. H. Tapscott, New York, N. Y. 1928–33
W. S. Gorsuch, New York, N. Y. 1933–34

Historical Museum Committee. Organized in 1910; discontinued in 1916.

T. C. Martin, New York, N. Y. 1910–16

Indexing Transactions Committee. Organized in 1910; discontinued in 1914.

G. I. Rhodes, Boston, Mass. 1910–14

Institute Policy Committee. Organized in 1911 as the public policy committee; name changed in 1933 to Institute policy.

J. J. Carty, New York, N. Y. 1911–12
Calvert Townley, New York, N. Y. 1912–19
H. W. Buck, New York, N. Y. 1919–25
Gano Dunn, New York, N. Y. 1925–27
H. W. Buck, New York, N. Y. 1927–28
D. C. Jackson, Boston, Mass. 1928–30
Bancroft Gherardi, New York, N. Y. 1930–33
H. P. Charlesworth, New York, N. Y. 1933–34

International Electrotechnical Commission, U.S. national committee of the. Organized in 1907; discontinued as a general committee in 1921, functioning since under "Institute Representatives."

Elihu Thomson, Lynn, Mass. 1907–09
A. E. Kennelly, Cambridge, Mass. 1909–11
C. O. Mailloux, New York, N. Y. 1911–13
F. B. Crocker, New York, N. Y. 1913–14
C. O. Mailloux, New York, N. Y. 1914–21

Iwadare Foundation Committee. Organized in 1932.

F. B. Jewett, New York, N. Y. 1932–34

Lamme Medal Committee. Organized in 1928.

C. F. Scott, New Haven, Conn. 1928–31
C. C. Chesney, Pittsfield, Mass. 1931–32
C. E. Skinner, Wilkinsburg, Pa. 1932–34

Legislation Affecting the Engineering Profession, Committee on. Organized in 1924 as licensing of engineers committee; name changed in 1929 to committee on the engineering profession, and in 1931 to the committee on legislation affecting the engineering profession.

Francis Blossom, New York, N. Y. 1924–29
H. A. Kidder, New York, N. Y. 1929–33
W. I. Slichter, New York, N. Y. 1933–34

Library Committee. Organized in 1889; discontinued in 1916.

J. Stanford Brown, Yonkers, N. Y. 1889–96
W. D. Weaver, New York, N. Y. 1901–06
W. J. Jenks, New York, N. Y. 1906–07
Edward Caldwell, New York, N. Y. 1907–11
Samuel Sheldon, Brooklyn, N. Y. 1909–16

Membership Committee. Organized in 1889 as the committee on membership, etc.; reorganized in 1902 as the membership committee; again in 1906 as the committee on increase of membership; in 1909 became the membership committee.

R. W. Pope, New York, N. Y. 1889–99
W. S. Barstow, New York, N. Y. 1902–04
P. H. Thomas, New York, N. Y. 1906–07
D. B. Rushmore, Schenectady, N. Y. 1907–08
C. W. Stone, Schenectady, N. Y. 1908–09
A. W. Berresford, Milwaukee, Wis. 1909–10
Bancroft Gherardi, New York, N. Y. 1910–11
C. E. Scribner, New York, N. Y. 1911–12
H. C. Snook, Philadelphia, Pa. 1912–13
A. M. Schoen, Atlanta, Ga. 1913–14
H. D. James, East Pittsburgh, Pa. 1914–15
W. A. Hall, West Lynn, Mass. 1915–16
Harold Goodwin, Jr., Philadelphia, Pa. 1916–17
H. A. Pratt, New York, N. Y. 1917–19
R. W. Krass, New York, N. Y. 1919–20
E. H. Martindale, Cleveland, Ohio 1920–22
R. B. Howland, New York, N. Y. 1922–23
M. E. Skinner, Pittsburgh, Pa. 1923–24
E. E. Dorting, New York, N. Y. 1924–25
J. L. Woodress, St. Louis, Mo. 1925–26
L. S. O'Roark, New York, N. Y. 1926–27
E. B. Merriam, Schenectady, N. Y. 1927–28
J. E. Kearns, Chicago, Ill. 1928–29
J. Allen Johnson, Buffalo, N. Y. 1929–31
R. L. Kirk, Pittsburgh, Pa. 1931–33
E. S. Lee, Schenectady, N. Y. 1933–34

Membership Committee, Additional Grade of. Organized in 1908 as the intermediate grade of membership committee; name changed in 1911 to the additional grade of membership committee; discontinued in 1912.

C. F. Scott, Pittsburgh, Pa. 1908–10
C. W. Stone, Schenectady, N. Y. 1910–11
P. H. Thomas, New York, N. Y. 1911–12

New York Museum of Science and Industry, Advisory Committee to. Organized in 1927 as the advisory committee to the museums of the peaceful arts; changed in 1930 to the advisory committee to New York Museum of Science and Industry.

J. P. Jackson, New York, N. Y. 1927–34

New York Reception Committee. Organized 1900 as a subcommittee of papers and meetings; name changed in 1901 to the reception committee and in 1904 to the New York reception committee; inactive for several years; discontinued in 1915.

T. C. Martin, New York, N. Y. 1900–03
C. W. Rice, New York, N. Y. 1903–04
A. H. Lawton, New York, N. Y. 1912–14
F. C. Bates, New York, N. Y. 1914–15

Patent Committee. Organized in 1912; discontinued in 1917.

B. J. Arnold, Chicago, Ill. 1912–13
R. D. Mershon, New York, N. Y. 1913–17

Popular Science Award Committee. Organized in 1930.

A. E. Knowlton, New York, N. Y. 1930–31
F. W. Peek, Jr., Pittsfield, Mass. 1931–33
Harold Pender, Philadelphia, Pa. 1933–34

Prizes, Committee on Award of Institute. Organized in 1923.

L. W. W. Morrow, New York, N. Y. 1923–25
E. B. Meyer, Newark, N. J. 1925–27
H. P. Charlesworth, New York, N. Y. 1927–29
A. E. Knowlton, New York, N. Y. 1929–31
W. H. Harrison, New York, N. Y. 1931–33
R. N. Conwell, Newark, N. J. 1933–34

Professional Conduct Committee, Code of Principles of. Organized in 1906 as the code of ethics committee; name changed to code of principles of professional conduct committee, 1912.

S. S. Wheeler, Ampere, N. J. 1906–08
G. F. Sever, New York, N. Y. 1911–12
B. A. Behrend, Boston, Mass. 1912–13
G. F. Sever, New York, N. Y. 1913–21
C. A. Adams, Cambridge, Mass. 1921–22
S. S. Wheeler, Ampere, N. J. 1922–23
J. W. Lieb, New York, N. Y. 1923–28
H. B. Smith, Worcester, Mass. 1928–29
F. B. Jewett, New York, N. Y. 1929–31
R. F. Schuchardt, Chicago, Ill. 1931–33
C. E. Stephens, New York, N. Y. 1933–34

Publication Committee. Organized in 1888 as the editing committee; operated as a subcommittee of the meetings and papers committee, 1893–1901; reorganized as editing committee, 1901; name changed to publication committee, 1919.

G. A. Hamilton, Elizabeth, N. J. 1888–96
Gano Dunn, Ampere, N. J. 1901–03
C. T. Hutchinson, New York, N. Y. 1903–05
R. W. Pope, New York, N. Y. 1905–06
T. J. Johnston, New York, N. Y. 1906–07
G. F. Sever, New York, N. Y. 1907–10
A. F. Ganz, Hoboken, N. J. 1910–11
W. I. Slichter, New York, N. Y. 1911–12
L. T. Robinson, Schenectady, N. Y. 1912–14
H. H. Norris, New York, N. Y. 1914–16
W. I. Slichter, New York, N. Y. 1916–18
H. H. Norris, New York, N. Y. 1918–19
W. I. Slichter, New York, N. Y. 1919–20
N. A. Carle, Newark, N. J. 1920–21
A. S. McAllister, New York, N. Y. 1921–22
Donald McNicol, New York, N. Y. 1922–25
L. F. Morehouse, New York, N. Y. 1925–27
E. B. Meyer, Newark, N. J. 1927–28
W. S. Gorsuch, New York, N. Y. 1928–31
E. B. Meyer, Newark, N. J. 1931–34

Research, Committee on Coöperative. Organized in 1898; discontinued in 1901.

A. E. Kennelly, Philadelphia, Pa. 1898–01

Safety Codes Committee. Organized in 1902 as the National Electric Code committee; name changed in 1907 to the code committee; and to the safety codes committee, 1918.

A. E. Kennelly, Cambridge, Mass. 1902–05
F. B. Crocker, New York, N. Y. 1905–06
F. A. C. Perrine, New York, N. Y. 1906–08
C. W. Stone, Schenectady, N. Y. 1908–10
Farley Osgood, Newark, N. J. 1910–11
G. F. Sever, New York, N. Y. 1911–12
Farley Osgood, Newark, N. J. 1912–21
H. B. Gear, Chicago, Ill. 1921–24
Paul Spencer, Philadelphia, Pa. 1924–26
J. P. Jackson, New York, N. Y. 1926–28
F. V. Magalhaes, Philadelphia, Pa. 1928–29
A. W. Berresford, New York, N. Y. 1929–31
J. C. Forsyth, New York, N. Y. 1931–32
F. V. Magalhaes, Hopewell, N. J. 1932–33
F. V. Magalhaes, West Lynn, Mass. 1933–34

Sections Committee. Organized in 1902 as the local organizations committee; name changed to Sections committee, 1907.

C. W. Rice, New York, N. Y. 1902–03
C. F. Scott, Pittsburgh, Pa. 1903–04
C. F. Scott, Pittsburgh, Pa. .... March–Sept. 1906
Paul Spencer, Philadelphia, Pa. 1906–09
P. M. Lincoln, Pittsburgh, Pa. 1909–14
H. A. Horner, Philadelphia, Pa. 1914–16
W. A. Hall, West Lynn, Mass. 1916–20
J. B. Fisken, Spokane, Wash. 1920–21
A. W. Berresford, Milwaukee, Wis. 1921–24
H. B. Smith, Worcester, Mass. 1924–27
W. B. Kouwenhoven, Baltimore, Md. 1927–30
E. S. Lee, Schenectady, N. Y. 1930–33
I. Melville Stein, Philadelphia, Pa. 1933–34

Standards Committee. Organized in 1898 as the standardization committee; name changed to standards committee, 1907.

F. B. Crocker, New York, N. Y. 1898–02
H. J. Ryan, Ithaca, N. Y. 1902–04
C. F. Scott, Pittsburgh, Pa. .... April–Oct. 1905
F. B. Crocker, New York, N. Y. 1905–07
Samuel Sheldon, Brooklyn, N. Y. 1907–09
A. E. Kennelly, Cambridge, Mass. 1909–10
C. A. Adams, Cambridge, Mass. 1910–11
A. E. Kennelly, Cambridge, Mass. 1911–15
C. A. Adams, Cambridge, Mass. 1915–18
L. T. Robinson, Schenectady, N. Y. 1918–20
D. C. Jackson, Boston, Mass. 1920–21
Harold Pender, Philadelphia, Pa. 1921–23
H. S. Osborne, New York, N. Y. 1923–26
J. F. Meyer, Washington, D. C. 1926–28
F. D. Newbury, East Pittsburgh, Pa. 1928–31
A. M. MacCutcheon, Cleveland, Ohio 1931–34

Student Branches Committee. Organized in 1916 as a special committee; in 1917 as a subcommittee of the Sections committee; in 1919 became an independent committee.

C. W. Green, Boston, Mass. 1916–17
P. H. Daggett, Chapel Hill, N. C. 1917–18
C. F. Harding, Lafayette, Ind. 1918–23
C. E. Magnusson, Seattle, Wash. 1923–27
J. L. Beaver, Bethlehem, Pa. 1927–29
W. H. Timbie, Cambridge, Mass. 1929–33
L. A. Doggett, State College, Pa. 1933–34

Transfers Committee. Organized in 1932.

E. B. Meyer, Newark, N. J. 1932–33
J. Allen Johnson, Buffalo, N. Y. 1933–34

Technical Activities Committee. Organized in 1925; discontinued in 1927.

A. G. Pierce, Cleveland, Ohio 1925–27

Technical Committees, special committee on organization of. Organized in 1912; discontinued in 1914.

H. G. Stott, New York, N. Y. 1912–13
W. S. Rugg, New York, N. Y. 1913–14

Technical Program Committee. Organized in 1889 as the committee on papers and meetings; became a subcommittee of the committee on papers, meetings, and editing, 1893; name changed in 1895 to committee on papers and meetings; in 1901 to committee on papers; in 1907 to committee on meetings and papers; in 1932 to technical program committee.

T. C. Martin, New York, N. Y. 1889–95
F. B. Crocker, New York, N. Y. 1895–96
H. L. Webb, New York, N. Y. 1896–00
W. S. Barstow, New York, N. Y. 1900–01
C. W. Rice, New York, N. Y. 1901–02
Samuel Sheldon, Brooklyn, N. Y. 1902–06
H. G. Stott, New York, N. Y. 1906–07
P. H. Thomas, New York, N. Y. 1907–08
A. H. Armstrong, Schenectady, N. Y. 1908–09
H. St. Clair Putnam, New York, N. Y. 1909–10
G. F. Sever, New York, N. Y. 1910–11
H. W. Buck, New York, N. Y. 1911–12
W. S. Rugg, New York, N. Y. 1912–14
L. T. Robinson, Schenectady, N. Y. 1914–18
W. I. Slichter, New York, N. Y. 1918–21
E. E. F. Creighton, Schenectady, N. Y. 1921–23
L. W. W. Morrow, New York, N. Y. 1923–25
E. B. Meyer, Newark, N. J. 1925–27
H. P. Charlesworth, New York, N. Y. 1927–29
A. E. Knowlton, New York, N. Y. 1929–31
W. H. Harrison, New York, N. Y. 1931–33
R. N. Conwell, Newark, N. J. 1933–34

Units and Standards, Committee on. Organized in 1890; discontinued in 1901.

A. E. Kennelly, Philadelphia, Pa., and Cambridge, Mass. 1890–01

Water Power, Committee on Development of. Organized in 1915; discontinued in 1917.

Calvert Townley, New York, N. Y. 1915–16
J. H. Finney, Washington, D. C. 1916–17

Technical Committees

Automatic Stations Committee. Organized in 1927.

Chester Lichtenberg, Philadelphia, Pa. 1927–28
W. H. Millan, St. Louis, Mo. 1928–29
Ferdinand Zogbaum, New York, N. Y. 1929–31
D. W. Taylor, Newark, N. J. 1931–34

Communication Committee. Organized in 1903 as the committee on telegraphy and telephony; name changed in 1924 to committee on communication.

A. E. Kennelly, Cambridge, Mass. 1903–04
K. B. Miller, Chicago, Ill. 1906–07
William Maver, Jr., New York, N. Y. 1909–10
Samuel Reber, New York, N. Y. 1910–11
Bancroft Gherardi, New York, N. Y. 1911–12
S. G. McMeen, Columbus, Ohio 1912–13
F. F. Fowle, New York, N. Y. 1913–14
C. E. Scribner, New York, N. Y. 1914–15
G. M. Yorke, New York, N. Y. 1915–16
F. L. Rhodes, New York, N. Y. 1916–17
L. F. Morehouse, New York, N. Y. 1917–18
Donald McNicol, New York, N. Y. 1918–22
O. B. Blackwell, New York, N. Y. 1922–25
H. P. Charlesworth, New York, N. Y. 1925–27
H. W. Drake, New York, N. Y. 1927–29
G. A. Kositzky, Cleveland, Ohio 1929–31
H. S. Osborne, New York, N. Y. 1931–34

Education Committee. Organized in 1907 as a subcommittee of the meetings and papers committee; became an independent committee in 1909.

H. H. Norris, Ithaca, N. Y. 1907–09
D. C. Jackson, Boston, Mass. 1909–10
A. S. Langsdorf, St. Louis, Mo. 1910–11
J. P. Jackson, State College, Pa. 1911–12
H. H. Norris, Ithaca, N. Y. 1912–14
Vladimir Karapetoff, Ithaca, N. Y. 1914–16
W. I. Slichter, New York, N. Y. 1916–17
E. J. Berg, Schenectady, N. Y. 1917–18
Vladimir Karapetoff, Ithaca, N. Y. 1918–19
J. C. Parker, Ann Arbor, Mich. 1919–20
C. E. Magnusson, Seattle, Wash. 1920–22
W. E. Wickenden, New York, N. Y. 1922–24
Harold Pender, Philadelphia, Pa. 1924–26
P. M. Lincoln, Ithaca, N. Y. 1926–28
Edward Bennett, Madison, Wis. 1928–30
W. R. Work, Pittsburgh, Pa. 1930–31
R. E. Doherty, New Haven, Conn. 1931–33
L. A. Doggett, State College, Pa. 1933–34

Electric Welding Committee. Organized in 1927.

J. C. Lincoln, Cleveland, Ohio 1927–28
A. M. Candy, East Pittsburgh, Pa. 1928–30
P. P. Alexander, West Lynn, Mass. 1930–32
K. L. Hansen, Milwaukee, Wis. 1932–34

Electrical Machinery Committee. Organized in 1917.

A. M. Gray, Ithaca, N. Y. 1917–19
B. A. Behrend, Boston, Mass. 1919–23
H. M. Hobart, Schenectady, N. Y. 1923–27
F. D. Newbury, East Pittsburgh, Pa. 1927–28
W. J. Foster, Schenectady, N. Y. 1928–29
P. L. Alger, Schenectady, N. Y. 1929–32
S. L. Henderson, East Pittsburgh, Pa. 1932–34

Instruments and Measurements Committee. Organized in 1917.

S. G. Rhodes, New York, N. Y. 1917–20
F. V. Magalhaes, New York, N. Y. 1920–22
G. A. Sawin, East Pittsburgh, Pa. 1922–24
A. E. Knowlton, New Haven, Conn. 1924–27
E. S. Lee, Schenectady, N. Y. 1927–30
E. J. Rutan, New York, N. Y. 1930–33
W. B. Kouwenhoven, Baltimore, Md. 1933–34

Electrochemistry and Electrometallurgy Committee. Organized in 1910 as the electrochemical committee; name changed in 1916 to committee on electrochemistry and electrometallurgy.

P. P. Barton, Niagara Falls, N. Y. 1910–11
A. F. Ganz, Hoboken, N. J. 1911–16
T. H. Schoepf, East Pittsburgh, Pa. 1916–17
F. A. J. FitzGerald, Niagara Falls, N. Y. 1917–18
Carl Hering, Philadelphia, Pa. 1918–19
F. A. J. FitzGerald, Niagara Falls, N. Y. 1919–21
Lawrence Addicks, New York, N. Y. 1921–22
J. L. Yardley, East Pittsburgh, Pa. 1922–24
G. W. Vinal, Washington, D. C. 1924–29
P. H. Brace, East Pittsburgh, Pa. 1929–32
W. C. Kalb, Cleveland, Ohio 1932–34

Electrophysics Committee. Organized in 1911.

E. B. Rosa, Washington, D. C. 1911–12
J. B. Whitehead, Baltimore, Md. 1912–16
F. W. Peek, Jr., Pittsfield, Mass. 1916–17
Frederick Bedell, Ithaca, N. Y. 1917–18
F. W. Peek, Jr., Pittsfield, Mass. 1918–24
J. H. Morecroft, New York, N. Y. 1924–26
Vladimir Karapetoff, Ithaca, N. Y. 1926–29
O. E. Buckley, New York, N. Y. 1929–31
Vannevar Bush, Cambridge, Mass. 1931–33
Joseph Slepian, East Pittsburgh, Pa. 1933–34

Iron and Steel Production, Committee on Applications to. Organized in 1914 as the committee on iron and steel industry; name changed in 1924 to the committee on (electrical) applications to iron and steel production.

J. C. Reed, Steelton, Pa. 1914–15
T. E. Tynes, Buffalo, N. Y. 1915–16
Wilfred Sykes, East Liberty, Pa. 1916–17
F. D. Egan, Midland, Pa. 1917–18
Eugene Friedlaender, Braddock, Pa. 1918–19
W. F. James, Philadelphia, Pa. 1919–21
E. S. Jefferies, Hamilton, Ont., Can. 1921–23
F. B. Crosby, Worcester, Mass. 1923–26
A. G. Pierce, Cleveland, Ohio 1926–28
M. M. Fowler, Chicago, Ill. 1928–30
A. C. Cummins, Duquesne, Pa. 1930–32
F. O. Schnure, Sparrows Point, Md. 1932–34

Light, Committee on Production and Application of. Organized in 1909 as the electric lightning committee; name subsequently was changed to electrical illumination committee (1913), electric lighting committee (1914), lighting and illumination committee (1916), and in 1924 to committee on production and application of light.

W. L. Robb, Troy, N. Y. 1909–10
Peter Junkersfeld, Chicago, Ill. 1910–12
W. C. L. Eglin, Philadelphia, Pa. 1912–13
C. H. Sharp, New York, N. Y. 1913–16
E. P. Hyde, Cleveland, Ohio 1916–18
C. E. Clewell, Philadelphia, Pa. 1918–21
G. H. Stickney, Harrison, N. J. 1921–25
P. S. Millar, New York, N. Y. 1925–28
B. E. Schackelford, Bloomfield, N. J. 1928–29
G. S. Merrill, Cleveland, Ohio 1929–31
W. T. Blackwell, Newark, N. J. 1931–33
J. W. Barker, New York, N. Y. 1933–34

Marine Work, Committee on Applications to. Organized in 1913 as the committee on use of electricity in marine work; name subsequently changed to marine committee (1916), and then to committee on applications to marine work (1924).

C. S. McDowell, New York, N. Y. 1913–16
H. A. Hornor, Philadelphia, Pa. 1916–19
Arthur Parker, Camden, N. J. 1919–22
G. A. Pierce, Philadelphia, Pa. 1922–24
L. C. Brooks, Wollaston, Mass. 1924–26
G. A. Pierce, Philadelphia, Pa. 1926–27
W. E. Thau, New York, N. Y. 1927–30
R. A. Beekman, Schenectady, N. Y. 1930–33
H. C. Coleman, East Pittsburgh, Pa. 1933–34

Mining Work, Applications to. Organized in 1912 as the committee on the use of electricity in mines; name subsequently changed to committee on mines (1919), and later (1924) to committee on applications to mining work.

G. R. Wood, Philadelphia, Pa. 1912–13
Wilfred Sykes, East Liberty, Pa. 1913–16
H. H. Clark, Pittsburgh, Pa. 1916–17
K. A. Pauly, Schenectady, N. Y. 1917–19
W. A. Chandler, Scottsdale, Pa. 1919–20
Graham Bright, East Pittsburgh, Pa. 1920–23
F. L. Stone, Schenectady, N. Y. 1923–26
W. H. Lesser, Frackville, Pa. 1926–28
Carl Lee, Chicago, Ill. 1928–31
D. E. Renshaw, East Pittsburgh, Pa. 1931–33
E. B. Wagner, Wilkes-Barre, Pa. 1933–34

Power Applications, Committee on General. Organized in 1908 as the committee on industrial power; name subsequently changed to industrial power committee (1909), committee on industrial and domestic power (1916), committee on general power applications (1924).

D. B. Rushmore, Schenectady, N. Y. 1908–10
N. T. Wilcox, Lowell, Mass. 1910–11
W. H. Powell, Milwaukee, Wis. 1911–12
J. M. Hipple, East Pittsburgh, Pa. 1912–13
Rudolph Tschentscher, South Chicago, Ill. 1913–14

D. B. Rushmore, Schenectady, N. Y.....1914–16
E. H. Martindale, Cleveland, Ohio.....1916–18
A. G. Pierce, Pittsburgh, Pa.....1918–21
W. C. Yates, Schenectady, N. Y.....1921–22
H. D. James, East Pittsburgh, Pa.....1922–24
A. E. Waller, Bronxville, N. Y.....1924–25
A. M. MacCutcheon, Cleveland, Ohio.....1925–28
J. F. Gaskill, Philadelphia, Pa.....1928–30
C. W. Drake, East Pittsburgh, Pa.....1931–33
M. R. Woodward, Chicago, Ill.....1933–34

Protective Devices Committee. Organized in 1913 as a subcommittee of the electric power committee; subsequently became the protective apparatus committee (1914), and then protective devices committee (1916).

C. P. Steinmetz, Schenectady, N. Y.....1913–14
E. E. F. Creighton, Schenectady, N. Y.....1914–16
D. W. Roper, Chicago, Ill.....1916–21
H. R. Woodrow, Brooklyn, N. Y.....1921–25
E. C. Stone, Pittsburgh, Pa.....1925–26
F. L. Hunt, Greenfield, Mass.....1926–28
E. A. Hester, Pittsburgh, Pa.....1928–30
Raymond Bailey, Philadelphia, Pa.....1930–32
R. T. Henry, Buffalo, N. Y.....1932–34

Power Generation Committee. Organized in 1910 as the power station committee; subsequently changed to prime movers committee (1913), power station committee (1914), and then to power generation committee (1924).

H. S. Putnam, New York, N. Y.....1910–11
S. D. Sprong, New York, N. Y.....1911–12
H. G. Stott, New York, N. Y.....1912–15
A. S. Loizeaux, Baltimore, Md.....1915–16
J. G. De Remer, New York, N. Y.....1916–17
Philip Torchio, New York, N. Y.....1917–20
H. P. Liversidge, Philadelphia, Pa.....1920–21
Nicholas Stahl, Providence, R. I.....1922–24
V. E. Alden, Baltimore, Md.....1924–26
W. S. Gorsuch, New York, N. Y.....1926–28
F. A. Allner, Baltimore, Md.....1928–31
J. R. Baker, Baltimore, Md.....1931–33
H. W. Leitch, New York, N. Y.....1933–34

Power Transmission and Distribution Committee. Organized in 1902 as a subcommittee of the meetings and papers committee; became the high tension transmission committee (1909), a subcommittee of the electric power committee (1913); in 1914 again became independent as the transmission committee; in 1916 became transmission and distribution committee; in 1924 became committee on power transmission and distribution.

R. D. Mershon, New York, N. Y.....1902–04
R. D. Mershon, New York, N. Y.....1906–10
P. H. Thomas, New York, N. Y.....1910–11
D. B. Rushmore, Schenectady, N. Y.....1911–12
P. H. Thomas, New York, N. Y.....1912–13
P. W. Sothman, New York, N. Y.....1913–14
P. H. Thomas, New York, N. Y.....1914–16
L. E. Imlay, Niagara Falls, N. Y.....1916–18
E. B. Meyer, Newark, N. J.....1918–23
F. G. Baum, San Francisco, Calif.....1923–24
P. H. Thomas, New York, N. Y.....1924–26
Philip Torchio, New York, N. Y.....1926–28
H. R. Woodrow, Brooklyn, N. Y.....1928–30
P. H. Chase, Philadelphia, Pa.....1930–33
D. M. Simmons, New York, N. Y.....1933–34

Research Committee. Organized in 1921 as a general standing committee; became one of the group of technical committees in 1923.

F. B. Jewett, New York, N. Y.....1921–22
J. B. Whitehead, Baltimore, Md.....1922–27
F. W. Peek, Jr., Pittsfield, Mass.....1927–29
S. M. Kintner, East Pittsburgh, Pa.....1929–30
L. W. Chubb, East Pittsburgh, Pa.....1930–32
C. W. Rice, Schenectady, N. Y.....1932–33
F. M. Farmer, New York, N. Y.....1933–34

Transportation Committee. Organized in 1907 as the railway subcommittee of the meetings and papers committee; became an independent committee on railways in 1909; traction and transportation committee in 1916; and committee on transportation, 1924.

A. H. Armstrong, Schenectady, N. Y.....1907–08
B. J. Arnold, Chicago, Ill.....1908–09
William McClellan, New York, N. Y.....1909–10
F. J. Sprague, New York, N. Y.....1910–14
D. C. Jackson, Boston, Mass.....1914–16
N. W. Storer, East Pittsburgh, Pa.....1916–18
C. F. Uebelacker, New York, N. Y.....1918–19
W. S. Murray, New York, N. Y.....1919–20
C. S. Ruffner, New York, N. Y.....1920–21
H. M. Brinckerhoff, New York, N. Y.....1921–22
N. W. Storer, East Pittsburgh, Pa.....1923–24
J. V. B. Duer, Altoona, Pa.....1926–28
W. M. Vandersluis, Chicago, Ill.....1928–29
Sidney Withington, New Haven, Conn.....1929–31
E. L. Moreland, Boston, Mass.....1931–34

Economics of Electric Service, Committee on. Organized in 1913 as the committee on records and appraisals of properties, this committee changed its name in 1916 to committee on economics of electric service; was discontinued in 1921.

W. B. Jackson, Chicago, Ill.....1913–15
Philander Betts, Newark, N. J.....1915–17
W. B. Jackson, Chicago, Ill.....1917–19
C. S. Ruffner, New York, N. Y.....1919–20
Philip Torchio, New York, N. Y.....1920–21

Chairmen of the Institute's Sections

A LIST of the 61 Sections of the Institute, together with the date of authorization of the Section, and the names and terms of service of all chairmen of these Sections are given below.

AKRON

Authorized August 12, 1920

H. C. Stephens.....1920–22
S. C. Henton.....1922–23
P. C. Jones.....1923–24
J. T. Walther.....1924–25
R. Higgins.....1925–26
A. R. Holden.....1926–27
A. L. Richmond.....1927–28
J. Grotzinger.....1928–29
W. A. Hillebrand.....1929–30
H. C. Paiste.....1930–31
R. R. Krammes.....1931–32
A. F. Regal.....1932–33
P. C. Smith.....1933–34

ATLANTA

Authorized January 14, 1904

A. M. Schoen.....1904–07
J. H. Finney.....1907–08
W. R. Collier.....1908–09
H. P. Wood.....1909–11
A. M. Schoen.....1911–20
H. L. Wills.....1920–21
J. E. Mellett.....1921–22
G. K. Selden.....1922–23
C. L. Emerson.....1923–24
W. R. Collier.....1924–25
W. E. Gathright.....1925–26
C. E. Bennett.....1926–27
T. H. Landgraf.....1927–28
H. L. Wills.....1928–30
H. C. Uhl.....1930–31
A. G. Stanford.....1931–32
O. O. Rae.....1932–33
D. H. Woodward.....1933–34

BALTIMORE

Authorized December 16, 1904

J. B. Whitehead.....1904–21
D. Burnett.....1921–22
W. B. Kouwenhoven.....1922–31
K. A. Hawley.....1931–32
J. Wells.....1932–33
L. G. Smith.....1933–34

BIRMINGHAM

Authorized May 2, 1929

W. E. Bare.....1929–30
.....1930–31
.....1931–32
.....1932–33
W. W. Ballew.....1933–34

BOSTON

Authorized February 13, 1903

C. L. Edgar.....1903–04
R. Fleming.....1904–05
C. A. Adams.....1905–06
H. E. Clifford.....1906–07
Wm. L. Puffer.....1907–08
A. E. Kennelly.....1908–09
D. C. Jackson.....1909–10
J. F. Vaughan.....1910–11
Wm. L. Hooper.....1911–12
F. P. Valentine.....1912–13
J. N. Neall.....1913–14
G. W. Palmer, Jr.....1914–15
L. L. Elden.....1915–16
G. A. Burnham.....1916–17
H. M. Hope.....1917–18
I. M. Cushing.....1918–19
I. E. Moultrop.....1919–20
W. I. Middleton.....1920–21
L. W. Abbott.....1921–22
E. L. Moreland.....1922–23
A. Macomber.....1923–24
F. S. Dellenbaugh.....1924–25
J. W. Kidder.....1925–26
Hartley Rowe.....1926–27
E. W. Davis.....1927–28
H. B. Dwight.....1928–29
W. H. Colburn.....1929–30
J. P. Kobrock.....1930–31
C. A. Corney.....1931–32
F. D. Hallock.....1932–33
W. H. Timbie.....1933–34

CHICAGO

Authorized 1893

.....1893
G. A. Damon.....1902–04
K. B. Miller.....1904–06
H. R. King.....1906–08
W. L. Abbott.....1908–10
J. G. Wray.....1910–12
R. H. Rice.....1912–13
D. W. Roper.....1913–14
E. W. Allen.....1914–15
W. J. Norton.....1915–16
T. Milton.....1916–17
Wm. J. Crumpton.....1917–18
C. A. Keller.....1918–19
A. F. Riggs.....1919–20
J. R. Bibbins.....1920–21
M. M. Fowler.....1921–22
F. E. Goodnow.....1922–23
J. E. Kearns.....1923–24
G. H. Jones.....1924–25
Carl Lee.....1925–26
K. A. Auty.....1926–27
B. E. Ward.....1927–28
P. B. Juhnke.....1928–29
T. G. LeClair.....1929–30
F. H. Lane.....1930–31
F. R. Innes.....1931–32
L. R. Mapes.....1932–33
E. C. Williams.....1933–34

CINCINNATI

Authorized June 30, 1920

J. D. Lyon.....1920–22
A. M. Wilson.....1922–24
O. Shepard.....1924–25
H. C. Blackwell.....1925–26
W. P. Beattie.....1926–27
R. C. Fryer.....1927–29
T. C. Reed.....1929–31
E. S. Fields.....1931–32
L. O. Dorfman.....1932–33
L. C. Nowland.....1933–34

CLEVELAND

Authorized September 27, 1907

H. B. Dates.....1907–08
C. W. Ricker.....1908–09
H. L. Wallau.....1909–10
A. M. Allen.....1910–11
B. A. Stowe.....1911–12
E. J. Edwards.....1912–13
J. C. Lincoln.....1913–14
H. Dingle.....1914–15
E. H. Martindale.....1915–16
E. W. P. Smith.....1916–17
C. N. Rakestraw.....1917–18
C. S. Ripley.....1918–19
B. W. David.....1919–20
A. M. MacCutcheon.....1920–21
I. H. Van Horn.....1921–22
L. D. Bale.....1922–23
G. B. Schneeberger.....1923–24
C. P. Cooper.....1924–25
C. L. Dows.....1925–26
H. L. Grant.....1926–27
A. M. Lloyd.....1927–28
E. W. Henderson.....1928–29
T. D. Owens.....1929–30
F. W. Braund.....1930–31
G. A. Kositzky.....1931–32
J. M. Smith.....1932–33
R. C. Putnam.....1933–34

COLUMBUS

Authorized March 17, 1922

F. C. Caldwell.....1922–23
E. M. Fitz.....1923–24
F. R. Price.....1924–25
R. J. B. Feather.....1925–26
A. W. Janowitz.....1926–27
F. C. Nesbitt.....1927–28
W. E. Metzger.....1928–29
R. A. Brown.....1929–30
C. D. Price.....1930–31
W. L. Everitt.....1931–32
K. Y. Tang.....1932–33
A. G. Gibbony.....1933–34

CONNECTICUT

Authorized April 16, 1921

C. F. Scott.....1921–22
E. H. Everit.....1922–24
Wm. A. Moore.....1924–25
A. A. Packard.....1925–26
A. R. Knowlton.....1926–28
E. J. Amberg.....1928–29
S. Withington.....1929–30
S. Ferguson.....1930–31
R. G. Warner.....1931–32
C. J. Daly.....1932–33
C. T. Hughes.....1933–34

DALLAS

Authorized May 18, 1928

G. A. Mills.....1928–29
J. B. Thomas.....1929–30
L. T. Blaisdell.....1930–31
G. A. Dyer.....1931–32
H. K. Handley.....1932–33
D. H. Levy.....1933–34

DENVER

Authorized May 18, 1915

W. A. Carter.....1915–16
H. S. Sands.....1916–17
Norman Read.....1917–18
F. J. Rankin.....1918–19
H. S. Evans.....1919–20
D. C. McClure.....1920–21
B. C. J. Wheatlake.....1921–22
H. B. Barnes.....1922–23
H. B. Dwight.....1923–24
W. C. DuVall.....1924–25
V. L. Board.....1925–26
W. H. Edmunds.....1926–27
A. L. Jones.....1927–28
L. N. McClellan.....1928–29
W. H. Bullock.....1929–30
R. B. Bonney.....1930–31
R. E. Nynwander.....1931–32
W. D. Hardaway.....1932–33
A. W. Ainsworth.....1933–34

DETROIT ANN-ARBOR

Authorized January 13, 1911

C. L. deMuralt.....1911–12
J. J. Woolfenden.....1912–13
A. R. Sawyer.....1913–14
H. H. Norton.....1914–15
R. Collamore.....1915–16
A. A. Meyer.....1916–17
H. H. Higbie.....1917–18
G. E. Lewis.....1918–19
J. C. Parker.....1919–20
C. Kittredge.....1920–21
A. S. Albright.....1921–22
J. H. Cannon.....1922–23
E. L. Bailey.....1923–24
F. L. Snyder.....1924–25
G. B. McCabe.....1925–26
Harold Cole.....1926–27
F. H. Riddle.....1927–28
A. H. Lovell.....1928–29
L. F. Hickernell.....1929–30
L. Braisted.....1930–31
J. J. Shoemaker.....1931–32
O. E. Hauser.....1932–33
R. Foulkrod.....1933–34

ERIE

Authorized January 11, 1918

C. P. Yoder.....1918–19
J. C. Barry.....1919–20
M. C. Goodspeed.....1920–21
A. H. Schum.....1921–22
W. J. Seibert.....1922–23
M. W. Metzner.....1923–24
B. L. Delack.....1924–25
H. J. Hansen.....1925–26
F. A. Tennant.....1926–27
L. H. Curtis.....1927–28
M. L. Elder.....1928–29
W. H. Pelton.....1929–30
J. R. McDonald.....1930–31
P. R. Urich.....1931–32
J. C. Milling.....1932–33
W. D. Bearce.....1933–34

FLORIDA

Authorized January 28, 1931

Joseph Weil.....1931–34

FORT WAYNE

Authorized August 14, 1908

E. A. Wagner.....1908–12
T. W. Behan.....1912–14
L. D. Nordstrum.....1914–15
J. J. Kline.....1915–18
P. C. Morganthaler.....1918–19
C. I. Hall.....1919–20
E. L. Simpson.....1920–21
R. H. Chadwick.....1921–22
S. W. Greenland.....1922–23
C. C. Grandy.....1923–24
A. B. Campbell.....1924–25
E. L. Gaines.....1925–26
D. W. Merchant.....1926–27
P. O. Noble.....1927–28
C. F. Beyer.....1928–29
F. W. Merrill.....1929–30
W. J. Morrill.....1930–31
E. J. Schaefer.....1931–32
B. A. Case.....1932–33
C. M. Summers.....1933–34

HOUSTON

Authorized August 7, 1928

C. A. Williamson.....1928–29
L. K. Del'Homme.....1929–30
C. D. Farman.....1930–31
E. M. Wise.....1931–32
J. B. Arthur.....1932–33
J. S. Waters.....1933–34

INDIANAPOLIS-LAFAYETTE

Authorized January 12, 1912

O. S. More.....1912–14
J. L. Wayne.....1914–17
H. O. Garman.....1917–18
G. B. Schley.....1918–19
J. L. Wayne.....1919–22
D. C. Pyke.....1922–24
W. A. Black.....1924–25
H. M. Anthony.....1925–26
J. B. Bailey.....1926–27
C. A. Fay.....1927–28
H. Kessel.....1928–29
J. B. Bailey.....1929–30
E. G. Ralston.....1930–31
E. L. Carter.....1931–32
E. G. Thoms.....1932–33
C. E. Chatfield.....1933–34

IOWA

Authorized June 25, 1929

C. L. Sampson.....1929–30
J. K. McNeely.....1930–31
H. B. Hoffhaus.....1931–32
L. F. Wood.....1932–33
E. R. McKee.....1933–34

ITHACA

Authorized October 15, 1902

Harris J. Ryan.....1902–06
E. L. Nichols.....1906–16
F. Bedell.....1916–18
A. Gray.....1918–20
J. G. Pertsch.....1920–26
R. F. Chamberlain.....1926–29
W. C. Ballard, Jr.....1929–31
W. E. Meserve.....1931–33
B. K. Northrop.....1933–34

KANSAS CITY

Authorized April 14, 1916

A. A. Thompson.....1916–17
W. F. Barnes.....1917–20
G. C. Shaad.....1920–23
R. L. Weber.....1923–24
D. D. Clarke.....1924–25
F. S. Dewey.....1925–26
R. L. Baldwin.....1926–27
S. M. DeCamp.....1927–28
B. J. George.....1928–29
A. B. Covey.....1929–30
J. S. Palmer.....1930–31
G. Fiske.....1931–32
G. O. Brown.....1932–33
R. W. Warner.....1933–34

LEHIGH VALLEY

Authorized April 16, 1921

C. Hodge.....1921–22
D. M. Petty.....1922–23
H. G. Hervey.....1923–24
J. L. Beaver.....1924–25
W. H. Lesser.....1925–26
W. E. Lloyd, Jr.....1926–27
M. R. Woodward.....1927–28
H. D. Baldwin.....1928–29
A. J. Althouse.....1929–30
W. M. Harbaugh.....1930–31
Morland King.....1931–32
J. G. Charest.....1932–33
N. S. Hibshman.....1933–34

LOS ANGELES

Authorized May 19, 1908

C. W. Koiner.....1908–09
J. A. Lighthipe.....1909–10
J. E. MacDonald.....1910–11
O. H. Ensign.....1911–12
G. A. Damon.....1912–13
E. R. Northmore.....1913–14
C. G. Pyle.....1914–15
E. Woodbury.....1915–16
R. H. Manahan.....1916–17
D. Morgan.....1917–18
J. H. Cunningham.....1918–19
C. A. Copeland.....1919–20
R. W. Sorensen.....1920–21
H. H. Cox.....1921–22
J. N. Kelman.....1922–23
E. R. Stauffacher.....1923–24
C. A. Heinze.....1924–25
R. A. Hopkins.....1925–26
R. E. Cunningham.....1926–27
L. C. Williams.....1927–28
H. L. Caldwell.....1928–29
N. B. Hinson.....1929–30
H. W. Hitchcock.....1930–31
P. S. Biegler.....1931–32
F. E. Dellinger.....1932–33
A. P. Hill.....1933–34

LOUISVILLE

Authorized October 15, 1926

D. C. Jackson, Jr.....1926–28
B. D. Wood.....1928–29
H. W. Wischmeyer.....1929–30
James Clark, Jr.....1930–31
P. P. Ash.....1931–32
C. M. Ewing.....1932–33
S. T. Fife.....1933–34

LYNN

Authorized August 22, 1911

E. E. Boyer.....1911–12
W. A. Hall.....1912–13
E. R. Berry.....1913–14
W. H. Pratt.....1914–15
G. N. Chamberlin.....1915–16
G. Campbell.....1916–17
J. M. Davis.....1917–18
L. E. Underwood.....1918–19
A. K. Warren.....1919–20
L. C. Loewenstein.....1920–21
F. J. Rudd.....1921–22
J. W. West.....1922–23
L. E. Smith.....1923–24
B. W. St. Clair.....1924–25
E. D. Dickinson.....1925–26
D. F. Smalley.....1926–27
W. F. Dawson.....1927–28
C. Skoglund.....1928–29
I. F. Kinnard.....1929–30
A. L. Ellis.....1930–31
J. A. Cook.....1931–32
W. K. Dickinson.....1932–33
S. A. Moss.....1933–34

MADISON

Authorized January 8, 1909

M. H. Collbohm.....1909–11
J. N. Cadby.....1911–12
E. H. Kifer.....1912–13
E. Bennett.....1913–14
J. W. Shuster.....1914–15
M. C. Beebe.....1915–16
F. A. Kartak.....1916–17
J. R. Price.....1917–18
J. W. Watson.....1918–19
C. J. Jansky.....1919–20
G. C. Neff.....1920–21
C. B. Hayden.....1921–22
H. M. Crothers.....1922–23
G. E. Wagner.....1923–24
R. G. Walter.....1924–25
L. E. A. Kelso.....1925–26
E. J. Kallevang.....1926–27
J. T. Rood.....1927–28
L. J. Peters.....1928–29
R. E. Purucker.....1929–30
L. C. Larson.....1930–31
N. H. Blume.....1931–32
G. F. Tracy.....1932–33
T. A. Brown.....1933–34

MEMPHIS

Authorized May 23, 1930

M. Eldredge.....1930–31
W. A. Gentry.....1931–32
G. O. MacFarlane.....1932–33
F. L. Christenbury.....1933–34

MEXICO

Authorized June 29, 1922

.....1922–23
D. K. Lewis.....1923–25
E. F. Lopez.....1925–26
Carlos Macias.....1926–27
B. Nikiforoff.....1927–28
P. M. McCullough.....1928–29
G. Solis Payan.....1929–30
B. E. Arias.....1930–31
E. F. Lopez.....1931–32
W. A. Schulenburg.....1932–33
C. E. Plumb.....1933–34

MILWAUKEE

Authorized February 11, 1910

W. H. Powell.....1910–11
F. A. Vaughan.....1911–12
T. E. Barnum.....1912–13
L. E. Bogen.....1913–14
L. L. Tatum.....1914–15
R. B. Williamson.....1915–16
F. W. Ells.....1916–17
A. Simon.....1917–18
F. A. Coffin.....1918–19
H. P. Reed.....1919–20
H. W. Cheney.....1920–21
F. J. Mayer.....1921–22
G. C. Post.....1922–23
S. H. Mortensen.....1923–24
C. T. Evans.....1924–25
H. R. Huntley.....1925–26
H. L. Van Valkenberg.....1926–27
J. D. Ball.....1927–28
E. R. Stoekle.....1928–29
E. W. Seeger.....1929–30
F. A. Kartak.....1930–31
H. E. Krueger.....1931–32
W. F. Lent.....1932–33
K. L. Hansen.....1933–34

MINNESOTA

Authorized April 7, 1902

G. D. Shepardson.....1902–05
E. P. Burch.....1905–06
H. J. Gille.....1906–07
E. H. Scofield.....1907–09
J. C. Vincent.....1909–11
C. L. Pillsbury.....1911–12
A. L. Abbott.....1912–13
W. T. Ryan.....1913–14
L. H. Cooper.....1914–15
E. T. Street.....1915–16
R. J. S. Carter.....1916–17
F. W. Springer.....1917–18
M. Barnert.....1918–19
F. Dustin.....1919–20
J. D. Marshall.....1920–21
W. T. Ryan.....1921–22
F. A. Otto.....1922–23
H. W. Meyer.....1923–24
E. H. Scofield.....1924–25
A. G. Dewars.....1925–26
S. B. Hood.....1926–27
J. E. Sumpter.....1927–28
M. E. Todd.....1928–29
V. E. Engquist.....1929–30
D. E. Lewis.....1930–31
O. Gaarden.....1931–32
H. J. Pierce.....1932–33
E. H. Hagensick.....1933–34

MONTANA

Authorized June 24, 1931

J. A. Thaler.....1931–34

NEBRASKA

Authorized January 21, 1925

P. M. McCullough.....1925–26
C. W. Minard.....1926–27
N. W. Kingsley.....1927–28
C. D. Robison.....1928–29
D. H. Braymer.....1929–30
W. O. Jacobi.....1930–31
A. L. Turner.....1931–32
C. Talsma.....1932–33
H. S. Pahren.....1933–34

NEW ORLEANS

Authorized December 8, 1933

James M. Todd.....1933–34

NEW YORK

Authorized December 10, 1919

H. W. Buck.....1919–21
Farley Osgood.....1921–22
Calvert Townley.....1922–23
L. F. Morehouse.....1923–24
H. H. Barnes, Jr.....1924–25
H. A. Kidder.....1925–26
E. B. Meyer.....1926–27
L. W. W. Morrow.....1927–28
R. H. Tapscott.....1928–29
H. P. Charlesworth.....1929–30
J. B. Bassett.....1930–31
O. H. Caldwell.....1931–32
T. F. Barton.....1932–33
C. R. Jones.....1933–34

NIAGARA FRONTIER

Authorized February 10, 1925

J. Allen Johnson.....1925–26
H. B. Alverson.....1926–27
L. E. Imlay.....1927–28
G. H. Calkins.....1928–29
R. T. Henry.....1929–30
E. S. Bundy.....1930–31
R. W. Graham.....1931–32
F. S. Wahl.....1932–33
J. S. Henderson.....1933–34

NORTH CAROLINA

Authorized March 21, 1929

E. P. Coles.....1929–30
J. H. Paget.....1930–31
J. E. Lear.....1931–32
F. L. Moser.....1932–33
H. M. Doerschuk.....1933–34

OKLAHOMA CITY

Authorized February 16, 1922

F. W. Insull.....1922–23
T. M. Faris.....1923–25
R. E. Page.....1925–27
E. Kurtz.....1927–28
C. V. Bullen.....1928–29
C. W. Mier.....1929–30
P. J. Meyer.....1930–31
C. T. Almquist.....1931–32
E. B. Jennings.....1932–33
R. P. Danner.....1933–34

PHILADELPHIA

Authorized February 18, 1903

Carl Hering.....1902-03
C. B. Hewitt.....1903-04
H. A. Foster.....1904-05
C. W. Pike.....1905-06
W. C. L. Eglin.....1906-07
J. F. Stevens.....1907-08
Paul Spencer.....1908-09
G. A. Hoadley.....1909-10
C. I. Young.....1910-11
H. C. Snook.....1911-12
H. A. Hornor.....1912-13
A. R. Cheyney.....1913-14
H. S. Sanville.....1914-15
J. H. Tracy.....1915-16
H. P. Liversidge.....1916-17
N. Hayward.....1917-18
W. F. James.....1918-19
C. E. Clewell.....1919-20
C. R. Bonine.....1920-21
P. H. Chase.....1921-22
E. B. Tuttle.....1922-23
R. B. Mateer.....1923-24
C. D. Fawcett.....1924-25
N. Shute.....1925-26
L. J. Costa.....1926-27
I. M. Stein.....1927-28
L. F. Deming.....1928-29
R. H. Silbert.....1929-30
D. H. Kelly.....1930-31
C. N. Johnson.....1931-32
Lewis Fussell.....1932-33
P. S. Harkins.....1933-34

PITTSBURGH

Authorized October 13, 1902

P. M. Lincoln.....1902-04
N. W. Storer.....1904-05
S. P. Grace.....1905-06
H. W. Fisher.....1906-07
C. E. Skinner.....1907-08
W. E. Reed.....1908-09
C. B. Auel.....1909-10
H. N. Muller.....1910-11
K. C. Randall.....1911-12
E. L. Farrar.....1912-13
A. M. Dudley.....1913-14
J. W. Welsh.....1914-15
T. H. Schoepf.....1915-16
G. C. Hecker.....1916-17
F. E. Wynne.....1917-18
W. R. Work.....1918-19
J. G. Carroll.....1919-20
B. C. Dennison.....1920-21
H. W. Smith.....1921-22
E. C. Stone.....1922-23
O. Needham.....1923-24
M. E. Skinner.....1924-25
G. S. Humphrey.....1925-26
D. M. Simmons.....1926-27
W. C. Goodwin.....1927-28
H. E. Dyche.....1928-29
J. A. Cadwallader.....1929-30
C. T. Sinclair.....1930-31
F. A. Conner.....1931-32
T. Spooner.....1932-33
R. L. Kirk.....1933-34

PITTSFIELD

Authorized March 25, 1904

F. A. C. Perrine.....1904-05
C. C. Cheney.....1905-06
G. Wright.....1906-07
J. Insull.....1907-08
W. A. Hall.....1908-09
H. W. Tobey.....1909-10
S. H. Blake.....1910-11
G. Faccioli.....1911-12
W. C. Smith.....1912-13
J. J. Frank.....1913-14
W. W. Lewis.....1914-15
M. O. Troy.....1915-16
V. E. Goodwin.....1916-17
F. F. Brand.....1917-18
N. Carrie.....1918-19
R. E. Wagner.....1919-20
F. W. Peek, Jr.....1920-21
I. H. Sclater.....1921-22
W. P. White.....1922-23
E. D. Treanor.....1923-24
N. F. Hanley.....1924-25
E. D. Eby.....1925-26
E. F. Gehrkens.....1926-27
H. O. Stephens.....1927-28
J. R. Rue.....1928-29
L. F. Blume.....1929-30
C. H. Kline.....1930-31
F. R. Pinch.....1931-32
V. M. Montainger.....1932-33
W. H. Cooney.....1933-34

PORTLAND

Authorized May 18, 1909

O. B. Coldwell.....1909-11
F. D. Weber.....1911-12
H. R. Wakeman.....1912-13
G. P. Nock.....1913-14
R. F. Monges.....1914-15
P. Lebenbaum.....1915-16
L. T. Merwin.....1916-17
E. D. Searing.....1917-18
R. M. Boykin.....1918-19
E. F. Whitney.....1919-21
W. C. Heston.....1921-22
D. W. Prochstel.....1922-23
E. F. Pearson.....1923-24
H. P. Cramer.....1924-25
L. W. Ross.....1925-26
J. C. Henkle.....1926-27
J. E. Yates.....1927-28
L. M. Moyer.....1928-29
H. H. Cake.....1929-30
A. H. Kreul.....1930-31
R. J. Davidson.....1931-32
F. M. Lewis.....1932-33
V. B. Wilfley.....1933-34

PROVIDENCE

Authorized March 12, 1920

W. C. Slade.....1920-21
N. Stahl.....1921-22
R. W. Adams.....1922-23
H. A. Stanley.....1923-24
W. B. Lewis.....1924-25
W. P. Field.....1925-26
E. E. Nelson.....1926-27
F. N. Tompkins.....1927-28
A. E. Watson.....1928-29
F. W. Smith.....1929-30
J. W. Young.....1930-31
W. S. Maddocks.....1931-32
I. W. Knight.....1932-33
O. W. Briden.....1933-34

ROCHESTER

Authorized October 9, 1914

J. C. Parker.....1914-15
E. L. Wilder.....1915-16
O. W. Bodler.....1916-17
F. C. Taylor.....1917-18
R. H. Manson.....1918-19
J. W. Morrison.....1919-20
H. J. Schiefer.....1920-21
S. Alling.....1921-22
G. A. Scoville.....1922-23
W. S. Burch.....1923-24
F. T. Bryne.....1924-25
A. R. Soderholm.....1925-26
E. C. Karker.....1926-27
R. D. DeWolf.....1927-28
H. E. Gordon.....1928-29
V. M. Graham.....1929-30
H. J. Klumb.....1930-31
F. C. Young.....1931-32
C. F. Estwick.....1932-33
E. G. Eidam.....1933-34

ST. LOUIS

Authorized January 14, 1903

W. E. Goldsborough.....1903-04
H. H. Humphrey.....1904-05
A. H. Timmerman.....1905-06
A. S. Langsdorf.....1906-10
G. W. Lamke.....1910-12
J. A. Osborn.....1912-13
F. J. Bullivant.....1913-14
S. N. Clarkson.....1914-15
W. O. Pennell.....1915-16
A. McR. Harrelson.....1916-17
H. W. Eales.....1917-18
J. L. Hamilton.....1918-19
G. A. Waters.....1919-21
J. L. Woodress.....1921-22
J. M. Chandlee.....1922-24
B. D. Hull.....1924-25
F. D. Lyon.....1925-26
W. H. Millan.....1926-27
L. F. Woolston.....1927-28
C. P. Potter.....1928-29
G. H. Quermann.....1929-30
C. B. Fall.....1930-31
C. H. Kraft.....1931-32
F. B. Wipperman.....1932-33
L. S. Washington.....1933-34

SAN ANTONIO

Authorized May 23, 1930

D. W. Flowers.....1930-31
J. E. Woods.....1931-32
I. A. Uhr.....1932-33
V. H. Braunig.....1933-34

SAN FRANCISCO

Authorized December 23, 1904

G. O. Squier.....1904-05
C. L. Cory.....1905-07
A. M. Hunt.....1907-08
C. W. Burkett.....1908-09
G. R. Murphy.....1909-10
S. J. Lisberger.....1910-11
S. B. Charters.....1911-12
H. W. Crozier.....1912-13
A. H. Griswold.....1913-14
C. J. Wilson.....1914-15
A. H. Babcock.....1915-16
J. E. Woodbridge.....1916-17
L. R. Jorgensen.....1917-18
J. C. Clark.....1918-19
W. G. Vincent.....1919-20
J. P. Jollyman.....1920-21
W. P. L'Hommedieu.....1921-22
H. H. Henline.....1922-23
J. A. Koontz, Jr.....1923-24
F. R. George.....1924-25
R. C. Powell.....1925-26
D. I. Cone.....1926-27
W. L. Winter.....1927-28
B. D. Dexter.....1928-29
L. F. Fuller.....1929-30
P. B. Garrett.....1930-31
E. A. Crellin.....1931-32
E. F. Maryatt.....1932-33
W. C. Smith.....1933-34

SASKATCHEWAN

Authorized October 14, 1925

S. W. Bull.....1925-26
S. R. Parker.....1926-27
J. D. Peters.....1927-28
E. W. Bull.....1928-29
J. R. Crowley.....1929-30
W. T. Hunt.....1930-31
N. W. Dubois.....1931-33
H. Forbes Roberts.....1933-34

SCHENECTADY

Authorized January 26, 1903

C. P. Steinmetz.....1903-05
D. B. Rushmore.....1905-08
E. J. Berg.....1908-09
M. O. Troy.....1909-10
E. A. Baldwin.....1910-11
E. B. Merriam.....1911-12
J. B. Taylor.....1912-13
G. H. Hill.....1913-14
H. M. Hobart.....1914-15
L. T. Robinson.....1915-16
C. E. Eveleth.....1916-17
W. L. Upson.....1917-18
K. A. Pauly.....1918-19
C. S. Van Dyke.....1919-20
H. R. Summerhayes.....1920-21
S. H. Blake.....1921-22
C. M. Davis.....1922-23
R. C. Muir.....1923-24
J. R. Craighead.....1924-25
W. J. Davis, Jr.....1925-26
R. E. Doherty.....1926-27
T. A. Worcester.....1927-28
E. S. Lee.....1928-29
R. Treat.....1929-30
E. S. Henningsen.....1930-31
R. A. Beekman.....1931-32
E. E. Johnson.....1932-33
D. W. McLenegan.....1933-34

SEATTLE

Authorized January 19, 1904

K. G. Dunn.....1904-05
Howard Joslyn.....1905-06
C. E. Magnusson.....1906-08
J. H. Harisberger.....1908-10
A. A. Miller.....1910-12
J. D. Ross.....1912-13
S. C. Lindsay.....1913-15
C. E. Magnusson.....1915-17
J. Harisberger.....1917-19
G. E. Quinan.....1919-21
J. P. Growden.....1921-22
C. F. Terrell.....1922-23
C. A. Lund.....1923-24
J. Hellenthal.....1924-25
E. A. Loew.....1925-26
C. E. Mong.....1926-27
C. R. Wallis.....1927-29
L. N. Robinson.....1929-30
C. E. Carey.....1930-31
M. T. Cornford.....1931-32
A. F. Darland.....1932-33
G. L. Hoard.....1933-34

SHARON

Authorized December 11, 1925

W. M. Dann.....1925-26
H. L. Cole.....1926-27
L. H. Hill.....1927-28
H. B. West.....1928-29
J. B. Gibbs.....1929-30
S. S. Cook.....1930-31
R. M. Field.....1931-32
A. P. Bender.....1932-33
W. W. Satterlee.....1933-34

SOUTHERN VIRGINIA

Authorized May 19, 1922

.....1922-23
Wm. C. Bell.....1923-24
H. B. Hawkins.....1924-25
W. S. Rodman.....1925-28
H. C. Leonard.....1928-30
J. H. Berry.....1930-32
Cecil Gray.....1932-33
E. L. Lockwood.....1933-34

SPOKANE

Authorized February 14, 1913

J. B. Fisken.....1913-14
J. W. Hungate.....1914-15
V. H. Greisser.....1915-16
D. F. Henderson.....1916-17
C. A. Lund.....1917-18
G. Nixon.....1918-19
J. E. E. Royer.....1919-20
R. S. Daniels.....1920-21
L. J. Pospisil.....1921-22
H. L. Melvin.....1922-23
E. R. Hannibal.....1923-24
J. S. McNair.....1924-25
G. S. Cover.....1925-26
R. McKay.....1926-27
L. R. Gamble.....1927-28
B. Olsen.....1928-29
E. Baughn.....1929-30
L. A. Traub.....1930-31
H. L. Vincent.....1931-32
C. F. Norberg.....1932-33
W. M. Allen.....1933-34

SPRINGFIELD

Authorized June 29, 1922

W. A. Dick.....1922-23
J. M. Newton.....1923-24
G. W. Atkinson.....1924-25
R. P. King.....1925-26
L. F. Curtis.....1926-27
C. A. M. Weber.....1927-28
J. F. Murray.....1928-29
F. L. Hunt.....1929-30
J. N. Alberti.....1930-31
B. V. K. French.....1931-32
Hans Passburg.....1932-33
L. C. Packer.....1933-34

SYRACUSE

Authorized August 12, 1920

E. T. Moore.....1920-22
R. D. Whitney.....1922-24
W. C. Pearce.....1924-26
C. E. Dorr.....1926-28
W. R. McCann.....1928-29
F. E. Verdin.....1929-31
C. W. Henderson.....1931-33
W. E. Mueller.....1933-34

TOLEDO

Authorized June 3, 1907

W. G. Nagel.....1907-08
C. R. McKay.....1908-09
M. W. Hansen.....1909-11
G. E. Kirk.....1911-16
W. E. Richards.....1916-17
W. A. Hill.....1917-21
G. Southern.....1921-24
P. R. Knapp.....1924-25
A. H. Stebbins.....1925-26
O. F. Rabbe.....1926-27
T. J. Nolan.....1927-28
W. T. Lowery.....1928-29
E. B. Featherstone.....1929-30
F. H. Dubb.....1930-31
J. A. Dinwiddie.....1931-32
I. H. Heitkamp.....1932-33
E. H. Howell.....1933-34

TORONTO

Authorized September 30, 1903

J. A. Kammerer.....1903-04
T. R. Rosebrugh.....1904-05
H. A. Moore,
R. T. MacKeen.....1905-06
R. G. Black.....1906-07
K. L. Aitken.....1907-08
W. A. Bucke.....1908-09
H. W. Price.....1909-10
E. Richards.....1910-11
A. L. Mudge.....1911-12
F. A. Gaby.....1912-13
H. D. McDougall.....1913-16
E. T. J. Brandon.....1916-17
W. G. Gordon.....1917-18
A. H. Hull.....1918-19
A. B. Cooper.....1919-20
F. R. Ewart.....1920-21
W. P. Dobson.....1921-22
S. E. M. Henderson.....1922-23
C. E. Schwenger.....1923-24
H. C. Don Carlos.....1924-25
L. B. Chubbuck.....1925-26
M. B. Hastings.....1926-27
C. E. Sisson.....1927-28
E. M. Wood.....1928-29
F. F. Ambuhl.....1929-30
D. A. McKenzie.....1930-31
T. W. Eadie.....1931-32
I. M. Maclean.....1932-33
G. D. Floyd.....1933-34

URBANA

Authorized November 25, 1902

W. H. Williams.....1902-06
J. M. Bryant.....1906-08
E. B. Paine.....1908-09
C. T. Knipp.....1909-10
Morgan Brooks.....1910-11
E. H. Waldo.....1911-12
A. M. Buck.....1912-13
Morgan Brooks.....1913-14
I. W. Fisk.....1914-15
P. S. Biegler.....1915-16
I. W. Fisk.....1916-17
L. V. James.....1917-18
A. R. Knight.....1918-19
Morgan Brooks.....1919-21
E. H. Waldo.....1921-22
H. A. Brown.....1922-23
E. B. Paine.....1923-24
C. T. Knipp.....1924-25
C. A. Keener.....1925-26
J. T. Tykociner.....1926-27
J. O. Kraehenbuehl.....1927-28
J. K. Tuthill.....1928-29
M. A. Faucett.....1929-30
C. E. Skroder.....1930-31
E. H. Waldo.....1931-32
E. A. Reid.....1932-33
H. N. Hayward.....1933-34

Past and Present Officers of the Institute

UTAH

Authorized March 9, 1917

A. S. Peters.....1917–19
M. Cheever.....1919–20
J. F. Merrill.....1920–21
P. P. Ashworth.....1921–22
C. C. Pratt.....1922–23
C. R. Higson.....1923–24
H. W. Clark.....1924–25
J. Salberg.....1925–26
B. C. J. Wheatlake...1926–27
D. L. Brundige.....1927–28
C. B. Shipp.....1928–29
A. C. Kelm.....1929–30
L. B. Fuller.....1930–31
Paul Ransom.....1931–32
A. L. Taylor.....1932–33
H. T. Plumb.....1933–34

VANCOUVER

Authorized August 22, 1911

F. D. Nims.....1911–13
R. M. Breed.....1913–14
E. P. LaBelle.....1914–15
R. F. Hayward.....1915–20
F. Sawford.....1920–21
J. R. Read.....1921–22
T. H. Crosby.....1922–23
F. W. MacNeill.....1923–24
C. N. Beebe.....1924–25
A. Vilstrup.....1925–26
R. L. Hall.....1926–27
A. C. R. Yuill.....1927–28
C. W. Colvin.....1928–29
J. Teasdale.....1929–30
H. Vickers.....1930–31
G. R. Wright.....1931–33
L. B. Stacey.....1933–34

WASHINGTON

Authorized April 9, 1903

F. A. Wolff.....1903–04
Samuel Reber.....1904–05
E. B. Ross.....1905–06
Edgar Russel.....1906–07
P. G. Burton.....1907–08
P. Betts.....1908–10
E. Wheeler.....1910–12
J. H. Finney.....1912–13
H. C. Eddy.....1913–14
C. B. Mirick.....1914–15
R. H. Dalgleish.....1915–16
A. Dunlop.....1916–17
P. G. Agnew.....1917–18
J. E. Smith.....1918–19
M. M. Flanders.....1919–21
A. R. Cheyney.....1921–22
L. T. Blaisdell.....1922–23
L. M. Evans.....1923–24
J. H. Ferry.....1924–25
A. F. E. Horn.....1925–26
C. A. Robinson.....1926–27
M. G. Lloyd.....1927–28
L. D. Bliss.....1928–29
W. A. E. Doying.....1929–30
G. W. Vinal.....1930–31
G. L. Weller.....1931–32
T. J. MacKavanagh..1932–33
R. Whitehurst.....1933–34

WORCESTER

Authorized February 18, 1920

C. R. Oliver.....1920–21
G. M. Hardy.....1921–22
F. J. Adams.....1922–23
L. E. Pierce.....1923–24
S. M. Anson.....1924–25
E. T. Harrop.....1925–26
C. F. Hood.....1926–27
G. F. Woodward.....1927–28
A. F. Snow.....1928–29
H. H. Newell.....1929–30
J. K. Oldham.....1930–31
J. P. McCann.....1931–32
H. A. Maxfield.....1932–33
L. S. Leavitt.....1933–34

*Abbott, Arthur V., *V-P.*, 1900–02.
Adams, Comfort A., *M.*, 1912–15; *V-P.*, 1915–17; *P.*, 1918–19.
Adsit, C. G., *V-P.*, 1921–23.
*Anthony, Wm. A., *V-P.*, 1886–89; *P.*, 1890–91; *V-P.*, 1894–6.
Armstrong, A. H., *M.*, 1903–06; *V-P.*, 1906–08.
Arnold, Bion J., *M.*, 1895–98; *V-P.*, 1902–03; *P.*, 1903–04.
Auty, K. A., *V-P.*, 1932– .

Babcock, A. H., *V-P.*, 1918–19.
Barnes, H. H., Jr., *M.*, 1910–13; *V-P.*, 1913–15.
Barstow, W. S., *M.*, 1900–03; *V-P.*, 1903–05.
†Bates, D. H., *V-P.*, 1885–87.
*Baum, Frank G., *V-P.*, 1906–08.
Beaver, J. L., *V-P.*, 1927–29.
Bedell, Frederick, *M.*, 1914–17; *V-P.*, 1917–18.
*Behrend, B. A., *M.*, 1913–16; *V-P.*, 1916–18.
*Bell, Alexander G., *V-P.*, 1884–85; *P.*, 1891–92.
*Bell, Louis, *M.*, 1891–94.
Bennett, Edward, *V-P.*, 1924–26.
Berresford, A. W., *M.*, 1909–12; *V-P.*, 1912–14; *P.*, 1920–21.
Bettis, A. B., *V-P.*, 1926–28; *D.*, 1928–32.
Bickelhaupt, C. O., *V-P.*, 1927–29.
†Black, R. G., *M.*, 1910–13.
Bonney, R. B., *V-P.*, 1933– .
*Brackett, Cyrus F., *M.*, 1886–89.
*Bradley, Chas. S., *M.*, 1894–97; *V-P.*, 1897–99; *M.*, 1899–1902.
*Brooks, David, M., *M.*, 1885–88.
Brooks, Morgan, *M.*, 1907–10; *V-P.*, 1910–12.
*Brush, Chas. F., *M.*, 1884–87.
Bryant, J. M., *M.*, 1924–28.
Buck, Harold W., *M.*, 1907–10; *V-P.*, 1910–12; *P.*, 1916–17.
*Buckingham, Chas. L., *M.*, 1885–88.
Bussey, H. E., *V-P.*, 1923–25.

Carle, N. A., *M.*, 1916–19; *V-P.*, 1919–20.
*Carlton, W. G., *M.*, 1908–11; *V-P.*, 1911–13.
Carpenter, H. V., *V-P.*, 1930–32.
*Carty, John J., *M.*, 1895–96; 1900–03; 1903–04; 1906–08; *V-P.*, 1904–06; 1908–11; *P.*, 1915–16.
*Chamberlain, J. C., *M.*, 1890–93.
Charlesworth, H. P., *M.*, 1923–27; *V-P.*, 1930–32; *P.*, 1932–33.
Chesney, C. C., *M.*, 1905–08; *V-P.*, 1908–10; *P.*, 1926–27.
Chesterman, F. J., *D.*, 1926–30.
Chubb, L. W., *D.*, 1931– .
Chubbuck, L. B., *V-P.*, 1931–33.
†Church, W. Lee, *M.*, 1887–88.
Clarke, Chas. L., *M.*, 1904–05.
Clifford, H. B., *M.*, 1908–11.
Coldwell, O. B., *V-P.*, 1921–22.
*Compton, Alfred G., *M.*, 1891–94.
Cooper, A. B., *V-P.*, 1927–29; *D.*, 1930– .
Copley, A. W., *V-P.*, 1931–33.
*Craft, E. B., *M.*, 1920–24.
Craft, P. M., *V-P.*, 1933– .
*Crocker, Francis B., *M.*, 1888–90; *V-P.*, 1890–92; 1894–96; *P.*, 1897–98.
†Crosby, Oscar T., *V-P.*, 1892–94.
*Cross, Chas. R., *V-P.*, 1884–85.
*Cuttriss, Chas., *M.*, 1888–91.

*Delany, Patrick B., *M.*, 1890–93; *V-P.*, 1893–95.
Del Mar, Wm. A., *M.*, 1917–21; *V-P.*, 1921–22.
Dobson, W. P., *V-P.*, 1925–27.
*Dolbear, A. E., *V-P.*, 1885–87.
Don Carlos, H. C., *D.*, 1926–30.
Downing, P. M., *V-P.*, 1925–27.
*Duncan, Louis, *P.*, 1895–97.
Dunn, Gano, *M.*, 1897–1900; *V-P.*, 1900–02; *M.*, 1902–05; *V-P.*, 1905–07; *P.*, 1911–12.

Eales, H. W., *V-P.*, 1921–26.
*Eckert, W. H., *M.*, 1884–85.
*Edgar, Chas. L., *M.*, 1905–08.
*Edison, Thos. A., *V-P.*, 1884–85.
*Eglin, W. C., *M.*, 1903–06; *V-P.*, 1907–09.
Emmet, W. L. R., *V P.*, 1900–02.
Evans, Herbert S., *V-P.*, 1929–31.
Ewart, F. R., *V-P.*, 1921–23.

*Faccioli, G., *M.*, 1918–22; *V-P.*, 1922–24.
Ferguson, Louis A., *M.*, 1904–07; *V-P.*, 1907–08; *P.*, 1908–09.
Ferguson, O. J., *V-P.*, 1927–29.
*Field, Stephen D., *M.*, 1884–86.
*Finney, John H., *M.*, 1914–17; *V-P.*, 1917–18.
Fisken, John B., *M.*, 1916–19; *V-P.*, 1919–20.
Fleager, C. E., *V-P.*, 1929–31.
*Foster, Horatio A., *M.*, 1890–93.
Fowle, F. F., *M.*, 1919–23.
*Fowler, A. C., *M.*, 1887.
Fowler, M. M., *D.*, 1925–29.
Freeman, W. E., *V-P.*, 1931–33.

*Geyer, Wm. E., *M.*, 1888–92.
Gherardi, Bancroft, *M.*, 1905–08; 1914–17; *V-P.*, 1908–10; *P.*, 1927–28.
Goldsborough, W. E., *M.*, 1901–04; *V-P.*, 1904–06.
*Gray, Elisha, *M.*, 1884–86.
*Green, Norvin, *P.*, 1884–86; *V-P.*, 1886–88.
*Greene, S. Dana, *M.*, 1899.
Hall, Walter A., *M.*, 1917–21; *V-P.*, 1921–22.
*Hamblet, Jas., *M.*, 1891–94; *V-P.*, 1894–96.
Hamilton, George A., *V-P.*, 1884–86; *Natl. Treas.*, 1895–1930.
*Hammer, William J., *V-P.*, 1891–93; *M.*, 1893–96.
Hanker, F. C., *D.*, 1927–31.
Harisberger, John, *V-P.*, 1924–26.
*Haskins, Chas. H., *V-P.*, 1884–86.
*Hasson, W. F. C., *V-P.*, 1895–97; *M.*, 1897–1900.
*Hazard, Rowland R., *Treas.*, 1884–86; *V-P.*, 1887–89.
*Hellings, M. L., *M.*, 1884–85.
Henderson, S. R. M., *V-P.*, 1923–25.
Henline, H. H., *Act. Natl. Secy.*, 1932; *Natl. Secy.*, 1933– .
*Hering, Carl, *V-P.*, 1891–93; 1895–98; *P.*, 1900–01.
*Herzog, F. Benedict, *M.*, 1887–92.
†Hewitt, Chas., *M.*, 1893–95.
†Hibbard, Angus S., *M.*, 1892–95; *V-P.*, 1895–97.
Higson, C. R., *V-P.*, 1932– .
Hobart, H. M., *M.*, 1922–26; *V-P.*, 1926–28.
*Houston, Edwin J., *M.*, 1884–87; *P.*, 1893–95.
Howell, John W., *M.*, 1888–90.
Hull, A. H., *V-P.*, 1933– .
Hull, B. D., *V-P.*, 1928–30; *D.*, 1931–.
Humphrey, H. H., *V-P.*, 1906–08.
Hunting, F. S., *M.*, 1911–14; *V-P.*, 1914–16.
Hutchinson, Cary T., *M.*, 1895–98; *V-P.*, 1898–1900.
*Hutchinson, F. L., *Natl. Secy.*, 1912–32.

Imlay, L. B., *M.*, 1919–23.

Jackson, Dugald C., *V-P.*, 1897–99; *P.*, 1910–11.
Jackson, W. B., *M.*, 1919–15; *V-P.*, 1918–19.
James, Wm. P., *V-P.*, 1923–25.
Jamieson, B. G., *V-P.*, 1926–28.
Jewett, F. B., *M.*, 1915–18; *V-P.*, 1918–19; *P.*, 1922–23.
Johnson, J. Allen, *D.*, 1928–32; *V-P.*, 1932– .
*Jones, Francis W., *M.*, 1884–85; *V-P.*, 1885–87.
Jorgensen, L. R., *V-P.*, 1919–20.
Juhnke, P. B., *D.*, 1933– .
*Junkersfeld, P., *M.*, 1913–16; *V-P.*, 1916–18.

Kearns, J. R., *D.*, 1929–33.
*Keith, Nathaniel S., *Secy.*, 1884–85.
Kelsch, Raymond S., *V-P.*, 1918–19.
Kennelly, Arthur E., *V-P.*, 1893–94; *M.*, 1894–97; *V-P.*, 1897–98; *P.*, 1898–1900.
Kidder, H. A., *M.*, 1925–28; *V-P.*, 1928–30.
Knight, G. L., *M.*, 1922–26; *V-P.*, 1926–28.
Knowlton, A. E., *D.*, 1930– .
Kositzky, G. A., *D.*, 1932– .
Kouwenhoven, W. B., *V-P.*, 1931–33.

Lacy, T. N., *V-P.*, 1930–32.
*Lamme, Benj. G., *M.*, 1907–10.
Lardner, H. A., *M.*, 1913–16.
Lee, Everett S., *D.*, 1933– .
*Lee, William S., *M.*, 1911–14; *D.*, 1929–30; *P.*, 1930–31.
*Leonard, H. Ward, *M.*, 1890–93; *V-P.*, 1893–95.
*Lieb, John W., *M.*, 1896–99; *V-P.*, 1899–1901; *M.*, 1901–03; *V-P.*, 1903–04; *P.*, 1904–05.
*Lighthipe, J. A., *V-P.*, 1913–15.
Lincoln, J. F., *M.*, 1920–24.
Lincoln, Paul M., *M.*, 1906–09; *V-P.*, 1909–11; *P.*, 1914–15.
Liversidge, H. P., *D.*, 1927–31.
*Lloyd, Herbert, *M.*, 1898–1901.
*Lockwood, Thos. D., *V-P.*, 1886–87; *M.*, 1888–90; *V-P.*, 1891–93.
Lovell, A. H., *D.*, 1932– .
*Lozier, R. T., *M.*, 1902–04.
Lunn, Ernest, *M.*, 1922–26.

MacCutcheon, A. M., *D.*, 1928–32.
Macdonald, J. E., *V-P.*, 1923–25.
*Macfarlane, Alexander, *M.*, 1897–1900.
Maclachlan, Wills, *V-P.*, 1919–20.
Magnusson, C. E., *V-P.*, 1920–21.
*Mailloux, C. O., *M.*, 1886–89; *V-P.*, 1898–99; *M.*, 1899–1902; *V-P.*, 1902–04; *M.*, 1905–07; *P.*, 1913–14.
*Martin, T. Commerford, *Act. Secy.*, 1884–85; *M.*, 1885–87; *P.*, 1887–8; *V-P.*, 1888–90.
Martindale, E. H., *M.*, 1917–20; *V-P.*, 1920–21.
*Maver, Wm., Jr., *M.*, 1888–91.
*Maynard, Geo. C., *V-P.*, 1888–88.
McAllister, A. S., *M.*, 1914–17; *V-P.*, 1917–18.
McClellan, William, *M.*, 1912–15; *V-P.*, 1915–17; *P.*, 1921–22.
†McConahay, W. M., *M.*, 1923–27.
McDowell, C. S., *V-P.*, 1920–21.
Merriam, E. B., *M.*, 1924–28; *V-P.*, 1928–30.
Mershon, Ralph D., *M.*, 1900–03; *V-P.*, 1903–08; *P.*, 1913–13.
Meyer, E. B., *D.*, 1927–31; *V-P.*, 1932– .
*Michaelis, O. E., *M.*, 1886–89; *V-P.*, 1889–90.
Mills, G. A., *V-P.*, Aug.–Oct. 1932.

Mitchell, W. R., *V-P.*, 1925–27.
Morehouse, L. F., *M.*, 1919–23; *V-P.*, 1924–26.
Morrow, L. W. W., *D.*, 1933– .
Moultrop, I. E., *D.*, 1926–30; *V-P.*, 1930–32.
*Mullin, E. H., *M.*, 1902–04.
Murray, Wm. S., *M.*, 1908–09; 1909–12; *V-P.*, 1912–14.

Newbury, F. D., *M.*, 1918–22.
Nichols, E. L., *V-P.*, 1889–91.
Norris, H. H., *M.*, 1909–12.
Northmore, E. R., *V-P.*, 1927–29.

*Osgood, Farley, *M.*, 1911–14; *V-P.*, 1914–16; *P.*, 1924–25.
†Owens, R. B., *V-P.*, 1898–1900.

Parker, J. C., *V-P.*, 1921–22.
Patton, P. H., *V-P.*, 1931–33.
*Peek, F. W. Jr., *D.*, 1930–33.
Pender, Harold, *M.*, 1915–18; *V-P.*, 1918–19.
*Perrine, Frederick A. C., *M.*, 1898–1900.
*Phelps, Geo. M., Jr., *M.*, 1885–87; *Treas.*, 1888–95.
*Pickernell, F. A., *M.*, 1896–99.
Pierce, A. G., *M.*, 1921–25; *V-P.*, 1925–27.
Plumb, H. T., *V-P.*, 1922–24.
*Pope, Franklin L., *V-P.*, 1884–86; *P.*, 1886–87; *V-P.*, 1887–89.
*Pope, Ralph W., *Secy.*, 1885–1911; *Hon. Secy.*, 1911–29.
Pratt, H. A., *M.*, 1921–25.
*Prescott, Geo. B., *M.*, 1884.
*Prescott, G. B., Jr., *M.*, 1888–1891.
Puffer, Wm. L., *M.*, 1896–99.
Pupin, Michael I., *M.*, 1892–95; *V-P.*, 1895–97; 1901–03; *P.*, 1925–26.

Quinan, G. E., *V-P.*, 1928–30.

*Reber, Samuel, *M.*, 1901–04; *V-P.*, 1904–06.
Rice, Calvin W., *M.*, 1900–03; *V-P.*, 1903–05.
Rice, E. W., Jr., *P.*, 1917–18.
†Robbins, Chas., *M.*, 1918–20; *V-P.*, 1920–21.
*Robinson, L. T., *M.*, 1913–16; *V-P.*, 1916–18; 1920–21.
Rodman, W. S., *V-P.*, 1929–31.
Ruffner, Chas. S., *M.*, 1916–20; *V-P.*, 1920–21
Rugg, W. S., *M.*, 1910–13.
Rushmore, D. B., *M.*, 1908–11; *V-P.*, 1911–13.
Ryan, Harris J., *M.*, 1893–96; *V-P.*, 1896–98; *P.*, 1923–24.
Ryan, W. T., *V-P.*, 1928–30.

Sands, Herbert S., *V-P.*, 1923–27.
*Sargent, W. D., *M.*, 1885–86.
*Schoen, A. M., *M.*, 1906–09; *V-P.*, 1919–20.
Schoolfield, H. H., *V-P.*, 1926–28.
*Schuchardt, R. F., *V-P.*, 1922–24; *P.*, 1928–29.
Scott, Chas. F., *M.*, 1895–98; *V-P.*, 1899–1901; *P.*, 1902–03.
*Seribner, Chas. E., *M.*, 1910–13; *V-P.*, 1913–15.
Sever, Geo. P., *M.*, 1898–1901; *V-P.*, 1901–03; *M.*, 1903–06.
Shaad, G. C., *V-P.*, 1930–32.
*Shelbourne, Sidney F., *M.*, 1886–87.
*Sheldon, Samuel, *M.*, 1898–1901; *V-P.*, 1901–03; *M.*, 1903–06; *P.*, 1906–07.
Sibley, R., *V-P.*, 1921–23.
Sisson, C. E., *V-P.*, 1929–31.
Skinner, C. E., *M.*, 1915–19; *V-P.*, 1919–20; *P.*, 1931–32.
Slichter, Walter I., *M.*, 1918–22; *V-P.*, 1922–24; *Natl. Treas.*, 1930–
*Smith, H. B., *M.*, 1920–24; *V-P.*, 1924–26; *P.*, 1929–30.
*Smith, W. W., *M.*, 1884–85.
Sorensen, R. W., *V-P.*, 1933– .
*Spencer, Paul, *M.*, 1906–09; *V-P.*, 1909–11.
Sprague, Frank J., *V-P.*, 1890–92; *P.*, 1892–93.
*Springer, F. W., *V-P.*, 1921–23.
Sprong, S. D., *M.*, 1909–12; *V-P.*, 1912–14.
*Stanley, Wm., *V-P.*, 1898–1900.
*Steinmetz, Chas. P., *M.*, 1892–95; *V-P.*, 1896–98; *M.*, 1898–1901; *P.*, 1901–02.
Stephens, C. E., *D.*, 1928–33.
Stevens, A. C., *D.*, 1932– .
*Stevens, J. Franklin, *M.*, 1912–15; *V-P.*, 1915–17.
Stillwell, Lewis B., *M.*, 1896–99; *V-P.*, 1899–1901; *P.*, 1909–10.
†Stine, Wilbur M., *V-P.*, 1896–98.
Stokes, Stanley, *V-P.*, 1932– .
Stone, Chas. W., *M.*, 1908–11; *V-P.*, 1911–13.
Stone, E. C., *D.*, 1925–29; *V-P.*, 1929–31.
Storer, Norman W., *M.*, 1911–14; *V-P.*, 1914–16; 1921–23.
*Stott, Henry G., *M.*, 1904–07; *P.*, 1907–08.
Sykes, Wilfred, *M.*, 1917–21.

Tapscott, R. H., *D.*, 1930– .
Taylor, John B., *M.*, 1915–18; *V-P.*, 1918–19.
Terry, Chas. A., *M.*, 1902–05; *V-P.*, 1905–07.
Tesla, Nikola, *V-P.*, 1892–94.
*Thomas, B. F., *M.*, 1885–87.
Thomas, Percy H., *M.*, 1907–10; *V-P.*, 1910–12.
†Thompson, Edward P., *M.*, 1887–88.
Thomson, Elihu, *V-P.*, 1887–89; *P.*, 1889–90.
*Townley, Calvert, *M.*, 1905–08; *V-P.*, 1908–10 *P.*, 1919–20.
Townsend, Henry C., *M.*, 1899–02.
*Trowbridge, Wm. P., *M.*, 1884–86.

*Upton, Francis R., *V-P.*, 1889–90; *M.*, 1890–92.

*Vail, Theo. N., *M.*, 1884–86.
Vanderpoel, W. K., *M.*, 1923–27.
*Van Hoevenbergh, H., *M.*, 1888–90.
*Vanzize, W. B., *M.*, 1894–97.

*Wallace, Wm., *V-P.*, 1893–95.
*Weaver, W. D., *M.*, 1894–97; 1899–1902.
†Webb, Herbert L., *M.*, 1891–94; 1897–1900.
Weston, Edward, *M.*, 1884–87; *P.*, 1888–89; *V-P.*, 1889–91.
*Wetzler, Jos., *M.*, 1888–90; *V-P.*, 1890–2.
*Wheeler, Schuyler S., *M.*, 1887–90; *V-P.*, 1890–91; 1902–04; *M.*, 1904–05; *P.*, 1905–06.
White, Jas. G., *M.*, 1904–07; *V-P.*, 1907–09.
Whitehead, John B., *M.*, 1924–28; *P.*, 1933– .
*Williamson, R. B., *M.*, 1921–25.
Wilson, A. M., *V-P.*, 1933– .
*Wirt, Chas., *M.*, 1892–95.
*Wolcott, Townsend, *M.*, 1902–05; *V-P.*, 1905–07.
Woodrow, H. R., *D.*, 1931– .

Abbreviations, *P.*, President; *V-P.*, Vice-President; *M.*, Manager; *D.*, Director; *Natl. Secy.*, National Secretary; *Secy.*, Secretary; *Hon. Secy.*, Honorary Secretary; *Natl. Treas.*, National Treasurer; *Treas.*, Treasurer.
* Deceased. † Non-members at present.

List of Women Members of the A.I.E.E.

Miss Edith Clarke (A'23–M'33)	Engineer, Central Station Engg., Dept., General Electric Co., Schenectady, N. Y.
Miss Helen W. Hardy (A'26)	Assistant to General Lighting Representative, Public Service Electric and Gas Co., 90 Park Pl., Newark, N. J.
Miss Vivien Kellems (A'30)	President, Kellems, Products, Inc., 100 Lafayette St., New York, N. Y.
Miss Ruth Kern (A'33)	444 Kenwood Road, Drexel Park, Drexel Hill, Pa.
Miss Deany C. LaZan (A'27)	Sales Engineer, Simplex Wire & Cable Co., 2019 Union Trust Bldg., Cleveland, Ohio
Miss Mabel MacFerran (A'28)	Assistant Engineer, Metropolitan Water District of Southern California, 306 West 3rd St., Los Angeles, Calif.
Mrs. Zella A. McBerty (A'24)	Secretary and Treasurer, The Federal Machine and Welder Co., Dana Ave., Warren, Ohio
Mrs. Paul McMichael (A'22)	Electrical Engineer, 530 E. 22nd St., Brooklyn, N. Y.
Mrs. Roland R. Miner (A'30)	820 North Pershing, Wichita, Kans.
Miss Frances H. Pettee (A'27)	Sales Department, Simplex Wire and Cable Co., 79 Sidney St., Boston, Mass.

Sections and Branches of the Institute

THE GROWTH of membership in the Institute led, in 1893, to consideration of the desirability of holding meetings in some of the larger cities. Upon the recommendation of a committee appointed to study the matter, a plan was adopted in November 1893, providing for the holding of local meetings in any city upon petition of 20 members. Subsequently, monthly meetings were held in Chicago, usually on the same evenings as the meetings in New York, with the presentation of the same papers.

Upon his election as president of the Institute in 1902, Charles F. Scott inquired among some of the leading members as to what activities should have special emphasis. Secretary Pope urged the extension of local meetings, a subject in which he long had retained keen interest, and expressed the view that conditions were favorable for further developments. Others agreed upon this need, and certain statements regarding the very rapid developments then occurring in the electrical industries deeply impressed President Scott with the need for better provisions for the training of young engineers who would be required in rapidly increasing numbers.

Consequently, he presented to the board of directors, in September 1902, a report including, among other recommended developments of the Institute, comprehensive proposals concerning the organization of local groups of members in the electrical centers and groups of engineering students in the universities and technical schools, in order to distribute as widely as possible the benefits of affiliation with the work of the

Table I—Record of Institute Sections and Branches

Year Ending April 30	No. of Sections	Sections No. of Meetings	Total Attend.	No. of Branches	Branches No. of Meetings	Total Attend.
1893 to 1901	1					
1902	2			0		
1903	11			7		
1904	16			12		
1905	18			14		
1906	18			14		
1907	18			15		
1908	22	141	7,476	26	143	4,128
1909	23	169	16,427	27	198	8,443
1910	25	187	16,694	31	237	10,255
1911	25	208	15,243	38	255	10,714
1912	28	231	19,800	42	281	10,255
1913	29	244	22,825	47	357	11,908
1914	30	233	22,626	47	306	11,617
1915	31	246	23,507	52	328	12,712
1916	32	251	28,553	54	360	15,166
1917	32	265	31,299	59	368	16,107
1918	34	245	34,814	59	268	10,683
1919	34	217	35,837	61	156	8,441
1920	36	263	30,741	63	360	16,827
1921	42	303	37,823	65	443	21,639
1922	45	373	54,378	67	439	25,358
1923	46	344	46,672	68	503	26,893
1924	47	381	58,945	77	530	25,674
1925	49	386	49,029	83	548	27,603
1926	51	405	58,959	86	714	35,270
1927	52	431	60,708	95	842	42,650
1928	52	431	64,276	98	915	44,334
1929	54	460	73,254	100	940	47,408
1930	56	480	84,615	106	1,009	50,401
1931	59	491	108,523	109	1,137	51,807
1932	60	497	105,325	109	1,135	54,197
1933	60	498	73,806	111	1,026	59,439
1934	61			113		

Table II—Record of A.I.E.E. Membership

Year Ending May 1	Total Membership	Year Ending May 1	Total Membership
1884	71	1910	6,681
1885	209	1911	7,117
1886	250	1912	7,459
1887	314	1913	7,654
1889	333	1914	7,876
1890	427	1915	8,054
1891	541	1916	8,212
1892	615	1917	8,710
1893	673	1918	9,282
1894	800	1919	10,352
1895	944	1920	11,345
1896	1,035	1921	13,215
1897	1,073	1922	14,263
1898	1,098	1923	15,298
1899	1,133	1924	16,455
1900	1,183	1925	17,319
1901	1,260	1926	18,158
1902	1,549	1927	18,344
1903	2,229	1928	18,265
1904	3,027	1929	18,133
1905	3,460	1930	18,003
1906	3,870	1931	18,334
1907	4,521	1932	17,550
1908	5,674	1933	17,019
1909	6,400	1934	15,200

The number of members given in this table is that compiled from the membership lists of May 1, of each year, except that no satisfactory list was available in 1888, which necessitated the use of the list of December 1, 1887. During the first few years the number of members carried on the rolls was greater than the number of active members. This situation was explained in the report of the secretary on May 18, 1888, and also in the report of May 17, 1887. (TRANS. v. 3, p. 12; BUS. PROC. May 17, 1887, p. 2). At the time of the founding of the Institute many names were proposed as eligible for membership and were counted as members. Many of these did not respond to communications, and a circular was prepared requesting that they definitely state their intentions. As a result of this, 70 names were dropped from the rolls. For this reason the membership given as 279 in the report for May 19, 1885, has been reduced to 209.

Institute. The board of directors promptly approved the organization of such local groups, now known as Sections and Branches.

The membership of the Institute on May 1, 1902, was 1,549, and it was the smallest of the 4 societies of civil, electrical, mechanical, and mining engineers. The numbers of sections and Branches increased rapidly after the fall of 1902, and the very rapid increase in membership brought the Institute to a total of more than 4,000 less than 5 years later, and made it the largest of the 4 societies, a distinction which it held until 1915. Steady increases in the numbers of Sections and Branches have continued during the period of 32 years, and the totals now are 61 and 113, respectively. In Table I is shown a record of the growth of Institute Sections and Branches, and in Table II is a record of total membership.

The activities of these local groups have expanded rapidly, especially during the past few years. Further information may be found in the annual report on Section and Branch activities for the fiscal year ending April 30, 1933, which was published on pages 426–28 of the June 1933 issue of ELECTRICAL ENGINEERING. The report for the present fiscal year is scheduled to appear in the June 1934 issue.

International Engineering Congresses

PRIOR to the Centennial Exposition in Philadelphia in 1876, the use of electricity had been practically limited to electroplating and to various forms of signaling, of which the telegraph was the most important. Only 8 years later, in 1884, the prospects of very rapid further developments, especially in electric lighting and electric railways, were such that the leaders "recognized the necessity of a society which should foster and encourage electrical applications in every useful art."

The American Institute of Electrical Engineers took its place among these new developments through a preliminary meeting held on April 15, 1884, as a result of the efforts of Dr. Nathaniel S. Keith, and an organization meeting on May 13, 1884.

At the time of its organization, preparations were in progress for an International Electrical Exhibition to be held in Philadelphia under the auspices of the Franklin Institute. During the exhibition, a National Conference of Electricians was held September 8–13, 1884, attended by about 100 "electricians" from Europe and America.

The first meeting of the Institute was held October 7 and 8, in connection with the exhibition, and 11 papers were presented. Thus, the early life of the Institute was closely related to an international conference, and, in fact, it appears that the conference was one of the principal influences causing the Institute to be organized in that year.

During the next few years, the Institute developed its activities and soon became established as a strong engineering society. Much interest was shown in proper efforts to identify it with international work and thus to secure recognition of the important researches of Americans.

The Institute appointed 5 delegates who attended a congress held in Paris in 1889, in connection with an international exposition, and appointed a delegation of 5 members to attend the Frankfort International Congress in 1891.

Beginning in 1891, the Institute made extensive preparations for the International Electrical Congress held in Chicago, August 21–25, 1893, in connection with the World's Columbian Exposition. On June 24, 1893, appropriately furnished and decorated rooms, in the electricity building at the exposition, were opened by the Institute to receive visitors. The register showed a total "of 612 visitors, among whom were many of the most distinguished electricians of the day."

The above will suffice to show the emphasis placed upon the international congresses during the first 20 years of the Institute's life. Since then, with the constantly expanding scope and increasing importance of international relations among engineers and scientists, the Institute and many of its leading members have participated in numerous international conferences, some of the more important being listed as follows:

International Electrical Congress, St. Louis, Mo., Sept. 12–17, 1904.

International Electrical Congress, Turin, Italy, Sept. 1911.

International Electrical Congress, San Francisco, Calif., Sept. 20–25, 1915.

International Engineering Congress, Rio de Janeiro, Brazil, Sept. 7–30, 1922.

World Power Conference, London, England, June 30–July 12, 1924.

World Engineering Congress, Tokyo, Japan, Oct. 28–Nov. 7, 1929.

International Electrical Congress, Paris, France, July 4–12, 1932.

The A.I.E.E. in Standardization

THE FIRST Institute committee to have anything to do with standardization came into being in 1889 "to formulate and submit for approval a standard wiring table." It was not, however, until 1898 that the first standardization committee, dealing with standards for electrical machinery and apparatus, was appointed. This committee decided to devote its efforts to the standards of performance, leaving matters of construction, dimensions, and design to the manufacturer. The wisdom of that early established policy is proved by the fact that almost without exception it has been adhered to with unqualified success down to the present day.

Out of the chaos that first committee faced there grew a recognized procedure for setting up apparatus standards through which all interested parties were given representation on A.I.E.E. standards making subcommittees. A series of nationally recognized electrical standards developed thus, devoted almost entirely to a definition of the terms and conditions which characterize the rating and behavior of electrical machinery and apparatus.

With the tremendous growth of the electrical industry in the United States, other organizations, professional and trade, sprang into being. They had a considerable interest in electrical standardization. Other standards were developed, sometimes overlapping. There was much duplication of work. Finally, it became evident that continued progress depended upon the formation of a central body on which all could have duly accredited representatives. From a plan promulgated within the A.I.E.E. standards committee, but in collaboration with the national societies of civil, mining, and mechanical engineers, there was eventually established the American Engineering Standards Committee, or as it is now known, the American Standards Association.

The Institute today still maintains its standardizing machinery, while coöperating to the fullest extent with the A.S.A. in the formulation of American standards. It is, however, acting largely as the originator of new standards, for through the discussions in the Institute technical committees the needs of the industry early became evident. The technical committees have therefore largely taken over the work formerly carried on by the subcommittees of the standards committee. The results of the technical committees standards activities all clear through the standards committee, which decides on final disposition. It also, from time to time, suggests fields of activity to the technical committee properly concerned. As Institute standards, either existing or new, reach a status seeming to warrant approval as American standards they are submitted to A.S.A. for action. At the present time over 20 former A.I.E.E. standards have received such recognition.

Probably at the present time the 2 projects of greatest moment to the entire electrical field developing under A.I.E.E. auspices are the series of test codes for electrical machinery and apparatus, and the proposed American standards for electrical definitions.

The test codes, of which 2 are available, as reports, meet a long felt need in that they provide in convenient form the more generally applicable and accepted methods of conducting and reporting tests of a commercial nature, which apply to the fulfillment of performance guarantees and to acceptance tests.

The glossary of electrical terms, the first report of which was issued in August 1932, will eventually contain over 5,000 definitions. Over 300 men have been at work on this proposition.

The Institute has also taken a leading part in international standardization. In 1904, when the international standardization call came, it was headed by the A.I.E.E., and, as a result, the Institute served for many years as the godfather of the United States National Committee of the International Electrotechnical Commission. While the difficulties have been great in international standardization there is now at least a language of common understanding in the various large industrial nations. This activity has now passed to the auspices of the A.S.A.

Such is the story in abstract of the A.I.E.E. in standardization.

Engineering Societies Library

THROUGH exchange lists established after the monthly publication of the A.I.E.E. PROCEEDINGS was begun in 1888, the Institute gradually accumulated valuable files of periodicals. In 1900, the first definite appropriation was made for the binding of periodicals and the erection of shelving.

Important new and old electrical and scientific books were contributed to the Institute from time to time singly and in sets, and, in 1901, Dr. Schuyler Skaats Wheeler presented the Latimer-Clark collection of books, pamphlets, and manuscripts, including about 7,000 titles. Andrew Carnegie presented cash equivalent of the Wheeler gift to be used in the preparation of a catalog of the Latimer-Clark collection.

The other national engineering societies had likewise built up libraries for the use of their members, and in 1913, the libraries of the societies of mechanical, mining, and electrical engineers were combined to form a free public engineering library to be known as the Engineering Societies Library. The library of the American Society of Civil Engineers was added in 1916, and a composite card catalog of the entire library was prepared during succeeding years.

With its large collection of books and periodicals on engineering and scientific subjects, its complete card index, and its well-trained staff, this library is prepared to serve effectively in practically the entire engineering field, and is one of the most important joint activities of the 4 societies.

Important new books are added promptly, and subscriptions and exchange arrangements bring to the library all of the more important technical periodicals published in all parts of the world.

The library operates a service bureau and a book lending plan which enable members of the societies located anywhere to make use of its facilities by mail.

The Engineering Foundation

ENGINEERING FOUNDATION was established in 1914 by the 4 national societies of civil, mining and metallurgical, mechanical, and electrical engineers "for the furtherance of research in science and in engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind." It was conceived by Ambrose Swasey, of Cleveland, Ohio, and toward its endowment he has made gifts intended as the nucleus of a "community trust" for engineers, to be contributed by many donors.

The Engineering Foundation Board has 12 members, 2 representatives of each founder society, 3 members-at-large chosen by the board of trustees, and the president of the United Engineering Trustees, Inc., *ex-officio*. This board has discretionary power in disposition of income from the Engineering Foundation Fund and other sources, but responsibility for administration of principal lies with the Board of Trustees.

The Engineering Foundation enjoys the coöperation of engineering societies, National Research Council, technical bureaus of the Government, universities, scientific associations, industries, bankers, and individual engineers. Foundation's endowment aggregates $880,000. The services, facilities, and materials given in addition have been estimated at $2,000,000. In the 20 years of its existence, it has aided in establishing National Research Council and has coöperated in researches in arch dams, steel columns, earths and foundations, blast furnace slags, properties of steam, lubrication of machinery, strength of gears, fundamentals of dielectrics, electric welding, and pure iron electrodes. It has worked through assistance rendered to the Society for the Promotion of Engineering

Education toward the betterment of engineering education and under its auspices there have been conducted 10 courses for disengaged engineers.

Origin and Adoption of the Institute's Badge

THE HISTORY of the development of the present badge of the Institute contains several items of interest, reflecting ideas and personalities of some 40 years ago. The fundamental form of the present badge dates back to 1897, when the original form, adopted in 1893, was superseded.

The first public mention of a badge appears to be in the report of the October 21, 1890, meeting of the council of the A.I.E.E. On that date the council "on motion of Dr. Schuyler Skaats Wheeler, voted that the secretary be instructed to secure a design for a badge and present the same to the council."

December 16, 1890, on motion of Doctor Wheeler, it was voted "that the design for a badge be laid upon the table." At a meeting on October 27, 1891, a letter was read from F. L. Woodward, enclosing a sample of a society pin. On motion of W. J. Hammer (Mr. Hammer's obituary item appears in the news section of this issue) it was voted that "the letter and sample be referred to the committee on certificate of membership, and that members generally be invited to contribute competitive designs." On October 27, 1891, the committee (Messrs. Herzog, Bell, and Foster) asked for advice, and was continued with the understanding that further designs should be secured. On February 16, 1892, Doctor Bell of the committee, submitted several designs which were examined. On motion of Professor Compton it was voted that the committee be instructed

The official badge of the Institute during the period 1893–97. This badge was about 15/16ths of an inch high

to prepare new designs embodying as principal features the kite and the electromagnet, with the initials of the Institute if there were sufficient space. Progress reports of the committee were presented at various council meetings, until, at a meeting of February 21, 1893, "on motion of Professor Compton, it was voted that the design for a badge presented by the committee be accepted and that the design be adopted as the badge of the Institute. It was also voted that the design of the badge be placed upon the certificate and the literature and stationery of the Institute."

Design of the Original Badge

This original badge appeared on the front cover of the monthly TRANSACTIONS of the Institute from August 1893 to April 1897, and was worn by the members during those years. The badge, shown in the accompanying reproduction, was of white enamel, the lettering and front portions of 18-karat gold, and the backing of 14-karat gold. The design was in the form of Franklin's kite, which demonstrated the identity between lightning and electricity, and was a recognition of America's first "electrician" and philosopher, Benjamin Franklin. The arms or border of the kite formed a diagrammatic representation of the wheatstone bridge. In the center was a tiny galvanometer, representing magnetism and induction. The galvanometer contained a blued steel needle, over which was a small disc of amber. The amber represents the first conception of electricity, dating back to 600 years B.C., when Thales, the Greek philosopher, recorded the fact that amber, when rubbed, attracted light particles to it; and the Greeks worshipped it, believing the Gods had endowed it with life and that it possessed a soul. Amber also represents the derivation of the word electricity, as Doctor Gilbert, court physician to Queen Elizabeth and in the year 1600 A.D., coined the word electricity from the Greek word for amber, which is elektron.

Above the galvanometer were the letters A.I.E.E., the initials of the Institute; and below the galvanometer $C = \frac{E}{R}$, representing Ohm's law.

New Badge Adopted in 1897

This badge apparently was not considered entirely satisfactory, and at a meeting of the council, November 20, 1895, a petition signed by 20 members was read, asking that steps be taken to secure a better design. A committee was appointed, consisting of W. J. Hammer, W. D. Weaver, M. I. Pupin, W. A. Anthony, and S. S. Wheeler, which made a final report March 24, 1897, "with designs and a sample" which was referred to the annual meeting for consideration. The report of the annual business meeting of May 18, 1897, included "at the conclusion of the discussion. . . the matter of the design reported by the committee was adopted." This emblem, essentially unchanged since 1897, has held and continues to hold a prominent place in Institute publication. It first appeared on the cover of the monthly TRANSACTIONS for May 1897, and, with only slightly changed proportions, now appears on the cover of each issue of ELECTRICAL ENGINEERING.

In a letter dated October 20, 1914, Dr. S. S. Wheeler, who was chairman of the above-mentioned committee on design of the present badge, stated that the design was chosen "after considerable thought, as a symbol of the broadest principle that could be found underlying our profession. Electricity always surrounds magnetism and magnetism always surrounds electricity and each forms a closed circuit; therefore the relation between them is always that of 2 closed links which pass through each other, and this holds true of course in every application of electricity or magnetism."

Form of the Present Badge

Several variations on the fundamental form of the present badge, shown in the illustration, are used to indicate different grades of membership. Except for the Student badge, which is of somewhat different design, the different forms are determined by the color and placing of the enamel. The Associate badge has an enameled background of maroon, with letters and border in gold. The badge for Members is similar except that the back ground is enameled in blue, while the badge for Fellows is the reverse in color of that provided for Members. On the badge for Students, the 2 circles surrounding the letters "E.E." are not used, and a large letter "S" extends from top to bottom of the badge, almost circling the "A" and "I"; the enamel background is black with gold letters and border.

There are several special badges, the form of which is similar to that for Associates, Members, and Fellows. The badge for Presidents has blue letters and blue circles on a gold background, with a white line just inside the gold border. The badge for Honorary Members has a white enamel background, with gold letters and border. The special badge to be presented the 6 living charter members at the Institute's summer convention this June, has a gold background, with blue letters and white circles, and a blue line extending around the badge just inside the gold border.

The fundamental form of badge adopted by the Institute in 1897 and used, with only minor changes in proportion, continuously since then. The badge is of gold and with different colors of enamel used to indicate the grade of membership

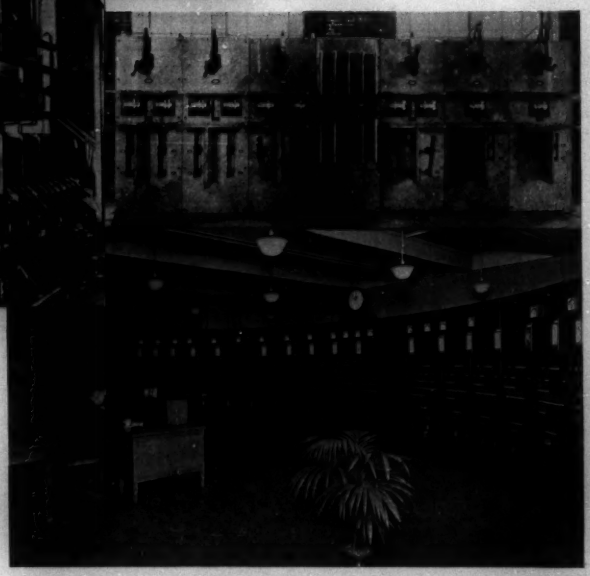
Some Contrasts in Power System Switchboards

Office of the load dispatcher in Oakland, Calif., as it appeared in 1907 (right) and (below) as it is today
(Pacific Gas and Elec. Co. photo)

(Above) When a switchboard was really a board with switches on it—a type of construction used 40 years ago
(Westinghouse photo)

(Below) One of the early switchboards using marble instead of wood. Note the heavy baffle boards between switches
(General Electric photo)

(Above) The original switchboard of Mill Creek No. 1 (Calif.) hydroelectric station. It was replaced by the one seen in the rear
(Southern Calif. Edison Co. photo



(Right) Supervisory control room for the entire power distribution system of the Cincinnati Street Railway Company. This system has a total capacity of 33,500 kw in rotary converters distributed among 20 automatic substations, for which constant supervision is provided

Significant Electrical Developments

SOME technological discoveries and developments of particular significance to the electrical industry, starting with the year 1729 and extending to the present day, are shown on this and the facing page.

In the chart extending diagonally upward across these pages, the significant developments during the 50-year existence of the A.I.E.E. are shown. This chart is based upon information supplied by the American Telephone and Telegraph Company, the General Electric Company, the Westinghouse Electric and Manufacturing Company, and other authoritative sources.

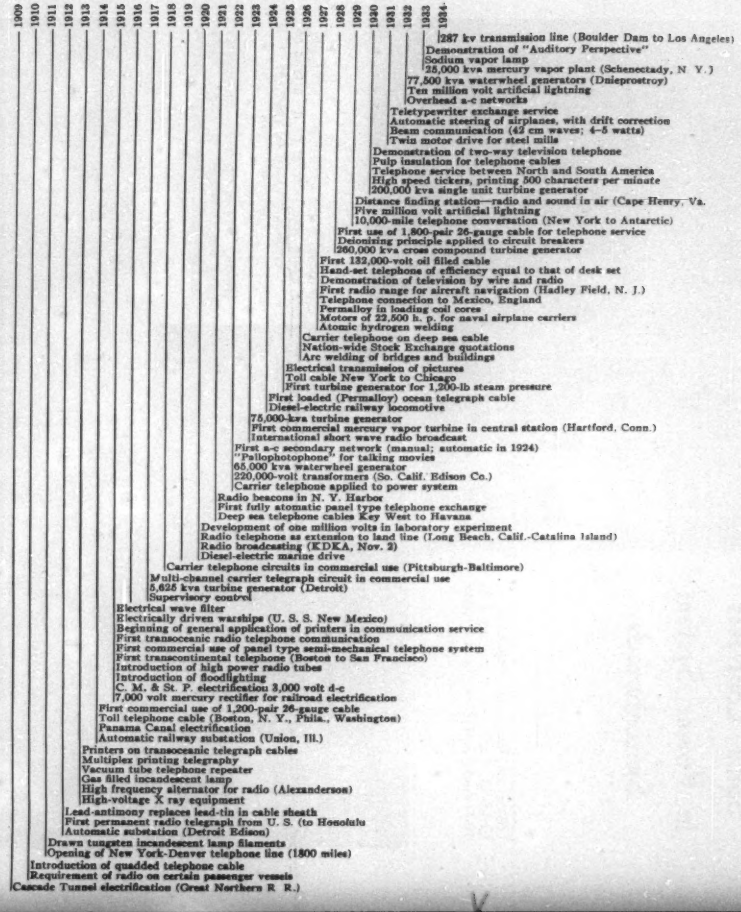
In the list that starts below on this page and is continued on the right-hand side of the facing page, the significant developments in the 155 years immediately preceding the founding of the Institute in 1884 are given. The items in this list are credited to Thomas G. Lockwood, a charter member of the Institute, who was, during his lifetime, an electrical expert and patent attorney, being in charge of the patent department of the American Bell Telephone Company for several years following 1881.

The history of electrical developments has been classified by one authority in 4 eras. The first of these, termed "frictional electricity," extends from the discovery of the electrical properties of amber in 600 B.C. to Franklin's experiments about 1750 A.D.; during the latter part of this period Dr. William Gilbert, court physician to Queen Elizabeth, undertook numerous scientific experiments. The publication about 1600 of his book "De Magnete Magneticisque Corporibus et de Magnete Tellure Physiologica" (London, Eng.) is credited by many as ushering in the earliest beginnings of scientific research. The second era of electrical development is classified as that of "battery current," and begins with Volta's discovery of his battery in 1800. The third period, that of "electric power" (dynamos), was ushered in by Faraday's discovery of electromagnetic induction in 1831. The fourth period, termed the "electronic" era, dates with the discovery of the "Edison effect" in 1883.

SIGNIFICANT ELECTRICAL DEVELOPMENTS, 1729–1883

1729 July 3—Electrical insulation discovered by Stephen Gray.
1747 July 14—Electricity passed through a wire across the Thames over Westminster Bridge, the circuit being completed through the water.
1752 July 4—Benjamin Franklin demonstrated the identity between lightning and electricity by flying a kite during a thunderstorm.
1753 Feb. 1—First suggestion of the electric telegraph in a communication signed "C. M." in *Scott's Magazine*.
1800 March 20—Alessander Volta announced his invention of the voltaic pile.
1800 April 30—Nicholson and Carlisle discovered the principle of electrochemical deposition.
1800 Sept. 22—Spark from voltaic battery as observed by Davy announced in Nicholson's Journal.
1800 Oct. 24—First telegraph patent taken out in the United States by Johnathan Grout.

(Continued on following page)



1884 — First electric driven newspaper presses
1885 — Lead tin alloy replaces lead in cable sheath
1886 — First New York-Boston hard drawn copper telephone circuit (230 miles)
1887 — Single phase 133 cycle lighting
1888 — Electric resistance welding
1889 — Introduction of Edison system of superposed telegraphy
1890 — Transposition on New York-Phila. telephone circuits
1891 — Adoption of commercial telephone desk stand
1892 — Discovery of properties of electromagnetic waves (Hertz)
1893 — Experimental installation of induction telegraphy (Lehigh Valley R. R.)
1894 — Feeder voltage regulator
1895 — Induction meter development (Shallenberger)
1896 — Tesla patent on induction motor
1897 — First electric street railway (Richmond, Va.)
1898 — Carbon brushes for motors and generators
1899 — A-c transformer system (Thomson-Houston)
1900 — Time signal service by telegraph
1901 — Recording wattmeter (Thomson)
1902 — Bridging bell (telephone)
1903 — "Solid back" telephone transmitter
1904 — Oil cooled & insulated transformers
1905 — A-c power transmission 3,000 v. single ø
1906 — A-c arc system
1907 — Dry core paper insulated telephone cable
1908 — Sixty cycle adoption as standard frequency
Carbon circuit breaker
Slotted armature d-c generator
Multipolar generator
10,000-volt transmission (Pomona, Cal.)
Series-parallel system for railway motors
Polyphase circuits (commercial)
Rotary converter
Automatic telephone ringing system
Lamp signals on telephone switchboards
Niagara power development—introduction of revolving field 4,500 kva alternators, [power switches, 25 cycles
A-c calculation simplification (Steinmetz)
Vertical shaft waterwheel generators of 500 kw capacity (Oregon City, Ore.)
First common-battery telephone exchange
Commercial induction motor (Columbia, S. C.)
Chicago Worlds Fair; 1,500 kw dc generator; polyphase plant; 850 kva alternators; [display illumination
Direct New York-Chicago telephone line (900 miles)
Chicago elevated railway electrification
Dial replaces push buttons in mechanical telephone system
Marconi application for wireless telegraphy patent (British)
Inductor type alternators
First motor cars, N. Y., N. H. & H.
Motor-driven warship turrets
Baltimore Tunnel electrification (B. & O. R. R.)
Buckingham high speed printing telegraphy
5,000 kw generators, 43' in diameter (New York, N. Y.)
5,000 kva oil switch
Multiple unit control system for railroad cars (Sprague)
Constant-current transformer (Thomson)
Radio telegraph across English Channel
Invention of telephone circuit loading
33,000 volt transmission
Steam turbine generator, 500 kva
Mercury vapor lamp
First U.S. commercial radio telegraph stations
First turbine generators in American central station,
13,200 volt generators [2,000 kva (Hartford, Conn.)
A-c series arc light system
80,000 volt transformers
Mechanical telephone repeater
Single phase compensated street railway motor
Gas-electric railroad car
Metallic flame arc lamps
6,250 kva turbine generator
Silicon steel transformer cores
9,250 kva waterwheel generators (Niagara Falls)
Magnetite arc lamp
First transatlantic radio telegraph message
Single phase railway system
Mercury rectifier
First main-roll drive for steel mill [11,000 volts
Long distance underground telephone cable
Grid in vacuum tube (De Forest)
Metalized filament incandescent lamp
New Haven R. R. electrification, single phase,
Interurban 1,200 volt d-c equipment
Suspension disk line insulator
Reversing motors for steel mills
Transatlantic radio telegraph service made public
Grand Central Terminal electrification (N. Y. C. R. R.)
Marine turbine electric drive

(*Continued from preceding page*)

1820 Sept. 15—The invention of the galvanometer announced by Schweigger.

1820 Sept. 25—Arago announced before the French Academy his discovery that a copper wire energized by electricity became magnetic.

1826 July 21—Oersted's discovery of electromagnetism just announced.

1827 Oct. 10—Joseph Henry announces his invention of a practical electromagnet.

1831 Aug. 27—An electric current from a permanent magnet developed by Faraday.

1831 Oct. 1—Faraday produced a current in one circuit by induction from a current flowing in another.

1832 March 30—Magnetic-electric spark first obtained from permanent magnet by Professor Forbes of Edinburgh, Scotland.

1832 Oct. 19—Morse first conceived his idea of an electromagnetic telegraph on board the ship "Sully" between Havre and New York.

1832 Dec. 15—Faraday used the earth to complete a voltaic circuit by means of water and gas pipes.

1836 July 23—Daniell announced the invention of his sulphate-of-copper constant battery.

1836 June 24—First patent in electrometallurgy issued in England to G. R. Elkington.

1836 Dec. 23—Steinheil's telegraph first described in the *Magazine of Popular Science*.

1837 June 6—English patent for electromotor issued to Thomas Davenport of Brandon, Vt.

1837 July 25—English needle telegraph first practically operated on a subterranean line between Easton and Camden Town.

1837 Oct. 2—Morse made his first experiment in telegraphy.

1839 May 4—The invention of electrotyping announced by Jacobi.

1839 May 21—Heat manifested by the transmission of electricity through suitable wire from the gymnotus orelectric eel.

1839 Nov. 2—Electromagnetic motor exhibited in England by Captain Taylor.

1840 June 20—Patent for electromagnetic telegraph issued to Professor Morse.

1841 Aug. 21—First patent describing the incandescent electric lamp issued in England to F. De Moleyns.

1842 Aug. 1—The use of the magneto-electric machine for electrodeposition suggested in a British patent taken out by J. S. Woolrich.

1844 May 24—First message sent over a telegraph wire by the Morse system.

1845 April 1—First American electric telegraph opened for business between Washington and Baltimore.

1845 Nov. 4—Incandescent carbon in a vacuum patented in England by Starr in the name of E. A. King.

1846 April 11—Patent granted to Prof. Morse for his invention of the local circuit operated by a main line relay.

1849 June 10—First experimental submarine cable laid by C. V. Walker, 2 miles out at sea from Folkestone, England.

1851 Feb. 7—Central office system patented by F. M. A. Dumont in England.

1851 April 29—Prof. Charles G. Page makes an experimental trip in his electromagnetic locomotive from Washington to Bladensburg and return, highest speed, 19 mph.

1858 May 18—First arc lamp patent issued in U.S.

1858 Aug. 5—The laying of the first Atlantic cable completed; cable worked for 26 days.

1858 Nov. 24—Dynamo principle described in an English patent.

1858 Dec. 8—Electric light first employed in lighthouse work at So. Foreland, England.

1859 Sept. 20—First patent granted in the U.S for heating by electricity.

1866 July 27—Telegraph communication successfully and permanently established between Europe and America.

1866 Dec. 24—S. A. Varley provisionally patented in England the dynamo principle first described and patented by Hjorth in 1854, and subsequently elaborated in an English patent of 1858.

1867 Jan. 17—Werner von Siemens proposed the name dynamo machine in an address before the Berlin Academy.

1867 Feb. 14—Sir Charles Wheatstone explains the dynamo principle before Royal Soc.

1873 June 3—The reversibility of the dynamo demonstrated by Hippolyte Fontaine.

1875 June 2—First practical form of the Bell Telephone made.

1876 March 7—Patent granted to Alexander Graham Bell for the telephone.

1876 March 23—First patent granted to Jablochkoff for his electric candle.

1876 Brush arc dynamo developed.

1877 April 4—First telephone line completed between Boston and Somerville, Mass.

1877 Direct current series arc lighting (developed by Brush).

1879 Direct current series arc lighting with automatic regulation developed by Thomson.

1879 First central-station arc-light system (Brush), installed, San Francisco, Calif.

1880 Jan. 27—Patent granted to Thomas A. Edison for an electric incandescent lamp having a carbon filament of high resistance.

1880 Oct. 20—The mechanical formation of secondary battery plates patented in France by Camille Faure.

1880 Direct current multiple incandescent lighting developed by Edison.

1880 Sawyer-Mann incandescent lamp patented.

1882 First incandescent central station system (Pearl Street station, New York City) placed in operation. (Edison.)

1883 Direct current 3-wire distribution system developed by Edison.

1883 Magnetic blowout principle discovered by Thomson.

1883 Gaulard and Gibbs first transformer.

News

Of Institute and Related Activities

The Institute's 50th Annual Summer Convention

THE ANNUAL summer convention this year marks the fiftieth meeting of its kind in the history of the Institute. On this occasion and in commemoration of the fiftieth anniversary of the Institute's organization, the committee has arranged for special addresses by Dr. W. E. Wickenden and Dr. William McClellan on educational and professional aspects of interest to electrical engineers, which will be given at the opening meeting. The committee also is using every endeavor to have present all officers of the Institute, all living past-presidents, and all living charter members, as well as a goodly representation of engineers from all sections. The convention will be held at Hot Springs, Va., June 25–29, 1934, with headquarters in The Homestead. Make your plans now to attend the fiftieth anniversary reunion of electrical engineers in this most attractive setting.

In addition to the fiftieth anniversary celebration, the 1934 summer convention committee has arranged an excellent schedule of events. The annual business meeting and the technical sessions will be held during the mornings, while the afternoons, with the exception of Monday and Tuesday afternoons on which the conference of officers, delegates, and members will take place, have been kept free for sports and other recreation. In the evenings, the president's reception, a get-together banquet with entertainment, and the convention banquet will be held and followed by dancing. These features and the program are given in the following columns as well as other pertinent information relative to hotel arrangements and reduced railroad rates.

Technical Sessions

The technical program includes 7 sessions: education, electrical machinery, communication, insulators, automatic stations, power generation, and instruments and measurements. The session on education and the activities of the Engineers' Council for Professional Development will be of broad general interest. The sessions on electrical machinery and communication will be more or less highly specialized and treat some of the latest developments in these phases of the art. The session on insulators is well rounded from the user's point of view as well as the manufacturer's. The subcommittee on lightning and insulators will present data on the flashover values of suspension insulators, and another paper will deal with the selection, life performance, and deterioration of insulators. Several papers by insulator manufacturers will present some of the latest developments in research and design of this product, as well as its radio influence characteristics. The automatic stations session will treat some of the latest developments in methods of load totalizing, voltage regulation, supervisory control, and automatic synchronizing. All who are interested in central stations and hydroelectric generation should find the power generation session of unusual interest. In addition, the final session on instruments and measurements will bring out some new and valuable data on sphere gap calibrations.

Entertainment Features

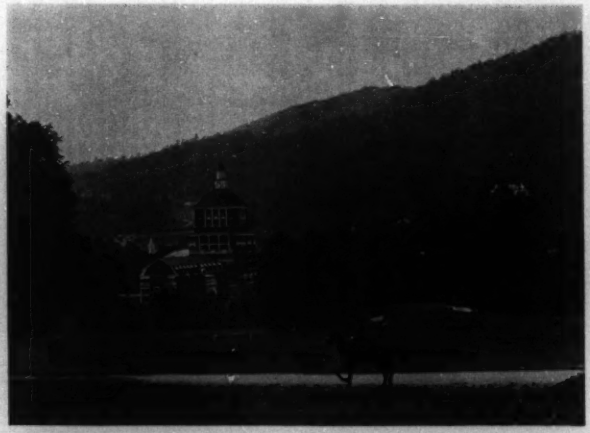
The president's reception, a get-together banquet with entertainment, and the convention banquet will be held on Monday, Tuesday, and Wednesday evenings, respectively. All these delightful social features will be followed by dancing. In addition, for the ladies there will be a drive to the Hotel Greenbrier, White Sulphur Springs, W. Va., where tea will be served. Facilities for bridge also will be arranged as desired. If there is sufficient registration a tournament will be arranged with prizes for the winners and runners-up.

For all persons registered at The Homestead or its Cottages an entertainment fee of $5 will be collected at time of registration. For all persons registered at Cascades Inn or elsewhere an entertainment fee of $10 will be charged. These fees will be devoted to the expenses involved in carrying out the plans of the general convention committee.

Sports

Excellent facilities are available for golf, tennis, skeet, and horseback riding at Hot Springs and its environs.

Golf: Three excellent golf links are available and the usual competition for the Mershon and Lee golf trophies will be held. The Mershon trophy is competed for on a match play handicap basis. The qualifying round for the Mershon trophy must be played on Monday, June 25. The second round, best 16, match play, will be played on Tuesday afternoon, followed by the third round on Wednesday afternoon, with the semi-final and final rounds played on Thursday morning and afternoon.



The Homestead, Hot Springs, Va., scene of the Institute's 50th annual summer convention, to be held June 25–29, 1934

The Lee trophy is awarded annually for the lowest net score for 36 holes, of which the first 18 may be the qualifying round and the other 18 must be played not later than Thursday afternoon. In addition, a putting contest, 18 holes, for the ladies will be held on Tuesday morning. Prizes for the winners and runners-up will be awarded in the above contests.

Tennis: Courts equipped for championship play are available at The Homestead. The first contests in men's singles for the Mershon Tennis Trophy competition will start on Monday, June 25. The second round will be played on Tuesday afternoon and the semi-final and final rounds will be played on Wednesday and Thursday afternoons, respectively. Contests in men's doubles, ladies' singles, and mixed doubles also will be arranged if there should be a sufficient registration for them. Prizes for the winners and runners-up will be awarded in the above contests.

Skeet: The Homestead operates a well-equipped skeet range, and this popular form of trap shooting may appeal to some members. If a sufficient number should register, a tournament will be arranged. A limited number of guns are available for rental; probably participants will desire to bring their own favorite guns for this sport. Fees are $1.25 for 25 birds; these include pigeons, shells, pull boys, and trap boys; also transportation to the shooting grounds from the hotel.

Horseback Riding: Hot Springs is surrounded by many lovely trails, and The Homestead maintains a fine stable of riding horses.

The prizes for the various sports will be presented at luncheon on Friday, June 29.

Reduced Railroad Rates

Fare and one-third for the round trip over the same route will be available to members and guests, provided 100 certificates (or 100 combinations of certificates and round-trip rail tickets with limiting dates from points from which the one-way fare is $2 or more) are validated at the registration desk. Consult your local ticket agent regarding the dates and territories to which this arrangement applies. Obtain your certificate authorized by the railroad passenger associations.

Hotel Rates and Accommodations

All rates, shown in Table I, are on the American plan and they, also, will be in effect a few days before and after the convention for any who may wish to make a longer stay at Hot Springs.

Table I—Hotel Rates, American Plan

	Rate per day per person
The Homestead	
Single room—private bath	$9.00
Double room—private bath—twin beds	8.00
Combinations—double room and single room, with bath between, or 2 double rooms with bath between	7.50
Cottages (meals at The Homestead)	7.00
The Cascades Inn	
(2½ miles from The Homestead, free transporation to and from The Homestead, meals at The Cascades Inn)	5.00

Members should make their reservations by writing directly to the hotel of their preference. For those stopping at places other than The Homestead and its Cottages, an extra charge will be made for the get-together dinner and the banquet. This extra charge is the occasion for 2 different entertainment fees listed under entertainment.

All baggage should be tagged with the owner's name before arrival, to facilitate prompt service. For this purpose, The Homestead will supply tags with the acknowledgment of each reservation. In case these tags are lost or mislaid, an additional

The Cascades Inn and Golf Course at Hot Springs, Va., 2½ miles from the Homestead

supply may be secured on the train between Covington, Va., and Hot Springs, so that all baggage, including golf bags, guns, etc., may be properly tagged. Your careful attention to this detail will avoid delay and greatly facilitate the handling of baggage. Free transportation from trains to the hotels will be supplied with no charge for hand baggage. Heavier baggage checked and requiring the service of the baggage van will be transported from the train at 50 cents a trip, or $1 for arrival and departure.

Register in Advance

Fill in and post promptly the mail registration card, which will be sent to members in nearby Districts. This will permit the committee to have badges ready and prevent congestion at the registration desk upon arrival. There will be a registration fee of $2.50 for nonmembers with the exception of Enrolled Students of the Institute, and the immediate families of members. This fee is in addition to the entertainment fee charged to all in attendance.

Reservations for hotel accommodations should be made by writing directly to the hotel preferred.

Notice of Annual Meeting

The annual meeting of the American Institute of Electrical Engineers will be held in The Homestead, Hot Springs, Va., at 10 a.m. on Monday, June 25, 1934. This will constitute one session of the annual summer convention which is to be held this year in Hot Springs, June 25–29.

At this meeting the annual report of the board of directors and the report of the committee of tellers concerning the ballots cast for the recent election of officers will be presented.

Such other business, if any, as properly may come before the annual business meeting may be considered.

(Signed) H. H. Henline
National Secretary

Schedule of Events

A summarized schedule of events follows: Time given is Eastern Standard Time. Capital letters A, B, etc., denote technical sessions.

Monday, June 25

9:00 a.m.—Registration

10:00 a.m.—Annual business and fiftieth anniversary meeting
- Annual report of board of directors (in abstract), H. H. Henline, *national secretary*
- Report of tellers' committee on election of officers; introduction of and response from president-elect
- Presentation of prizes for papers
- Presentation of the Lamme Medal to Dr. Lewis B. Stillwell
- Addresses: Dr. W. E. Wickenden, president, Case School of Applied Science
  - Dr. William McClellan, past-president, A.I.E.E.
  - Dr. John B. Whitehead, president, A.I.E.E.

2:00 p.m.—Conference of Officers, Delegates, and Members
- Golf—Qualifying round for Mershon Trophy
- Tennis—Men's singles for Mershon trophy

9:00 p.m.—President's reception—dancing

Tuesday, June 26

9:00 a.m.—Registration

9:30 a.m.—(A) Education

Morning—Putting contest for ladies

2:00 p.m.—Conference of Officers, Delegates, and Members (continued)
- Golf—Second round, match play—Mershon trophy
- Tennis—Second round—Mershon Trophy

7:00 p.m.—Get-together banquet—entertainment, dancing

Wednesday, June 27

9:30 a.m.—(B) Electrical machinery
(C) Communication

12:00 p.m.—Directors' luncheon and meeting

2:00 p.m.—Golf—Third round—Mershon trophy
Tennis—Semi-finals—Mershon trophy

7:00 p.m.—Convention banquet—dancing

Thursday, June 28

9:30 a.m.—(D) Insulators
(E) Automatic stations
Morning—Golf—Semi-finals—Mershon trophy
2:00 p.m.—Golf and tennis finals
Afternoon—Drive for ladies to White Sulphur Springs, with tea at Hotel Greenbrier

Friday, June 29

9:30 a.m.—(F) Power generation
(G) Instruments and measurements
12:30 p.m.—Award of sports prizes at luncheon

Technical Program

Several papers on the program have been published in ELECTRICAL ENGINEERING, April 1934 issue. The remainder are scheduled for inclusion in the June issue. Pamphlet copies of these papers will not be available, and members should take these issues with them to the convention.

Tuesday, June 26

9:30 a.m.—(A) Education, L. A. Doggett, *chairman*

ENCOURAGEMENT OF INITIATIVE IN THE ENGINEERING STUDENT, C. L. Dawes, Harvard University.

INDUSTRY DEMANDS AND ENGINEERING EDUCATION, L. W. W. Morrow, McGraw-Hill Publishing Co.

THE NEXT GENERATION OF ENGINEERS, C. F. Hirshfeld, The Detroit Edison Co.

Wednesday, June 27

9:30 a.m.—(B) Electrical Machinery, S. L. Henderson, *chairman*

VOLTAGE CONTROL OF VAPOR RECTIFIERS, D. Journeaux, Allis-Chalmers Mfg. Co.

RECTIFIER AND INVERTER CHARACTERISTICS OF THE GRID CONTROLLED MERCURY ARC RECTIFIER, C. C. Herskind, General Electric Co.

INSULATION RESISTANCE OF ARMATURE WINDINGS, R. W. Wieseman, General Electric Co.

SPLIT WINDING TRANSFORMERS, D. D. Chase and A. N. Garin, General Electric Co.

FACTORS INFLUENCING THE INSULATION COORDINATION OF TRANSFORMERS—II, P. L. Bellaschi and F. J. Vogel, Westinghouse Electric & Mfg. Co.

9:30 a.m.—(C) Communication, F. M. Craft, *chairman*

IRON SHIELDING FOR TELEPHONE CABLES, H. R. Moore, American Telephone & Telegraph Co.

A STUDY OF IRON-ARMORED CABLE AS A REMEDIAL MEASURE FOR COMMUNICATION CIRCUITS IN A SEVERE INDUCTIVE EXPOSURE, C. L. Gilkeson, Edison Electric Institute, and A. J. Hanks, Western Union Telegraph Co.

RECENT DEVELOPMENTS IN POWER LINE CARRIER, T. Johnson, Jr., General Electric Co.

THE COMPANDOR—AN AID AGAINST STATIC IN RADIO TELEPHONY, R. C. Mathes, Bell Telephone Laboratories, and S. B. Wright, American Telephone & Telegraph Co.

Thursday, June 28

9:30 a.m.—(D) Insulators, D. M. Simmons, *chairman*

FLASHOVER VALUES OF SUSPENSION INSULATORS AND GAPS, Subcommittee on Lightning and Insulators.

SELECTION, LIFE PERFORMANCE, AND DETERIORATION OF INSULATORS, Philip Sporn, E. L. Peterson, and V. A. Mulford, American Gas and Electric Co.

HIGH VOLTAGE INSULATORS—RESEARCH, DESIGN, MANUFACTURE, W. A. Smith and J. T. Lusignan, Jr., Ohio Brass Co.

THE SUSPENSION INSULATOR, K. A. Hawley, Locke Insulator Corp.

RADIO INFLUENCE CHARACTERISTICS OF INSULATORS, G. I. Gilchrest, Westinghouse Electric & Mfg. Co.

RECENT DEVELOPMENT IN SUSPENSION INSULATORS, G. M. Barrow, Westinghouse Electric & Mfg. Co.

A NEW PORCELAIN POST INSULATOR FOR TRANSMISSION LINES, G. W. Lapp, Lapp Insulator, Inc.

9:30 a.m.—(E) Automatic Stations, D. W. Taylor, *chairman*

LOAD TOTALIZING IN THE NEW YORK METROPOLITAN AREA, F. Zogbaum, The New York Edison Co.

ELECTRONIC TYPE VOLTAGE REGULATORS FOR A-C GENERATORS, F. H. Gulliksen, Westinghouse Electric & Mfg. Co.

NEW DEVELOPMENTS IN THE DIRECT SELECTION SYSTEM OF SUPERVISORY CONTROL, M. E. Reagan, Westinghouse Electric & Mfg. Co.

DEVELOPMENTS IN AUTOMATIC SYNCHRONIZING, H. T. Seeley, General Electric Co.

Friday, June 29

9:30 a.m.—(F) Power Generation, H. W. Leitch, *chairman*

HYDROELECTRIC SURVEY—PART I, Subcommittee on Hydroelectric Survey, A. V. Karpov, *chairman*.

NEW YORK GENERATING SYSTEM AIDS NETWORK OPERATION, H. C. Forbes and H. R. Searing, The New York Edison Co.

INDUCTIVE HEATING AND SPACE LIMITATION PROBLEMS SOLVED IN DESIGN OF 7,000-AMP BUS, H. L. Unland and V. R. Bacon, United Engineers & Constructors, Inc., and W. B. Morton, Philadelphia Electric Co.

9:30 a.m.—(G) Instruments and Measurements, W. B. Kouwenhoven, *chairman*

CROSS CURRENT OF A 5-ARM NETWORK, A. C. Seletzky and J. R. Anderson, Case School of Applied Science.

THEORY AND PERFORMANCE OF SELSYN INSTRUMENTS, T. M. Linville and J. S. Woodward, General Electric Co.

A NEW CURRENT TELEMETER WITH PILOT COIL TRANSMITTER, L. J. Lunas and H. L. Bernarde, Westinghouse Electric & Mfg. Co.

SPHERE GAP CALIBRATIONS, J. R. Meador, General Electric Co.

RULES ON PRESENTING AND DISCUSSING PAPERS

At some of the technical sessions, papers will be presented only by title. This will permit the devotion of more time to discussion. At other sessions, papers will be presented in abstract, 10 min being allowed for each paper unless otherwise arranged, or the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion. Authors will be notified officially in each case about one month in advance.

Any member is free to discuss any paper when the meeting is thrown open for general discussion. Usually 5 min are allowed to each discusser for the discussion of a single paper or of several papers on the same general subject. When a member signifies his desire to discuss several papers not dealing with the same general subject, he may be permitted to have a somewhat longer time.

It is preferable that a member who wishes to discuss a paper give his name in advance to the presiding officer of the session at which the paper is to be presented. Each discusser is to step to the front of the room and announce, so that all may hear, his name and professional affiliations. Three typewritten copies of discussion prepared in advance should be left with the presiding officer.

Other discussion to be considered for publication should be typewritten and submitted in triplicate to C. S. Rich, secretary of the technical program committee, A.I.E.E. headquarters, 33 West 39th St., New York, N. Y., on or before July 13, 1934.

COMMITTEES

The general convention committee for the 1934 summer convention consists of the following members: W. S. Rodman, *chairman;* C. A. Robinson, *vice-chairman;* R. C. Bailey, *secretary;* and E. P. Coles, R. N. Conwell, F. M. Craft, S. A. Flemister, J. T. Graff, E. L. Lockwood, W. R. McCann, and I. M. Stein. The chairmen of the various subcommittees working with the general convention committee are as follows: entertainment, C. A. Robinson; registration and hotels, E. L. Lockwood; finance, E. P. Coles; technical sessions, R. N. Conwell; and sports, J. T. Graff.

Future AIEE Meetings

North Eastern District meeting,
Worcester, Mass., May 16–18, 1934

Summer convention,
Hot Springs, Va., June 25–29, 1934

Pacific Coast convention,
Salt Lake City, Utah, Sept. 3–7, 1934

District Meeting at Worcester, May 16–18

The tenth annual meeting of the Institute's North Eastern District will be held at Worcester, Mass., May 16–18, 1934, with headquarters at the Bancroft Hotel. The technical sessions will be held at the Bancroft Hotel and in the lecture rooms of the Worcester Polytechnic Institute.

The program of the Worcester District Meeting was announced in ELECTRICAL ENGINEERING for April 1934, p. 627–9. Since the time of publication of this program in the April issue, the paper by Hutchins and Livington has been replaced by "The Behavior of Distance Relays During System Oscillations," by E. H. Bancker and E. M. Hunter, of the General Electric Company. This paper has not previously been published in ELECTRICAL ENGINEERING.

The session on selected subjects will be presided over by Prof. T. H. Morgan, instead of by T. A. Worcester.

The report of the Worcester Meeting is scheduled for the June issue of ELECTRICAL ENGINEERING and the discussion of the

papers will be published as soon as they are made available. To be considered for publication, discussions should be typewritten and submitted in triplicate to C. S. Rich, secretary of the technical program committee, A.I.E.E. headquarters, 33 West 39th Street, New York, N. Y., on or before June 1, 1934.

All meetings at Worcester are scheduled to start on daylight saving time.

"Science Makes More Jobs" the Topic of an Interesting Meeting

AT A meeting held in New York, N. Y., February 22, 1934, under the coöperative action of the New York Electrical Society, the American Institute of Physics, and the New York Museum of Science and Industry, a group of addresses was delivered which were devoted to showing how "Science Makes More Jobs." These addresses, delivered in an attempt to combat charges recently brought by individuals not acquainted with all the facts, were presented by prominent educators and industrial leaders. Excerpts from 3 of these addresses are presented herewith.

Address of Doctor Karl T. Compton

Sections of the address given by Dr. Karl T. Compton (F'31), president, Massachusetts Institute of Technology, Cambridge, chairman of the American Institute of Physics, and chairman of President Roosevelt's science advisory committee follow:

"The idea that science takes away jobs, or in general is at the root of our economic and social ills, is contrary to fact, is based on ignorance or misconception, is vicious in its possible social consequences, and yet has taken an insidious hold on the minds of many people. Conscious of the fallacy of this idea, but characteristically intent on their work and averse to publicity, the productive scientists of the country have thus far taken little or no part in discussions of the subject.

"It has become evident, however, that the spread of this idea is threatening to reduce public support of scientific work, and in particular, through certain codes of the N.R.A., to stifle further technical improvements in our manufacturing processes. Either of these results would be nothing short of a national calamity—barring us from an advanced state of knowledge and standard of living and soon placing us at an economic disadvantage in respect to foreign countries who have not let themselves be swayed by such a short-sighted point of view.

"Consequently the New York Electrical Society and the American Institute of Physics are combining in a national service to combat this insidious and dangerous propaganda. They do not, of course, hold that scientific and technical advances have not brought difficulties, like social growing pains. But they strive to prevent us from killing the goose that lays the golden eggs, just because some of these eggs happen to be tarnished. They would advocate careful attention to polishing the eggs, and encouraging the goose to lay more of them. In other words, they advocate intelligent and effective attention to remedy such social and economic difficulties as have accompanied the advance of science, and at the same time they advocate the further advancement of science and its applications for human welfare just as vigorously as possible. They do this because the effects of science on human welfare are preponderatingly good and beneficial. . . .

"Think for a moment where we would be if our ancestors, alarmed by the progress of science, had taken steps by codes or by public sentiment to stop its progress! . . . And if we, in this day and generation, act to stop science, our descendants will similarly miss the corresponding new advantages which they might otherwise have. . . .

"That great human benefactor, Pasteur, had a grasp of the truth when he wrote: 'What really carries us forward is a few scientific discoveries and their applications.'

"Those in charge of this meeting. . . have chosen not to try to handle the whole field of science and its effects on society but to concentrate primarily upon just one aspect of these social effects, namely, the effect of science upon employment. This is a very live issue in these days of unemployment. It is here that a misunderstanding of the effects of science are likely to be most dangerous, because of possible political influences. Let us therefore consider very briefly what these effects are.

"We will immediately admit that technological advances frequently result in labor-saving devices which throw large numbers of men and women out of work. This is distinctly unfortunate. Its evil effects can be mitigated by wise handling of these new devices; as, for example, the American Telephone and Telegraph Company has handled its introduction of automatic switching so as not to throw employees out of work.

"But the other side of the picture is immensely more significant in that the major result of science is the creation of entirely new industries which cater to new human desires, and which not only create a multitude of new jobs but which increase the per capita productiveness of men so as, first, to permit of an increasing population which is not limited by starvation and misery and, second, to reduce the hours necessary for men to labor to produce their necessities, and in this way to give them their opportunity to appreciate and experience some of the better opportunities of living which formerly were available only to those of wealth or of politically favored position.

"Let me give a few examples of what I mean: Two years ago was celebrated the centennial anniversary of the discovery of the principles of electromagnetism which underlie practically all of the modern electrical industry. According to the 1930 census there were in this country about 360,000 persons employed in the manufacture of electrical machinery and equipment, and about 676,334 people employed in the distribution of electrical materials, exclusive of the field of communication, namely, the telephone, telegraph, and radio, which contribute in addition an immense number of workers.

"I believe. . . that the argument can be made more fundamental even than this. Man has an irrepressible curiosity for new knowledge. This is the fundamental basis and urge for scientific work. Man has also an irrepressible desire to use his knowledge for the accomplishment of his desires. This is the basis of invention and of engineering. These, I believe, are so fundamentally a part of human psychology that they cannot, be fettered, though their free exercise may of course, be hampered or, on the other hand, be encouraged. The early Egyptian who discovered that a wheel driven by the current or by oxen could lift up water from the Nile for the irrigation of his fields did not worry because this invention relieved him of the job of carrying his water by hand. He simply took advantage of this invention to increase his range of interests and activities in other directions. He cultivated more land, he experimented in early science, he built monuments which he could not have done had he toiled morning to night carrying water by hand. Similarly, I believe that in the last analysis the extent of man's employment is governed by man's inherent desire and urge to do something. If science can relieve him of the more routine tasks, he is free to turn his attention to other things which excite his curiosity or satisfy his desires. In the last analysis, therefore, I believe that science simply increases man's power and the range of his activities. Most certainly, however, both theory and experience prove more conclusively that science has made jobs, not taken them away."

Address of Dr. F. B. Jewett

Excerpts from the address delivered at the same meeting by Dr. Frank B. Jewett (A'03, F'12, past-president), vice-president of the American Telephone and Telegraph Company, and president of the Bell Telephone Laboratories, Inc., New York, N. Y., trustee of the New York Museum of Science and Industry, and a member of President Roosevelt's science advisory committee, follow:

"This allegation, that science has shot its bolt, and that there should be a holiday on scientific research, of course, is nothing substantially new. Some of us have been hearing this thing for a good many years but it has reached its crisis in this economic depression. That it is a false assumption, I think is quite easily demonstrable, if one is willing to look at things in somewhat of a broad prospective. . . .

"One of the first things which appears to be of first importance—is what has happened in the Western world in the last 35 years or so, in comparison to what happened in the rest of the world, relatively. . . . Let us

go back to the period of time in the Middle Ages—or later—even up to the end of the 18th century. . . . What you find, is that goods were produced similarly in all parts of the world and that consequently, scientific progress was about the same throughout the world. . . .

"Then something happened—at about the beginning of the 19th century—in the Western world, which upset existing conditions. That something was the introduction in the western society of science—and the furtherance of the scientific principle in living conditions.

"During the 19th century, and more importantly, the first part of the 20th century, that influence has grown and what has been its result, is that it is the only major factor which has done more to correlate the markets of the Western world to those of the rest of the world. Consequently, if scientific progress is not the sole cause of whatever has happened to strengthen world relations, it is the major factor in changing existing conditions. . . . During this period of time, the population of the world has increased enormously. More people have been added to the world's population in that short period of time, than in any preceding time—and they have been added in the very places where science has found its work—in the Western world, in America particularly, and in Japan, the only one of the Oriental countries which has applied Science. . . .

"Now to the question that Science has reduced employment. It has greatly increased employment because it has increased the number of people gainfully occupied in its various aspects. Further than that, it has unquestionably increased the pleasure and ease of living in the sphere in which it has been operating. . . .

"Let us see what progress resulted from the advance in the use of science in industry. At the time of the Centennial Exposition there was no telephone system, no electric light, or power industry. There was no automotive industry. There were no aeroplanes—nothing which involved internal combustion engines. There were no chemical industries which have grown up in the last recent years. There was no motion picture machine. No talking machine. No radio—no picture transmission. We can get up a list of things that are extremely important today, which did not exist at all at the time of the Fair. Out of these have been built huge industries—the greatest outside of agriculture, which have given employment to untold thousands.

"One thing which this Exposition did and which they did not expect it to do—was that it acted as a great inspiration to the youth of the country, and the result is a vast expansion to the application of science in an enormous number of industries and activities which had not so been benefited before. . . .

"If one is willing to look at facts in broad prospective, it seems to me, that one cannot but see that history, in the last 150 years at least, has proved that scientific research, applied to the forces of life, has resulted in better living conditions and an increase of employment for people who are gainfully working in scientific industries. I think that any argument to the contrary is based on complete ignorance—or based on a too-narrow survey of specific, unrelated facts."

ADDRESS OF
DR. R. A. MILLIKAN

Excerpts from the address delivered at the meeting on "Science Makes More Jobs" in New York, N. Y., February 22, 1934, by Dr. R. A. Millikan (M'22, HM'33), director of the Norman Bridge Laboratory of Physics and chairman of the executive council of California Institute of Technology, Pasadena, and a member of President Roosevelt's science advisory committee, follow:

"If anyone. . . .doubt that the common man. . . .is vastly better off here today in depressed America than he has ever been at any other epoch in history, I beg of you to begin to read carefully a bit of that history—or if you haven't time for that, then to make friends with some historian and pump him on the living conditions of the common man in any preceding age as compared with those existing right now in the midst of the world's greatest depression... If you haven't even time for either of the foregoing procedures then let me ask you at least to take 10 minutes to read a brief article by Henry M. Robinson published in the December 1933 number of the *Readers' Digest* entitled, "No Time Like the Present." Its simple statement of historic facts will be an eye-opener to some of you. . . .Let me first quote Mr. Robinson's conclusions from his historic studies. He says, 'For all its chafings and imperfections our age is superior in security, comfort, leisure, and economic rewards to any other period or condition of life that ever existed in this sweating, tear-drenched world.' Or again, 'In terms of political justice, economic coöperation, health, happiness, and human sympathy there has, as yet, been no time like the present.'

"For what is science actually responsible in this American civilization of ours? Let me first give to that question the answers upon which there will and can be no essential disagreement. Science and its applications have so increased the efficiency of labor that here in the United States we produce more of the fundamental food-stuffs, clothing, building materials, and fuels than we, just now, know what to do with; and in spite of the present jam in our social machinery which we call the depression the great bulk of all this produce goes now, and always has gone to the common man, that is, to labor. So nearly is that true that any economist will tell you that the standard of living in the different countries of the earth is in general directly proportional to the total productivity of these countries per inhabitant. That is why in spite of the depression the standard of living here has remained relatively high and there has been no appreciable starvation, while in Russia where the opportunity for, and stimulus to, individual effort has been removed through state paternalism, not less than 5 million people, according to Whiting Williams, starved to death last year, and also where he says that the well-being of the common man is incomparably lower than it is here when at its worst.

"In the second place I need to bring forth no figures to convince anybody that the productivity of labor, brought about by the applications of science in America, has opened up to the common man the opportunities of leisure such as he has never known at any other time or place. . . .

"Every labor-saving device creates in general as many, oftentimes more, jobs than it destroys and the new jobs are in general better for the individual affected, and much better for society as a whole than the old ones. Labor-saving devices do not in general destroy the jobs that demand intelligence. They cannot do it. The heavy, grinding, routine, deadening jobs are the ones that machinery destroys. . . .

"Taking the long range view, not the short range one, I have no hesitation whatever in saying that there is no such thing as technological unemployment. By what authority do I say that? By the authority of the official census of the United States. This lists every decade the percentage of the population 'gainfully employed.' This was 34 per cent in 1880 and almost exactly 40 per cent in 1930—a depression year—and it has shown a steady increase decade by decade, save for a negligible drop from 1920—when war conditions were still on—to 1930. In other words in this precise period in which science has been applied most rapidly to industry the percentage of our population living by means of jobs has continually increased—comment enough on the soundness of the judgments of those who attribute the depression, which seems to me to be in fact a purely social phenomenon, to technological unemployment."

Bell Telephone System Centralizes Its Researches

Announcement has been made that the research activities of the Bell Telephone System have been centralized through the consolidation of the development and research department of the American Telephone and Telegraph Company with the Bell Telephone Laboratories, Inc. A brief history of the research organization of the Bell system follows:

Before there was a telephone there was a telephone laboratory. In a corner of a Boston workshop Alexander Graham Bell carried on his researches. Ever since that time the parent company of the Bell Telephone System, which evolved from his invention, has maintained a telephone laboratory. In the early years of the Bell System the laboratory was at its headquarters in Boston. Two other laboratories, meanwhile, developed in conjunction with the Western Electric Company, the manufacturing unit; one in Chicago, and the other in New York. In 1907, these 3 laboratories were consolidated into a single unit in New York City. This combination of laboratories was then operated as the engineering department of the Western Electric Company.

Not all, however, of the research problems of communication, in which the American Telephone and Telegraph Company was interested, were of a laboratory character. In its own organization, therefore, that company continued to maintain a development and research group. This group

stood intermediate between the laboratory research and the actual operation of communication systems.

Bell Telephone Laboratories Organized

By 1925 the work of the laboratory unit had so grown in range and in intensity, and the magnitude of the personnel involved, that it could best be carried on in a corporation devoted solely to research and development. The organization, therefore, which had been maintained and operated as the engineering department of the Western Electric Company since 1907, was incorporated as Bell Telephone Laboratories. Its dual responsibility to the American Telephone and Telegraph Company, for fundamental researches, and to the Western Electric Company as the manufacturing unit of the system, for the embodiment of the results of these researches in designs suitable for manufacture, was emphasized in its corporate organization. The laboratory company is owned jointly by the American company and by the Western Electric.

In the executive direction of the work of the laboratories there was emphasized the responsibility, which the American Telephone and Telegraph Company has assumed, as the corporate successor of Alexander Graham Bell, for ensuring to its associated companies in the system the technical progress of the communication arts. This was accomplished in part by organization, and in part by the choice of executive personnel. As president of the laboratories there was elected Dr. F. B. Jewett (A'03, M'10, F'12, and past-president). Dr. Jewett was also elected vice-president of the American Telephone and Telegraph Company to have charge of its research and development activities. Coördination of all the research activities within the American company and within the laboratory unit was thereby assured under the supervision of a single executive.

It was while the laboratories were operated as the engineering department of the Western Electric Company that there came into existence the laboratory group known as the "research department." Its head in its early days was Dr. E. H. Colpitts (A'11, F'12), who had entered the Bell System in its Boston laboratory. In 1924 he returned to the American company as assistant vice-president to take charge under the late General J. J. Carty (A'90, M'03, F'13, member for life and past-president), of the "development and research department" of that company; and he continued in that capacity under Dr. Jewett.

The department of development and research in the American Telephone and Telegraph Company has had that particular name only since 1919. Its characteristic activities, however, preceded by years the adoption of its name, for they were part of those of the engineering department of the American company. That department, organized under General J. J. Carty, as chief engineer, was concerned with the technical progress of the telephone art, the establishment and maintenance of suitable standards, and the solution of peculiar problems arising in the operating field.

In 1919 there was taken another step in functional organization. The much augmented engineering department was divided into 2 groups, namely, that concerned with problems of operation and engineering and that concerned with problems of development and research. The first mentioned problems became the particular care of Bancroft Gherardi (A'95, M'04, F'12, member for life, and past-president), who was then appointed vice-president of the American Telephone and Telegraph Company; and the research problems continued to be the care of Vice-President J. J. Carty (deceased 1932). It was to the leadership of this department that Dr. Jewett succeeded when he returned to the American company from the Western Electric.

Further Centralization

March 1, 1934, a further centralization of the research activities of the Bell System was accomplished. The development and research department of the American Telephone and Telegraph Company and the laboratories were consolidated. All of their activities are now carried on under the corporate name of Bell Telephone Laboratories. A year earlier when this centralization was first definitely projected Mr. Colpitts was elected vice-president of the laboratories, in charge of its operation. These 2 units which are now merged have had, therefore, for almost a year, identical executives.

The combination with Bell Telephone Laboratories of the development and research department of the American company means an organization with a marked increase in responsibilities, and concurrently a commensurate increase in its technical efficiency. The direction of the enlarged organization continues to be the responsibility of Dr. Jewett in his dual capacity as vice-president of the American Telephone and Telegraph Company and president of Bell Telephone Laboratories.

Obituary

William Joseph Hammer (A'87, M'87, F'12, and life member) retired, major, U.S. Army, long regarded as one of the country's foremost electrical experts, who served the Institute as vice-president (1891–93) and manager (1893–96), died of pneumonia in New York, N. Y., on March 24, 1934. He was born at Cressona, Pa., February 26, 1858, and was educated at public and private schools in Newark, N. J., and at the University of Berlin and the Technische Hockshule (Berlin). Major Hammer became an assistant to Edward Weston in the Weston Malleable Nickel Company in 1878 and the following year entered Edison's laboratory at Menlo Park, N. J., as general assistant, where for a long time he had charge of the tests and records on incandescent lamps. In 1880 he was made chief electrician of the first Edison Lamp Works, at Menlo Park, N. J., and in 1881, chief engineer of the English Edison Company. He was the Edison representative at the Paris Electrical Exposition, constructing what is reported to be the first central station for incandescent electric lighting in the world at Holborn Viaduct, which was put into operation in 1882. He also installed the plant using 12 Edison dynamos at the Crystal Palace Electric Exposition (1882) and Edison's Paris Exhibit, 1889. In 1883 he became chief engineer of the German Edison Company (now known as the Allgemeine Elektricitaets Gesellschaft) and installed many plants through Germany. At the Berlin Health Exposition that year Major Hammer placed on exhibition his invention of the automatic motor-driven "flashing" electric lamp sign. He returned to the United States in 1884 to take charge of the interests of Mr. Edison and of 8 Edison companies at the Franklin Institute Electrical Exhibition in Philadelphia and became confidential assistant to the president of the parent Edison Electric Light Company. In 1889 he was Edison's personal representative at the Paris Exposition, setting up and operating all the Edison inventions; for this he was made Chevalier of the Legion of Honor (France, 1925). From 1884 to 1885 he was chief inspector of central stations of the Edison company. In 1886 he was chief engineer and general manager of the Boston Edison Company. He was one of the incorporators and trustees of the Sprague Electric Railway and Motor Company. From 1890 until his death, he carried on a consulting practice and maintained offices in New York. Among his important achievements were the installation of the 8,000-light plant of the Ponce de Leon Hotel at St. Augustine, Florida, the largest private plant in the world at that time, overhauling of the Jacksonville Edison plant which had been struck by lightning, and installation of the electrical effects at the Cincinnati Exposition of 1888. He early advocated the use of radium in treating cancer and he gave a series of 88 lectures and published the first book on the subject, entitled "Radium and Other Radioactive Substances." He was an aviation enthusiast and one of the first to privately own an airplane. At the entrance of the United States into the World War he was appointed a major on the general staff of the Army in the inventions section of the War Plans Division, and later in the Operations Division of the Army War College at Washington. Major Hammer was active on the committee on Local Meetings which studied and reported on the advisability and plans for establishing local meetings, now referred to as local Sections, of the Institute in 1893. In 1906–07 he represented the Institute at the Hall of Fame ceremonies. In 1932 he was a member of the special committee on the Edison Memorial. He was the recipient of several scientific honors, including the Elliott Cresson gold medal; John Scott legacy medal and premium; the grand prize of the St. Louis Exposition, 1904; gold medal, St. Louis Exposition, 1906. He was awarded the World War medal (U.S.) and the World War medal (New York State), 1920. He was an officer and member of numerous societies, including the American Physical Society, New York, the Franklin Institute, Edison Pioneers,

American Acoustics Electrical Society, and the Aeronautical Society.

George Owen Squier (A'91, F'19, and member for life), retired, major-general, U.S. Army, Washington, D. C., who attained distinction in the electrical field because of his early work in the invention of the multiplex telegraphy systems, and development of a monoplane system of communication for transmitting broadcast programs over telephone wires, died of pneumonia at the George Washington Hospital, Washington, D. C., March 24, 1934. He was a researcher of some note and while some of his ideas did not prove practically advantageous, many of them were suggestive of new lines of attack and stimulated research and investigation, this particularly true in regard to his valuable suggestions concerning submarine cable telegraphy and high-frequency multiplex operation. He was born March 21, 1865, at Dryden, Michigan, and was educated at the United States Military Academy, graduated in 1887, and at Johns Hopkins University where he studied electrical engineering and general physics for 3 years subsequently. He was a fellow of the university in 1891 and a fellow by courtesy the following year. Some years later, in 1903, he received the Ph.D. degree. He entered the military service as a second lieutenant of artillery, but was transferred later to the Signal Corps, attaining in 1917 the rank of chief signal officer of the Army and in 1917 major-general, retiring in 1924. He had served as military attaché at the American embassy in London from 1912 to 1913. During the World War he founded the Signal Corps School at Leavenworth, Kansas. He represented the War Department at the international conference on electrical communications at Washington in 1920 and the State Department on a committee of the conference in Paris the following year. He was a technical adviser at the Washington Arms Conference in 1921. His interest in electrical communication dated from the early days of his military career. Over a long period of years he was in responsible charge of the electrical work of the Signal Corps. In 1900–02 he commanded the U. S. S. "Burnside" in laying the cable telegraph of the Philippines. He put his multiplex telegraphy system into actual practice on a 3-mile line between the laboratory of the Signal Corps Bureau of Standards in Washington and the Signal Corps Laboratory and filed the patent for it in 1910, in the name of the people. He first demonstrated the amplifying apparatus which enables a physician to make a stethoscopic study of a patient's heartbeats at a distance of hundreds of miles. He was awarded the Elliott Cresson gold medal and the Franklin medal for his researches. He held the distinguished service medal of the United States. He was a Knight Commander of the Order of St. Michael and St. George of Great Britain, a Commander of the Order of the Crown of Italy, and a Commander of the Legion of Honor of France. He was a fellow of the London Physical Society and the Royal Institute of Great Britain, and a member of the National Academy of Sciences.

Membership

Recommended for Transfer

The board of examiners, at its meeting held April 11, 1934, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed with the national secretary at once.

To Grade of Fellow

Funk, Nevin E., vice-pres., in charge of engg., Phila. Elec. Co., Pa.
Goodale, Josiah E., E.E., N. Y. & Queens Elec. Lt. & Pwr. Co., Flushing, N. Y.
Hill, Frederick W. L., engr., Potomac Elec. Pwr. Co., Washington, D. C.
Smith, L. G., asst. to gen. supt., Consolidated Gas Elec. Lt. & Pwr. Co., Baltimore, Md.
Weber, Ernst, research prof. of E.E., Polytechnic Inst. of Bklyn., Bklyn., N. Y.

To Grade of Member

Bjorndal, Magnus, chief engr., The Daven Co., Newark, N. J.
Boyce, Edward O., engg. asst., Brooklyn Edison Co. Inc., N. Y. City.
Bush, Richard M., supt. elec. dept., Virginia Elec. & Pwr. Co., Williamsburg.
Carr, John L., asst. to E.E., Potomac Elec. Pwr. Co., Washington, D. C.
Curtis, Ralph F., asst. E.E., Western Mass. Companies, Springfield.
Dudley, Homer W., telephone engg., Bell Tel. Labs., Inc., N. Y. City.
Grigsby, Logan C., E.E., Pub. Serv. Co. of Okla., Tulsa.
Knopp, Otto A., chief of bureau of tests and inspection, Pacific Gas & Elec. Co., Emeryville, Calif.
Lamb, John F., industrial motor engg. dept., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Maunder, Sydney T., power transformer engr., Gen. Elec. Co., Pittsfield, Mass.
Webber, Thomas T., tour chief-dispatcher in charge of tour, N. Y. Fire Dept., Woodhaven.

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before May 31, 1934, or July 31, 1934, if the applicant resides outside of the United States or Canada.

Brown, L. B., Westinghouse Elec. & Mfg. Co., Salt Lake City, Utah.
Burnstead, H. A., Dept. of Pub. Works, Olympia, Wash.
Burton, R. W., 1523 Chapel St., New Haven, Conn.
Cain, B. M., Gen. Elec. Co., Schenectady, N. Y.
Callis, P. A., Louisville Gas & Elec. Co., Ky.
Candler, M. A., Southern Bell Tel. & Tel. Co., Charlotte, N. C.
Christensen, H. C., Pub. Serv. Dept., City of Glendale, Calif.
Coon, C. C., 600 Fuller St., Oakland, Calif.
Craig, S. A., Louisville Gas & Elec. Co., Ky.
Davison, A. L., Empresa Telefonos Ericsson, S. A., Mexico, D. F., Mexico.
Fettig, J. J., Duncan Elec. Co., Lafayette, Ind.
Floyd, J. L., Southern Bell Tel. & Tel. Co., Charlotte, N. C.
Fuller, A. W., Adrian, Ga.
Gilcrest, R. V., Box 305, Carlyle, Ill.
Greenfield, E. W., Johns Hopkins Univ., Baltimore, Md.
Gregory, G. A., Dept. of Pub. Works, Olympia, Wash.
Grimmett, R. B., Arkansas Pwr & Lt. Co., Marion
Hedke, H. A. W. (Member), 726 Edmund St., St. Paul, Minn.
Herzstein, A., Gen. Elec. Co., Pittsfield, Mass.
Hibben, S. G., Westinghouse Lamp Co., Bloomfield, N. J.
Jessop, R. A., Am. Tel. & Tel. Co., Chicago, Ill.
Johnson, L. N., Meter Serv. Corp., Chicago, Ill.
Jones, H. L., Southern Bell Tel. & Tel. Co., Charlotte, N. C.
Keane, J. M., Va. Elec. & Pwr. Co., Petersburg, Va.
Kemp, J. W., 554 Arden Place, Toledo, Ohio.
Koenigsberg, M., 968 Whitlock Ave., N. Y. City.
Krog, F. G. F., Potomac Elec. Pwr. Co., Washington, D. C.
Kurtichanof, L. E. (Fellow), Ry. Exchange Bldg., Portland, Ore.
Lantz, G. J., Lantz Elec. Co., Orlando, Fla.
Leake, W. S., Gen. Elec. Co., New Orleans, La.
Leavitt, S. M., 138 32nd St., Woodcliff, N. J.
Leeds, D. A., Northern Ind. Pub. Serv. Co., Hammond, Ind.
Long, R. P., Bell Tel. Co. of Pa., Phila.
McGovern, W. R., Jr., Wis. Tel. Co., Milwaukee.
McKenzie, D. B., c/o Mrs. Stevens, 14 Clinton St., Cambridge, Mass.
McWilliam, C. R., Canadian Gen. Elec. Co., Ltd., Toronto, Ontario, Can.
Meyerend, F. M., John A. Roebling's Sons Co., Trenton, N. J.
Miller, R. A., Bell Tel. Lab., Inc., N. Y. City.
Molis, B. W., Denver & Rio Grande Western R. R. Co., Denver, Colo.
Morgan, M. I., Memphis Pwr. & Lt. Co., Tenn.
Nelson, O. L., Southern Calif. Tel. Co., Los Angeles, Calif.
Nishimura, B., Japanese Government Ry., N. Y. City.
Plaisted, R. J., P. O. Box 31, Brecksville, Ohio.
Ruhlin, L. H., Libbey-Owens Ford Glass Co., Toledo, Ohio.
Sevouny, H., Elec. Engg. & Contracting Co., N. Y. City.
Sievers, E. S., Weston Elec. Istrument Corp., Newark, N. J.
Sinclair, B. G., Dept. of Pub. Works, Olympia, Wash.
Skrynski, W. J., Hydro Elec. Pwr. Comm. of Ontario, Hydro, Ont., Can.
Smith, A. V., Gibbs & Hill, N. Y. City.
Steensen, A. P., Foxboro Co., Foxboro, Mass.
Swan, H. C., Sewerage & Water Board, New Orleans, La.
Towner, J. M., 537 Chateau Ave., Baltimore, Md.
Venturine, J. B., Industrial Elec. & Engg. Co., Portland, Ore.
Weeks, F. D., Commonwealth Edison Co., Chicago, Ill.
Whitman, E. B. (Member), The West Penn Elec. Co., Pittsburgh, Pa.
Williams, E. W., Gen. Elec. Co., Baltimore, Md.
Williams, G. S., Cypress, Ill.
57 Domestic

Foreign

Appadurai, V. P., Electricity Dept., Chepauk, Madras, India.
Bowen, D. H., Cape Times Ltd., Cape Town, South Africa.
Norinder, E. H. (Member), Univ. of Uppsala, Husyborg, Uppsala, Sweden.
Oswald, T. D., Newcastle & District Elec. Ltg. Co., Ltd., Newcastle-upon-Tyne, Eng.
Soderquist, C. G. D., Trafikaktiebolaget Grangesberg-Oxelosund, Grangesberg, Sweden.
Vepa, V. L. R., Indian Inst. of Science, Bangalore, S. India.
Young, A. H. (Member), Jamaica Pub. Serv. Co., Ltd., Kingston, Jamaica, B. W. I.
7 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Bonell, R. K., 45 Clifton St., Newark, N. J.
Brayman, Chas. E., c/o J. J. Murphy & Son, 38 Ford St., Hartford, Conn.
Chilberg, Ernest E., Gen. Elec. Co., 230 S. Clark St., Chicago, Ill.
Crowder, H. G. Y., 1019 Nelson St., Vancouver, B. C., Can.
Darcy, Harris B., 305 M. & M. Bldg., Houston, Texas.
Dean, George H., Corrie, Old Shoreham Road, Shoreham-by-Sea, Eng.
Garvey, Fred A., 4144 Cottage Grove, Chicago, Ill.
Goulding, Harold, 404 W. 116th St., New York, N. Y.
Gray, L. Tenney, Jr., 6452 Hillegas Ave., Oakland, Calif.
How, John H., 42 Wai Oi Road East, Canton, China.
Isler, Harry F., 108 W. Harris Ave., San Angelo, Texas.
MacDonald, Robert, 6 Rue Nicolas Charlet, Paris, France.
Miller, Frank D., Box 34, Yatesboro, Pa.
Nemkowski, B., 104–25 115th St., Richmond Hill, N. Y.
Pauli, Henry F., 217 Greylock Pkwy., Belleville, N. J.
Sparks, Losey D., 1507 Sherwin Ave., Chicago, Ill.
Valier, Chas. E., Jr., 1804 Tel. Bldg., St. Louis, Mo.

Published Monthly by

American Institute of Electrical Engineers

(Founded May 13, 1884)

Electrical Engineering

Registered U. S. Patent Office

June 1934
Volume 53
No. 6

The Official Monthly Journal and Transactions of the A.I.E.E.

J. B. Whitehead, President
H. H. Henline, National Secretary

Publication Committee
E. B. Meyer, Chairman
R. N. Conwell — **H. H. Henline**
W. S. Gorsuch — **H. R. Woodrow**

Publication Staff
G. Ross Henninger, Editor
C. A. Graef, Advertising Manager

PUBLICATION OFFICE, 20th and Northampton Streets, Easton, Pa.

EDITORIAL AND ADVERTISING OFFICES, 33 West 39th Street, New York, N. Y.

ENTERED as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918.

SUBSCRIPTION RATES—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii and the Philippine Islands, Central America, South America (except Argentina), Haiti, Spain and Spanish Colonies; $13 to Canada; $14 to all other countries. Single copy $1.50.

CHANGE OF ADDRESS—requests must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered due to incorrect address cannot be replaced without charge. Be sure to specify both old and new addresses and any change in business affiliation.

ADVERTISING COPY—changes must be received by the fifteenth of the month to be effective for the issue of the month succeeding.

STATEMENTS and opinions given in articles appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters.

REPUBLICATION from "Electrical Engineering" of any Institute article or paper (unless otherwise specifically stated) is hereby authorized provided full credit be given.

COPYRIGHT 1934 by the American Institute of Electrical Engineers.

ELECTRICAL ENGINEERING is indexed in Industrial Arts Index and Engineering Index.

Printed in the United States of America. Number of copies this issue—

17,500

This Month—*Summer Convention Issue*

Front Cover

Where the James River breaks through the Blue Ridge Mountains near Glasgow, Va., as seen from the Lynchburg-Natural Bridge highway (U.S. No. 60). This is but one of the many beauty spots that may be enjoyed by those motoring to the Institute's 50th annual summer convention. The hydroelectric station at the left is the 2,400-kva Balcony Falls plant of the Virginia Public Service Company

Photo by F. A. Lewis (A'31)

Educational Series—No. 6

Structure of Atoms and Molecules—Electronic Theory of Valence . 851
By MAURICE L. HUGGINS

A.I.E.E. Papers

Engineers of the Next Generation 857
By C. F. HIRSHFELD

The "Compandor"—An Aid Against Radio Static 860
By R. C. MATHES and S. B. WRIGHT

Recent Developments in Suspension Insulators 867
By G. M. BARROW

Factors Influencing the Insulation Coördination of Transformers—II . . 870
By P. L. BELLASCHI and F. J. VOGEL

Electronic Regulator for A-C Generators 877
By F. H. GULLIKSEN

Flashover Voltages of Insulators and Gaps 882
An A.I.E.E. Committee Report

Load Totalizing in the New York Area 886
By F. ZOGBAUM

—Turn to Next Page

Iron Armored Aerial Communication Cable . . . 890
By C. L. GILKESON and A. J. HANKS

The Suspension Insulator 895
By K. A. HAWLEY

Radio Influence Insulator Characteristics . . . 899
By G. I. GILCHREST

Voltage Regulation and Load Control 903
By H. C. FORBES and H. R. SEARING

Encouraging Initiative in the Engineering Student . . 910
By CHESTER L. DAWES

Split Winding Transformers 914
By D. D. CHASE and A. N. GARIN

A New Porcelain Post Insulator 922
By G. W. LAPP

Grid Controlled Rectifiers and Inverters 926
By C. C. HERSKIND

Selection and Performance of Suspension Insulators 936
By PHILIP SPORN, E. L. PETERSON, and V. A. MULFORD

Calibration of the Sphere Gap 942
By J. R. MEADOR

Some New Developments in Supervisory Control . 949
By M. E. REAGAN

Selsyn Instruments for Position Systems 953
By T. M. LINVILLE and J. S. WOODWARD

A Compensated Automatic Synchronizer . . . 960
By H. T. SEELEY

High Voltage Insulators 969
By W. A. SMITH and J. T. LUSIGNAN, Jr.

A Telemeter With Pilot Coil Transmitter 974
By L. J. LUNAS and H. L. BERNARDE

Voltage Control of Vapor Rectifiers 976
By DIDIER JOURNEAUX

A Survey of Hydroelectric Developments . . . 988
An A.I.E.E. Committee Report

A 7,000-Ampere Station Bus 994
By H. L. UNLAND, W. B. MORTON, and V. R. BACON

Cross Current of a 5-Arm Network 1004
By A. C. SELETZKY and J. R. ANDERSON

Insulation Resistance of Armature Windings . . . 1010
By R. W. WIESEMAN

News of Institute and Related Activities 1022

Summer Convention to Be Held This Month at Hot Springs, Va. 1022

Pacific Coast Convention Plans Being Made . . . 1022

North Eastern District Holds Tenth Annual Meeting at Worcester, Mass. 1023

Institute Prize Awards Announced for 1933 Papers 1026

Section and Branch Activities Summarized in Annual Report for 1933–34 1027

Legislative and Administrative Policy Affecting Engineers 1029

Letters to the Editor 1031

Membership 1034

Engineering Literature 1035

Industrial Notes. 1036

Employment Notes. . . . . (See Advertising Section)

Officers and Committees (For complete listing see p. 658–81, September 1933 issue of ELECTRICAL ENGINEERING)

To each member of the A.I.E.E.

Dear Sir:

Under date of November 8, 1933, we wrote you asking for your support of the membership activities of the Institute. We asked you specifically to send in the name of one person who you feel should be asked to join the Institute. Now we are asking you to do this again. Just send the name to the chairman of the membership committee of your Section. Please do this now.

Since we wrote you last, 345 applications have been submitted for membership from other than students. Your contribution helped to make this possible. We are asking for your continued support.

Very truly yours,

Chairman National Membership Committee

Structure of Atoms and Molecules

Electronic Theory of Valence

By MAURICE L. HUGGINS
FELLOW AM. PHYS. SOC.
The Johns Hopkins Univ., Baltimore, Md.

A digest of present theories regarding the structure of atoms and molecules is presented herewith. In an article of this length it is impossible to show adequately how bulk properties of substances are related to atomic properties; the article is intended primarily as a general introduction to the subject, and for those wishing to delve deeper into the matter a list of references is given at the end of the article. This is the sixth of a series of special articles prepared under sponsorship of the A.I.E.E. committee on education.

THE POSTULATE that matter is composed of tiny discrete *atoms* dates back to the early Greeks. Dalton in 1808, however, was the first to show how such an assumption explains the constancy of composition of pure substances and the simple relationships existing between the compositions of different substances composed of the same *elements*, for instance carbon monoxide, CO, and carbon dioxide, CO_2.

Dalton assumed that *compounds* consist of "compound atoms," now called *molecules*, but there was no satisfactory way of determining the correct molecular formulas (*e. g.*, HO or H_2O or HO_2 for water) until Avogadro in 1811 showed that the densities of different gases under identical conditions of temperature and pressure are proportional to the weights of the molecules of which they are composed. Knowing the formulas, relative *atomic weights* then could be calculated from measurements of the weights of substances consumed and formed in chemical reactions. The names, symbols, and atomic weights of many of the elements are listed in Table I.

Nothing was known regarding the structures of atoms until the discovery (Thomson, 1895) that they contain negatively charged *electrons*. Later, evidence was presented (Rutherford, 1911) to show that these are in continuous rotation around a minute positively charged *nucleus*. All electrons in all atoms now are known to be alike in having the same charge ($-e$) and the same mass. The mass of the lightest nucleus, that of hydrogen, is about 1,840 times that of an electron. For most purposes, therefore, the mass of an atomic nucleus can be considered to be the same as the mass or weight of the whole atom. The charge on the nucleus is always positive and equal to an integer N (called the *atomic number*) times e, the magnitude of the electron charge. The value of N is 1 for hydrogen, 2 for helium, 3 for lithium, etc., increasing in the same order as the atomic weight (with 3 exceptions) as an examination of Table I will show.

The nucleus of a hydrogen atom consists of a single *proton*, a particle with a charge of $+e$ and a mass of approximately one atomic weight unit. The nucleuses of other elements are complex, containing protons, *neutrons* (Bothe and Becker, 1930), electrons, and *positrons* (Anderson, 1932). A neutron is an uncharged particle of (practically at least) the same mass as a proton. A positron has (approximately at least) the same magnitude of charge and mass as an electron; its charge, however, is of opposite sign. Although the masses and the net charges of most kinds of nucleuses are known, the arrangements and relative motions of the component particles and in most cases even the numbers of each component at present are unknown.

The charge on the nucleus of an atom determines the number of electrons rotating around it and so the chemical and physical properties, other than those that depend on the mass. In many instances nucleuses that differ in mass, because of differences in the numbers of protons and neutrons they contain, have the same charge and hence are of the same element. Atoms containing these nucleuses of differing mass are called *isotopes* (Soddy and Fajans, 1913). The most important example is that of hydrogen. Although most atoms of hydrogen have nucleuses consisting of a single proton, as stated previously, it has been shown recently (Urey, Brickwedde, and Murphy, 1932) that about 1 atom in 5,000 has a mass twice as great as that of a proton. The "heavy hydrogen" or "deuterium" nucleus consists of one proton and one neutron. Molecules containing heavy hydrogen atoms differ very slightly in chemical and physical properties from corresponding molecules containing ordinary hydrogen atoms. Differences between the properties of isotopes of any other element (and between corresponding compounds containing these isotopes) are so extremely small as to make their separation very difficult.

The elements can be listed in the order of their atomic numbers in such a way (Table I) that elements with similar properties are placed in the same vertical column (Mendelèeff, 1869). For example, helium, neon, argon, and krypton are similar in being inert gases, forming no stable chemical compounds whatever. Fluorine, chlorine, bromine, and iodine are colored substances consisting of diatomic molecules, F_2, Cl_2, etc. Melting and boiling points increase regularly in the series. They react vigorously with many other elements, forming compounds with similar formulas—HF, HCl, HBr, HI; NaF,

Table I—An Abbreviated Periodic Table

	1 H 1.0 Hydrogen *1*						
2 He 4.0 Helium 2	3 Li 6.9 Lithium 2, *1*	4 Be 9.0 Beryllium 2, *2*	5 B 10.8 Boron 2, *3*	6 C 12.0 Carbon 2, *4*	7 N 14.0 Nitrogen 2, *5*	8 O 16.0 Oxygen 2, *6*	9 F 19.0 Fluorine 2, 7
10 Ne 20.2 Neon 2, 8	11 Na 23.0 Sodium 2, 8, *1*	12 Mg 24.3 Magnesium 2, 8, *2*	13 Al 27.0 Aluminum 2, 8, *3*	14 Si 28.1 Silicon 2, 8, *4*	15 P 31.0 Phosphorus 2, 8, *5*	16 S 32.1 Sulfur 2, 8, *6*	17 Cl 35.5 Chlorine 2, 8, *7*
18 A 39.9 Argon 2, 8, 8	19 K 39.1 Potassium 2, 8, 8, *1*	20 Ca 40.1 Calcium 2, 8, 8, *2*					
	29 Cu 63.6 Copper 2, 8, 18, *1*	30 Zn 65.4 Zinc 2, 8, 18, *2*	31 Ga 69.7 Gallium 2, 8, 18, *3*	32 Ge 72.6 Germanium 2, 8, 18, *4*	33 As 74.9 Arsenic 2, 8, 18, *5*	34 Se 79.2 Selenium 2, 8, 18, *6*	35 Br 79.9 Bromine 2, 8, 18, *7*
36 Kr 83.7 Krypton 2, 8, 18, 8	37 Rb 85.4 Rubidium 2, 8, 18, 8, *1*	38 Sr 87.6 Strontium 2, 8, 18, 8, *2*					
	47 Ag 107.9 Silver 2, 8, 18, 18, *1*	48 Cd 112.4 Cadmium 2, 8, 18, 18, *2*	49 In 114.8 Indium 2, 8, 18, 18, *3*	50 Sn 118.7 Tin 2, 8, 18, 18, *4*	51 Sb 121.8 Antimony 2, 8, 18, 18, *5*	52 Te 127.5 Tellurium 2, 8, 18, 18, *6*	53 I 126.9 Iodine 2, 8, 18, 18, *7*

To the left of each symbol (F) is the atomic number (9); to the right is the atomic weight (19.0). Below the name (Fluorine) is the distribution of extranuclear electrons into shells (2, 7) in order from the nucleus out. The numeral in *italics* indicates the number of valence electrons in an uncharged atom.

NaCl . . . . .; MgF_2, $MgCl_2$ . . . . .; etc. Each of the other columns of Table I likewise contains a group of elements similar to each other.

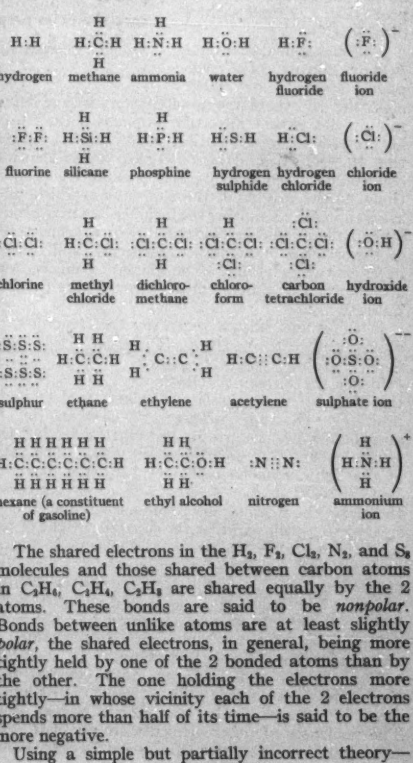
Lewis (1902) and Thomson (1904) showed that the periodicity in properties exhibited by the elements can be accounted for by assuming that the electrons (outside of the nucleus) are in shells, the number of electrons in the outermost shell of an uncharged atom determining the column of the periodic table in which the element belongs. The distribution into shells is indicated for each element in Table I.

The word *kernel* frequently is used to signify all of the atom but the valence shell. The charge on the kernel is positive or zero and equal in magnitude to the number of valence electrons in the uncharged atom times *e*, the charge on each electron.

Uncharged atoms can either lose electrons or gain them, becoming positively or negatively charged atoms or *ions:* H^+, Na^+, Mg^{++}, F^-, Cl^-, etc. Thomson assumed all chemical combination to be the result of electron transfers from atom to atom, the oppositely charged ions so produced attracting each other. Lewis (1916) showed that electrons are also *shared*, usually in pairs. Including shared electrons and those transferred from other atoms, *atoms having kernel charges of +4e or greater nearly always have 8-electron valence shells* in stable compounds or in the uncombined elements at ordinary temperatures. In molecules containing atoms with kernel charges less than 4*e*, each of these atoms usually shares with other atoms a number of electron pairs equal to the kernel charge. Although 2 adjacent atoms in a molecule normally share but one electron pair between them, an atom of carbon, nitrogen, and oxygen can form *double* and *triple bonds*, consisting of 2 and 3 shared electron pairs, with another atom of one of these elements.

In any neutral molecule the total number of valence electrons, of course, must equal the sum of the charges on the kernels. In an ion the difference between these quantities gives the ionic charge.

To illustrate the statements in the 2 preceding paragraphs, *dot formulas* of some simple molecules and ions are presented herewith. In these the kernels are represented by the atomic symbols, the valence electrons by dots.



The shared electrons in the H_2, F_2, Cl_2, N_2, and S_8 molecules and those shared between carbon atoms in C_2H_6, C_2H_4, C_2H_2 are shared equally by the 2 atoms. These bonds are said to be *nonpolar*. Bonds between unlike atoms are at least slightly *polar*, the shared electrons, in general, being more tightly held by one of the 2 bonded atoms than by the other. The one holding the electrons more tightly—in whose vicinity each of the 2 electrons spends more than half of its time—is said to be the more negative.

Using a simple but partially incorrect theory—

involving the assumption that the electrons rotate continuously around the nucleus of an atom, but only in certain particular circular or elliptical orbits—Bohr (1913) was able to calculate the different possible energy states of atoms corresponding to these orbits and from them the frequencies of light emitted and absorbed by these atoms. More recently it has been shown that the same quantitative agreement can be obtained (with better concordance with experiment in a few instances in which the Bohr theory led to unsatisfactory results) assuming a more random type of electron motion. A *new quantum mechanics*, of which the ordinary mechanics is a special case, has been developed (deBroglie, 1922; Heisenberg, 1925; Schrödinger, 1926). With this it is possible to calculate what atomic energy states are possible and, for each of these, the probability of an electron being in any given position relative to the nucleus. An *electron probability* distribution so obtained also can be considered as a time-average *electron density* distribution. These distributions, for a hydrogen atom in 3 different energy states, are represented somewhat qualitatively in Fig. 1.

The electron-pair bond of Lewis has been shown (Heitler and London, 1927) to consist of 2 electrons rotating about 2 nucleuses, each of these electrons having a probability distribution concentrated near the line joining the nucleuses (Fig. 2). Each electron spins on its own axis while it rotates about the nucleuses, but the 2 spins are in opposite directions. With some exceptions the unshared electrons in atoms under ordinary conditions are paired similarly.

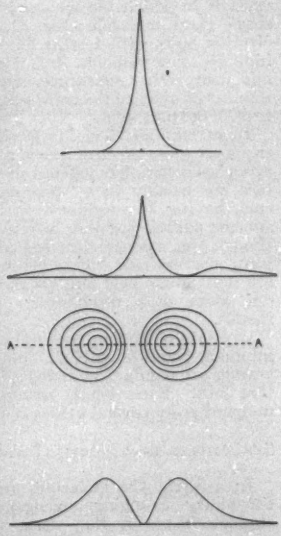
Since its introduction, the new quantum mechanics treatment of molecules has been extended by Pauling (1931) Slater (1931) and others to much more complicated cases. Among other things it has been shown that a shell of 4 pairs of electrons, with their probability distributions having maxima directed toward the corners of a tetrahedron, is especially stable and that the strength of a bond between 2 atoms is roughly proportional to the amount of overlapping of the probability distributions for the single atoms. Thus the observed orientations of the bonds (i. e., the atomic centerlines) in H_2O, NH_3, CH_4, and many other compounds approximately toward 2, 3, or 4 corners of a tetrahedron are accounted for.

Quantum mechanics, moreover, accounts for the exceptions to the usual tetrahedral arrangement. Some atoms form bonds with 4 others situated at the corners of a square; in other cases 6 bonds connect an atom to other atoms located at the corners of an imaginary octahedron or trigonal prism. The new mechanics shows under what circumstances such arrangements have greater stability than a tetrahedral one.

Structures of Crystals

Much of the present knowledge of molecular structures and of the forces between atoms has come from studies of the structures of crystals. Many years ago crystallographers had shown that to account for the forms and other crystallographic properties of crystals it was necessary to assume that they consist of regular arrangements of discrete particles—atoms or molecules—with distances between their centers of the order of magnitude of 10^{-8} cm. These distances are about the same as the wave lengths of X rays, which are otherwise like visible light. Noting this correspondence, Laue, Friedrich, and Knipping (1912) sent a beam of X rays through a thin crystal and recorded the diffraction effects on a photographic plate. The crystal acts as a 3-dimensional diffraction grating. The following year W. H. and W. L. Bragg showed how to use X ray diffractions from crystals to deduce the crystal structures. Since then a great many structures have been analyzed by this means.

Some important relationships between crystal structures and the structures of the component atoms are well illustrated by a consideration of the crystal structures of some uncombined elements. As already pointed out, a 7-valence-electron atom (F, Cl, Br, I) forms diatomic molecules. These



Figs. 1a (above) and 1b (below). Variation of electron probability (average electron density) with distance from the nucleus for 2 energy states of the hydrogen atom

These probability distributions are spherically symmetrical; the scales are arbitrary

Fig. 1c. Representation by contours of a cross section of the electron probability distribution for a third energy state of the hydrogen atom (qualitative only)

Fig. 1d. Electron probability along a line AA of Fig. 1c

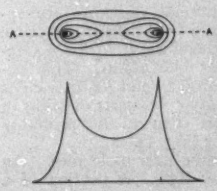


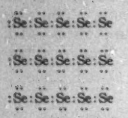
Fig. 2a. Representation by contours of a cross section of the electron probability distribution in a hydrogen molecule (qualitative only)

Fig. 2b. Electron probability along a line AA (Fig. 2a) through the atomic centers in a hydrogen molecule

molecules exist as distinct units even in the solid state. In solid iodine, for instance, the distance between the centers of closest atoms in the same molecule is about 2.7×10^{-8} cm; that between closest atomic centers in different molecules is about 3.6×10^{-8} cm. Intermolecular attractions are quite weak; hence, the substance is easily liquefied and vaporized.

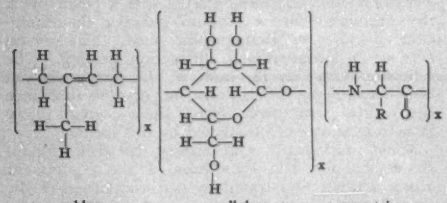
An uncharged sulphur atom has 6 valence electrons. The 2 common crystalline forms of this element are aggregates of molecules, each molecule containing 8 sulphur atoms. The dot formula for this molecule already has been given.

Selenium, also with 6 valence electrons, similarly forms Se_8 molecules. In addition, a form is known in which the atoms are bonded together in parallel spiral strings, extending completely through the crystal:



Cleavage across these strings is difficult; between the strings it is very easy. This crystal form has much higher melting and sublimation points than the form containing ring molecules. Moreover, it dissolves only when acted upon by substances capable of breaking the Se:Se bonds, whereas the ring molecules dissolve readily in suitable solvents.

It may be mentioned that other giant *string molecules* occur in rubber, cellulose, proteins, and many other substances. Representing each shared electron-pair bond by a straight line, the formulas of these are:



rubber cellulose protein

In the formula for protein, "R" denotes any one of many groups of atoms—CH_3, C_2H_5, and more complicated ones.

An uncharged atom of phosphorus or arsenic has 5 valence electrons; 3 additional electrons are required for a complete valence shell. In the absence of atoms of other kinds, therefore, it forms 3 electron-pair bonds with other like atoms. This accounts both for the tetrahedral P_4 and As_4 molecules (Fig. 3) and for the giant *layer molecules* existing in one solid form of the latter element and probably also in one form of the other (Fig. 4).

Many compounds also form layer molecules. An example is mercuric iodide, HgI_2. A portion of a layer of this substance can be represented by the dot formula:

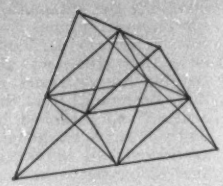
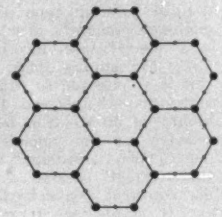


Fig. 3. A representation of the P_4 or As_4 molecule

Each atom is depicted as a regular tetrahedron, the small circles at the tetrahedron corners representing pairs of valence electrons



The large dots are the atomic kernels; the small circles, pairs of valence electrons. As in the As_4 molecule (Fig. 3) there are 4 valence electron pairs around each kernel, 3 of these being shared with other atoms

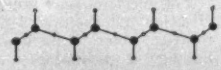


Fig. 4. Diagram representing a portion of a layer molecule of arsenic, in plan and elevation

Carbon, silicon, and other 4-electron elements form crystals in which the whole structure constitutes a single giant molecule (Fig. 5). Each atom shares electron pairs with 4 other like atoms. Silicon carbide, SiC, zinc sulphide, ZnS, cuprous chloride, CuCl, and many other substances with the same average number of valence electrons per atom have the same type of arrangement.

In crystals of elements having less than 4 electrons per atom no structure is possible in which each atom has a complete valence shell. The atomic centers are usually in a "close-packed" arrangement, each having 12 neighbors, as in an assemblage of spheres packed together as closely as possible. Although the valence electrons in most cases do not form electron-pair bonds between the atoms, they are not tightly held and are easily transferred from one atom to a neighboring one. These are the metals.

Crystals of sodium chloride, NaCl (Fig. 6), ammonium chloride, NH_4Cl, and many other compounds are regular assemblages of positive and negative ions. Each ion is surrounded, usually symmetrically, by several others of opposite charge.

Structures in Liquids, Glasses, and Solutions

In a liquid the molecules are in a random and constantly changing arrangement. In some instances, however, they form small aggregates of

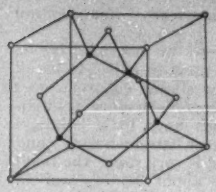


Fig. 5. A portion of the diamond structure

Both dots and circles represent carbon atoms. Each is bonded tetrahedrally by electron-pair bonds to 4 others. The same type of arrangement, but with 2 kinds of atoms, is possessed by SiC, CuCl, ZnS, and other compounds

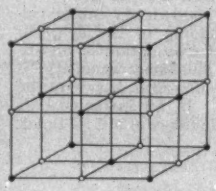


Fig. 6. A portion of the sodium chloride (NaCl) structure

Dots denote the centers of Na^+ (or Cl^-)ions; circles, the centers of Cl^- (or Na^+) ions. Many other ionic crystals have this type of arrangement

regular or semiregular structure. Liquid hexane, C_6H_{14} (see the dot formula given previously) contains groups of zigzag molecules having their chain axes approximately parallel to each other. In a liquid consisting of polar molecules, such as water, the positive ends (hydrogens) of each molecule tend to point toward the negative (oxygen) ends of other molecules. This gives a semiregular though constantly changing structure to the whole body of liquid. Sodium chloride is ionized in the liquid state as in the solid. The instantaneous arrangement in the liquid possesses some degree of regularity; this is a result of the tendency of each positive ion, Na^+, to have as immediate neighbors only negative ions, Cl^-, and the similar tendency of each negative ion to be surrounded by a shell of positive ions.

A *glass* lacks the regularity of arrangement of a crystal and the mobility of a liquid. Each atom vibrates about a fixed position, being restrained by the surrounding atoms. As in the case of liquid sodium chloride, each of the more positive atoms or ions (sodium, calcium, and silicon in ordinary glass) tends to be surrounded by more negative atoms or ions (oxygen) and *vice versa*.

In a water solution of an ionizing substance such as sodium chloride, each ion is *hydrated;* that is, it attracts and carries with it a shell of water molecules. The negative (oxygen) ends of these are closer to the central ion if it is positively charged; the positive (hydrogen) ends are closer if the ion has a negative charge. Occasionally, especially in concentrated solution, a water molecule in the shell surrounding a positive ion is replaced by a negative ion; likewise a positive ion occasionally enters the shell surrounding a negative ion.

Water solutions of polar but un-ionized molecules also are hydrated to some extent, the polar ends of these molecules attracting the ends of the water molecules having opposite polarity. In solvents which, unlike water, consist of molecules having little or no polarity, there is little solvation.

Some Properties of Atoms and Interatomic Bonds

Many physical and chemical properties of substances are closely related to the tightness with which the valence electrons of the component atoms are held. This may be measured by the *ionization energy*, the energy increase in the process of removing one electron completely from the atom:

$$M \longrightarrow M^+ + E^-$$

The ionization energies of some of the elements are given in Table II. These are in kilocalories per *gram atom*. One gram atom contains 0.6064×10^{24} atoms; it has a mass in grams equal to the atomic weight (1.008 g of H, 4.002 g of He, 16.000 g of O, etc.). To remove a second electron from an atom always requires more energy than to remove the first.

With some exceptions, for atoms with similar kernels (those in the same *row* of Table II) the greater the kernel charge the greater the energy required to remove a valence electron. Again with some exceptions, for atoms having the same kernel charge (those in the same *column* of Table II) the larger the atomic number the smaller the ionization energy. Elements with the smaller values of ionization energy are metals; those with the larger values are nonmetals.

Those elements having the greatest ionization energies have an attraction for an additional electron. The energy decrease in the change is called

$$X + E^- \longrightarrow X^-$$

the *electron affinity*. The electron affinities of F, Cl, Br, and I are about 98, 88, 83, and 76 kilocalories per gram atom, respectively.

It is evident from a consideration of the electron probability distribution in atoms that the "size" of an atom has no absolute meaning; however, *relative* sizes with a definite meaning can be determined. It is useful to define an *atomic radius* as "that distance which, when added to the corresponding 'radius' of another atom gives the equilibrium distance between the 2 in a molecule or crystal"; that is:

$$2r_c = d_{C-C} \qquad \text{and} \qquad r_C + r_H = d_{C-H}$$

Distances between atoms in a large number of molecules and crystals are known. It is found, however, that in general atomic radii are not additive. No set of radii can be obtained that will lead to the observed interatomic distances in substances of widely differing types.

An approach to additivity of radii is obtained if different sets of radii are used for different types of attractive forces between the atoms—one set for ionic compounds, another for atoms joined by electron-pair bonds, and a third for metals. Still greater additivity results if, for each of these classes, different sets of radii are used for different *coördination numbers*. The coördination number is merely the number of close neighbors. Some of the more useful and more accurately known radii are given in Table II.

As a rough rule, ionic radii for a coördination number (co. No.) of 8 are about 3 per cent greater

than those for a coördination number of 6. Similarly, octahedral atomic radii (co. No., 6) are about 5 per cent greater than the corresponding tetrahedral radii (co. No., 4). "Metallic" radii for a coördination number of 8 are about 3 per cent smaller than those for a coördination number of 12. In most cases, adding the proper radii together gives the corresponding interatomic distance correct to within 0.02×10^{-8} cm.

Table III gives relative values of the *negativity* of some atoms, for use in determining the direction and approximate magnitude of the polarity of different bonds. A bond between carbon (negativity, 2.6 units) and chlorine (negativity, 4.5 units) has a polarity of 1.9 units, the chlorine end of the bond being the more negative. Bond polarities are important in determining attractions between different molecules (hence melting and boiling points) and mechanisms of chemical reactions. A highly polar bond is more readily split "unsymmetrically" (both electrons of the shared pair remaining with the more negative atom) than "symmetrically" (one electron staying with each atom).

The strength of a bond may be measured by its *bond energy*, the energy that must be added to break the bond so that one of the shared electrons goes with each atom. Bond energy values are approximately additive if the bonds have little polarity. Since the N:N and Cl:Cl bonds have no polarity and the polarity of an N:Cl bond is very small, the bond energies of these bonds are about 34, 56, and 45 kilocalories, respectively, calculated from the nonpolar atomic bond energies given in Table III.

For more polar bonds the bond energy can be calculated quite roughly by adding to the *nonpolar bond energy*, obtained on the assumption of additivity, the *polarity energy*. This latter quantity is obtained by squaring the difference between the negativities (Pauling, 1932). If, for instance, it is desired to calculate the bond energy of a C:O bond:

Nonpolar bond energy = 42 + 17 = 59 kilocalories
Polarity energy = $(6.7 - 2.6)^2$ = 17 kilocalories

Total bond energy of C:O bond = 76 kilocalories

In an article of this length it is impossible to show adequately how the bulk properties of substances are related to atomic properties and to the arrangements of atoms. Such correlations, however, can be made and often are very enlightening. The more that is known about atomic structures and the forces between atoms, the more can be predicted about the structures, interatomic distances, forces, and energy relationships in aggregates of atoms and from these about the gross physical and chemical properties of different kinds of matter. A better understanding of these things is of use in many widely different fields of science and industry.

Table II—Ionization Energies and Ionic and Atomic Radii

		H						
		312						
	He	Li	Be	B	C	N	O	F
	564	*124*	*214*	*191*	*259*	*334*	*312*	*429*
(a)		0.60	0.31				1.40	1.36
(b)		1.35	1.07	0.89	0.77	0.70	0.66	0.64
(c)			1.11					
	Ne	Na	Mg	Al	Si	P	S	Cl
	495	*118*	*175*	*137*	*187*	*256*	*238*	*299*
(a)		0.95	0.65				1.84	1.81
(b)		1.70	1.40	1.26	1.17	1.10	1.04	0.99
(c)			1.59	1.43				
	A	K	Ca					
	361	*100*	*140*					
(a)		1.33	0.99					
(b)								
(c)			1.96					
		Cu	Zn	Ga	Ge	As	Se	Br
		177	*216*	*138*	*186*	*230*	*219*	*272*
(a)		0.96	0.74				1.98	1.95
(b)		1.35	1.31	1.26	1.22	1.18	1.14	1.11
(c)		1.28	1.37		1.39			
	Kr	Rb	Sr					
	322	*96*	*131*					
(a)		1.48	1.13					
(b)								
(c)			2.15					
		Ag	Cd	In	Sn	Sb	Te	I
		174	*206*	*133*	*168*	*192*	*206*	*241*
(a)		1.26	0.97				2.21	2.18
(b)		1.53	1.48	1.44	1.40	1.36	1.32	1.28
(c)		1.44	1.52	1.57	1.58	1.61		

Ionization energies in kilocalories per gram atom are shown in *italic* type.
(a) = Ionic radius (in 10^{-8} cm) for a coördination number of 6.
(b) = Tetrahedral atomic radius (in 10^{-8} cm) for a coördination number of 4.
(c) = "Metallic" radius (in 10^{-8} cm) for a coördination number of 12.

Table III—Nonpolar Atomic Bond Energies (*italic* numerals) and Negativities

H	C	N	O	F	kilocalories per gram atom
51	*42*	*17*	*17*	*32*	polarity units
0	2.6	4.6	6.7	9.6	
	Si	P	S	Cl	
	?	?	*32*	*28*	
	−0.7	0.5	2.1	4.5	
		As	Se	Br	
		44	*12*	*22*	
		0	0	3.6	
		Sb	Te	I	
		35 ?	*17*	*17*	
		0	0	1.9	

References

Crucibles, Jaffe. Simon and Schuster, N. Y., 1930.

Valence and the Structure of Atoms and Molecules, Lewis. Chem. Catalog Co., N. Y., 1923.

The Electronic Theory of Valency, Sidgwick. Clarendon Press, Oxford, 1927.

The Structure of the Atom, Andrade. G. Bell & Sons, London, 1927.

An Outline of Atomic Physics, Physics Staff of the Univ. of Pittsburgh. John Wiley & Sons, N. Y., 1933.

Atoms, Molecules and Quanta, Ruark and Urey. McGraw-Hill Book Co., N. Y., 1930.

The New Conceptions of Matter, Darwin. Macmillan, N. Y., 1931.

Chemistry at the Centenary (1931) Meeting of the British Assoc. for the Advancement of Science, W. Heffer & Sons, Ltd., Cambridge, Eng., 1932 (discussion on the structure of simple molecules).

The Structure of Crystals, Wyckoff. Chem. Catalog Co., N. Y., Second Edition, 1931.

Some Significant Results of Crystal Structure Analysis, Huggins. *Chem. Reviews*, v. 10, 1932, p. 427.

The Nature of the Chemical Bond, Pauling. *Jl. Am. Chem. Soc.*, v. 53, 1931, p. 1367.

Chemistry and Atomic Structure, J. D. Main Smith. D. Van Nostrand Co., Inc., N. Y., 1924.

Magnetism and Atomic Structure, Ed. C. Stoner. E. P. Dutton & Co., N. Y., 1926.

Polar Molecules, P. Debye. Chem. Catalog Co., 1929.

Dielectric Constant and Molecular Structure, C. P. Smyth. Chem. Catalog Co., 1931.

The Problem of Physico-Chemical Periodicity, Hedges and Myers. Longmans, Green, 1926.

Some Recent Changes in Our Attitude Towards the Nature of the Physical World, V. Karapetoff. *Jl.* Franklin Inst., v. 209, 1930, p. 361.

Engineers of the Next Generation

As the social and economic significance of engineering becomes plainer every day, the world looks to the engineer of the future as a leader capable of shouldering broader social responsibilities. The organization of the Engineers Council for Professional Development is the first step in preparing the coming generation of engineers for the tasks ahead. This paper describes the formation, aims, and activities of E.C.P.D. and espouses its importance.

By
C. F. HIRSHFELD
ASSOCIATE A.I.E.E.

Detroit Edison
Detroit, Mich.

THE engineering profession of today is charged with the education and other preparation of the next generation of engineers. If it does not address itself to this task and with a full realization of its own shortcomings, this next generation will find itself as handicapped as the profession is now. In the Engineers' Council for Professional Development an organization capable of taking the first steps in the desired direction has been created, and it contains the potential power to develop a united engineering profession that knows where it is headed and how to get there. Not that huge affairs can be planned in advance and completely controlled in progress (as is now so commonly believed, possibly in desperation); but, that affairs which are of such small magnitude and are influenced by so few factors that they can be encompassed completely or nearly so by human mentality, are much more likely to maintain an ordered and intelligent course if properly planned in advance and properly supervised later.

A large part of the proposed activities of E.C.P.D. has to do with engineering education in the broadest interpretation of that term. It contemplates a conscious planning and a conscious following of the education of individuals to the end that they may be able best to fill their places in the world. In fact, all else thus far contemplated is nothing more than the setting up of yardsticks to determine the acquisition of such education and the formulation of names and definitions.

The E.C.P.D. is not the end and all, nor is its organization perfect or its program complete and flawless; but it possesses the required potentialities for achieving its aims and it is capable of functioning advantageously now, while we are engaged in learning from experience where and how it and its program should be changed. The organization of the E.C.P.D. came about largely as a result of recognition on the part of the profession of the following facts:

1. More than half the states in this country have laws for licensing engineers, requiring the establishment and maintenance of state boards to perform the function of licensing, and it is very probable that the other states will enact similar laws shortly.

2. To be effective these licensing laws must define in some way both the education and other training and the degree of accomplishment required of a candidate for license.

3. Laws already in existence indicate that state licensing boards will adopt lists of accredited engineering schools. In other words, these bodies, which are likely to be more or less political in character in at least some states, will be authorized by law to determine which engineering schools of the nation meet acceptable standards in their respective states.

4. There are wide variations between the laws for licensing engineers in the different states. It is a bit disconcerting to discover that a man proclaimed by one state as an individual perfectly competent to practice engineering is, by law, wholly incompetent to practice engineering in another state.

These facts are just as important in connection with engineering education as are the characteristics of electric circuits in certain electrical engineering problems, and they may be expected to modify greatly the profession of engineering as the next generation of engineers will live and practice it. No longer will an individual be free to go his own way in a professional sense. He must meet criteria written into the law of the land; he must conform to certain requirements of the law. In short, whether we like it or not and whether we believe in it or not, the states have come or are coming to the conclusion that the public weal requires the state licensing of engineers and all that that involves; and it involves, among other things, the evaluation of the courses given in our engineering schools.

In accordance with its sovereign rights each state may set the minimum definition of an engineer for its own purposes according to its own discretion. Nothing that any outside body can do, unless our federal government finds new constitutional powers, can force a state to formulate or to adopt a definition not to its own liking. The necessity for professional guidance in the formulation of these laws is obvious.

Medical Profession Sets Example

The engineering profession may profit by the experience and activities of the medical profession which has had this problem before it for many years. That profession long ago adopted a very farsighted policy. Working through a competent and almost militant professional organization it has molded legislation and the enforcement thereof to the general good of both the profession and the public. As in the medical profession, there are great differences between the different fields of engineering practice; but the success of the national organization in those matters having to do with the educational, legal, and professional aspects of the medical profession should

Full text of a paper recommended for publication by the A.I.E.E. committee on education, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 27, 1934; released for publication May 1, 1934. *Not published in pamphlet form.*

lend encouragement to a somewhat parallel organization movement among engineers.

The engineering profession has recognized differentiation very clearly, in fact too clearly. It has not seen the forest for the trees. The characteristic of engineering is the universal use of the engineering method. It is the common bond between engineers. Specialization consists only of the application of this method to certain specific types of problems. The history of engineering gives many examples of engineers of such superlative mentality that they were capable of using this method in many of, if not all, the different fields of engineering specialization. It is important that the engineering profession should act in a unified way, both as individuals and as differentiated groups. Differentiation into groups is purely a matter of convenience or a concession to limited mentality; certainly it is not at all fundamental. A comprehensive national organization of the engineering profession is not only possible but essential. Such an organization must exist and function effectively if the engineer and the engineering profession are to meet the demands of government, industry, and, in fact, social and economic progress in the immediate and distant future. The coming generation of engineers will call us remiss if they do not find such an organization ready to their hands.

Many practicing engineers are so busy with daily problems that they do not have time to mix with and obtain the views of those who shortly will replace them. There has appeared recently a very marked change in the viewpoint of the younger men. They no longer are satisfied to enter an unorganized profession functioning only through a member of specialized national societies. They insist that the profession shall be organized in such a way that it can function as a unit in those matters having to do with its social and economic problems. Although history shows us that in many respects the ideas and ideals of youth become very similar to those of the older generation, as experience is acquired, it also shows that there are significant differences between generations. The recognition of the need for a comprehensive national organization appears to be one of the ideas that the younger generation will carry over with it.

Formation of E.C.P.D.

Recently there has been formed a joint body known as Engineers' Council for Professional Development. It was organized to fill the need for a joint engineering body that could represent the engineering profession properly and effectively with respect to certain types of problems and activities. Space does not permit detailing these causative phenomena, but 5 of the most outstanding ones are enumerated briefly.

1. There was, for example, the very insistent demand of the younger generation of engineers already mentioned.

2. There was a feeling on the part of certain farsighted men connected with the state licensing of engineers that the engineering profession could and should coöperate in the formulation of criteria and methods to be used by those licensing boards. These men, themselves engineers of attainment and with high ideals for the engineering profession, feared that state licensing boards and practicing engineers might not coöperate on problems demanding joint action for the good of the public and of the profession.

3. The third driving force was the realization by engineering educators of the significance of some of the powers that had been given state licensing boards. These boards, acting independently, were empowered to compile lists of accredited schools of engineering. Certain early attempts at such activities by some of the boards caused consternation among a few of our best known engineering educators.

4. Further, industry and the nation at large were recognizing more and more the need for the development of engineers who, while well trained technically, should also be more broadly educated so that they possessed knowledge and ability in other fields of human history and activity. The leaders in such thought recognized that the production of well rounded engineers would involve more than a mere college education, good as that might be made. They conceived the necessity for a nation-wide organization that could guide men in postgraduate self-education. They recognized the probability that in the course of time such broadening study might well become a prerequisite to acceptance into the profession as a fully competent engineer.

5. Finally, certain engineers prominent in the affairs of different engineering societies had become convinced that there existed a real need for a joint body to represent the engineering profession as a whole in matters having to do with the educational, legal, and professional aspects of the engineer's life.

The E.C.P.D. was formally organized by the American Society of Civil Engineers, American Institute of Electrical Engineers, The American Society of Mechanical Engineers, American Institute of Mining Engineers, American Institute of Chemical Engineers, Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners.

Program and Activities of E.C.P.D.

This joint body consists of representatives named by the parent organizations. It has delegated powers only; that is, it is not authorized to act until instructed by the parent bodies. It constitutes an instrumentality through which the engineering profession, considered in its broadest aspect, not only may express its opinions and desires, but also may become effective in action. It gives the engineering profession a reason for uniting. It does not detract any powers from any existing organization; it does not propose to do so.

The immediate program of E.C.P.D. is briefly:

1. Proper selection and guidance of prospective engineering students.

2. Development and maintenance of proper and effective curriculums in schools of engineering.

3. Effective guidance in such postgraduate, self-education as is deemed necessary to produce a well rounded engineer. Incidentally, provision also is made for the guidance and assistance of those who desire to study engineering without attending a recognized school of engineering.

4. Coöperative agreement upon and enforcement of the degrees of achievement or accomplishment that should be attained by an individual as he mounts the rungs of the ladder leading to the status of a full fledged engineer.

In spite of the simplicity of these statements, and of the essential simplicity of the aims themselves, the actual conduct of the program is fraught with great difficulties. By no means the least springs from the individualistic characteristics of the engineer and of existing institutions. He and his insti-

tutions give ready lip service to the program that these institutions already have approved in a general sense, but the units of that program are not always considered as parts of a whole; they sometimes are considered only in their effect upon some conventional thought process or some existing way of doing things. This is but human and is to be expected. But, one might be sufficiently idealistic to hope that the engineer who prides himself on the recognition of fact and upon clear and impersonal thought could rise above such petty considerations to view matters of this sort in the light of the profession as a whole and of the advancement of the profession.

An example may serve to illustrate the sort of difficulty referred to. After lengthy and careful consideration E.C.P.D. decided to recommend that it be authorized to prepare and maintain a list of accredited engineering schools. This recommendation was made by duly accredited representatives from the professional engineering societies, from S.P.E.E. and from the national organization of state boards of engineering examiners so that all parties in interest are represented. The recommendation indicates it to be the considered judgment of these individuals that such a centralized and representative body as E.C.P.D. should accredit these schools. Now what happens when this recommendation is received by the parent bodies whose favorable action is required before any active work can be undertaken? Is there the universal recognition of facts to be expected from engineers and the consideration of the subject in the light of those facts and in a broad way? On the contrary we find in some cases a very human tendency to ignore the broader question and to concentrate upon details. The facts of the matter are that the state engineer licensing boards must prepare lists of accredited schools; the national organization of the members of these boards must prepare such a list. These men and the national society devoted to engineering education have said through E.C.P.D. to the engineers of the country, "Here is a task which merits the best judgment of all of us. We must have such lists. We would prefer that we arrive at them coöperatively. We invite your help." Would it not be most in the line of engineering thought to recognize that there is to be such accrediting and that it probably will be done best by coöperation?

No one really knows the best method to use in accrediting engineering curriculums, but the author maintains that discussion of the method to be used properly comes after a decision regarding the major proposition. Certain costs are involved, but this fact need not preclude the approval of the general principle subject to a later satisfactory solution of the problem of defraying those costs. Is not the question very simply this: If there must be accrediting, should engineers recognize the desirability of national accrediting by a most representative body, or should the matter drift until there are almost innumerable lists, differing widely among themselves and serving the individual purposes of small and disconnected bodies? There is but one answer: The engineer stands for organization properly set up and smoothly functioning. The alternative of favorable action in this case leads to the worst kind of disorganization or, at least, lack of organization.

Permanent Value of E.C.P.D.

The formation of E.C.P.D. is an almost spontaneous recognition of a radical change in the status of the engineering profession. It is the culmination of many more or less obscure movements which combined toward the formulation of a comprehensive national organization of engineers representing the educational, legal, and professional aspects of the engineer's life. Its formation does not represent a consciously planned march of an organized army across country. Instead it suggests the rather blind, instinctive concentration upon a central point by small groups coming from all possible directions. It is probable, therefore, that E.C.P.D. is not a temporary creation set up to meet a seeming need of the moment, but that it is in reality an instrument, still imperfect, for meeting a real and permanent need of our social and economic structure. It is demanded by our social evolution. It might have been initiated differently; it might have been constituted differently; its program might have been worded differently; but it was inevitable.

The organizing of E.C.P.D. is the first step in preparing matters for the coming generation of engineers. The world is becoming conscious of the social and economic significance of engineering as never before. It is already demanding a greater responsibility on the part of the engineer for the changes that his works have brought about; and, in very plain language, it finds a dearth of engineers trained and experienced to carry the responsibilities that the world desires to place upon their shoulders. The engineering profession has arrived at the point corresponding to the place in the medical profession where the witch doctor is replaced by the student of anatomy, pathology, and drugs, but the stage of public health officers and of public sanitation has not yet been reached. Engineers can handle individual engineering problems, but are not prepared to accept their share of national responsibility in the further evolution of the social and economic structure that they are influencing more and more.

The writer does not refer to the depression out of which we appear to be emerging and to the causes thereof, but to a process that has been going on for several centuries and has been particularly active in the past half century. Lawyers, military men, and business men still are wrestling with problems that engineers have created. This is not because these men are preëminently fitted for such tasks. They themselves frequently admit this. They are required to carry a disproportionate share of the burden because hitherto the engineer has not deemed it necessary to prepare himself to share such burdens.

As a comprehensive national organization, E.C.P.D. represents a very reasonable starting point, and the governing bodies of its parent organizations should become thoroughly cognizant of its aims and activities. If these governing boards can do this, no essential difficulty will be placed in the way of carrying through this epoch-marking movement.

The "Compandor"—An Aid Against Radio Static

By
R. C. MATHES
MEMBER A.I.E.E.

S. B. WRIGHT
MEMBER A.I.E.E.

Bell Telephone Labs.,
New York, N. Y.

One of the important conditions that must be met by any speech transmission system is that it should transmit properly a sufficient range of speech intensities. In long wave radio telephony, even after the speech waves are raised to the maximum intensity before transmission, there remain energy variations such that weak syllables and important parts of strong syllables may be submerged under heavy static. The "compandor" is an automatic device which compresses the range of useful signal energy variations at the transmitting end and expands the range to normal at the receiving end, thus improving the speech-to-noise ratio. This paper deals with some of the fundamental characteristics of speech waves and explains how the task of changing them for transmission over the circuit and restoring them at the receiving end is accomplished.

WHEN the original New York-London long wave radio-telephone circuit was designed, it was recognized that radio noise would often limit transmission, especially for the weaker voice waves. Accordingly, provision was made for manually adjusting the magnitude of the speech waves entering the radio transmitters to a value that would load these transmitters to capacity.[1] Although this treatment was very effective in improving the average speech-to-noise ratio and in preventing the strong peaks of speech from overloading the transmitter, it was, of course, unsuitable for following the rapidly varying amplitudes of the various speech sounds.

The total range of significant intensities applied to the circuit is in the order of 70 db, an energy ratio of 10 million to 1. The manual adjustments already referred to were successful in reducing this range to about 30 db. To reduce further this residual range an interesting device called the "compandor" has been developed. This device, which works automatically, makes a further reduction of one-half in the residual db range so that the range transmitted over the circuit then is only 15 db, an energy ratio of about 32 to 1. Advantages gained through the use of the "compandor" may be summarized as follows:

1. The allowable increase of about 5 db in noise before reaching the commercial limit increases the time when the circuit can be used for service. The increased circuit time is greatest in the seasons of the year when it is needed the most.

2. For conditions of moderate disturbances now classed as commercial, a reduction of the noise transmission impairment to very low values is accomplished by the compandor.

3. The improvement in the operation of voice controlled relays results in delivering substantially higher volumes to the subscribers.

4. The beneficial effect of the compandor might alternatively be applied to a reduction of transmitted power.

Speech Energy

Quantitative designation of speech intensity, and hence of a range of intensities is rendered difficult by the rapidly varying amplitude characteristics of the various speech sounds. Devices called volume indicators are used fairly extensively to indicate the so-called "electrical volume" of speech waves. (The term "volume" will be used through the rest of this paper to designate this quantity and not as synonymous with loudness.[2]) A volume indicator is essentially a rectifier combined with a damped d-c indicating meter on which are read in a specified manner the standard ballistic throws due to partly averaged syllables at a particular speech intensity. These devices are so designed and adjusted that they are insensitive to extremely high peak voltages of short duration, but their maximum deflection is approximately proportional to the mean power in the syllable. It has been found that, if commercial telephone instruments are used, the ear does not detect amplifier overloading of the extremely high peaks of short duration. Consequently, the volume indicator is a useful device for indicating the noticeable repeater overloading effect of a voice wave. These devices do not reveal much about the effect of the weaker voltages in overriding interference or operating voice-operated devices but they give a fairly satisfactory indication of loudness and possibilities of interference into other circuits.

The sound energy that the telephone transmits consists of complicated waves made up of tones of different pitch and amplitude. The local lines and trunks connecting the telephone to the subscribers' toll switchboard have little effect in changing the fundamental characteristics of these waves but, on account of various amounts of dissipation, the waves received at the toll switchboard always are weaker than those transmitted by the telephone. Furthermore, the strength of signals varies with the method

Full text of a paper recommended for publication by the A.I.E.E. communication committee, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Virginia, June 25–29, 1934. Manuscript submitted March 22, 1934; released for publication April 13, 1934. *Not published in pamphlet form.*

of using the telephone, loudness of talking, battery supply, and transmitter efficiency. The subscriber may be talking over a long distance circuit from a distant city, in which case the loss of the toll line further attenuates the received waves. The curve in Fig. 1 (plotted on so-called "probability paper," in which the scale is such that data distributed in accordance with the "normal law" will produce a straight line) shows that the range of outgoing speech volumes as measured by a volume indicator at the transatlantic switchboard at New York is nearly 40 db for terminal calls. When via calls and variation in volume of the individual talker are taken into account, it is even greater than 40 db.

Volume Range of a Telephone Circuit

There are 2 limits on the range of volumes which a system can transmit. The upper limit of volume is set by the point at which overloading appreciably impairs the signal quality or endangers the life of the equipment. It is an economic limit set by the cost of building equipment of greater load capacity.

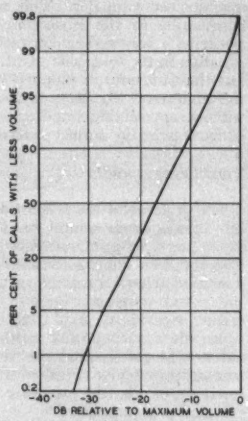


Fig. 1. Range of outgoing speech volume of 950 local subscribers at New York transatlantic switchboard as measured from January to April 1931

The lower limit of volume is set by the combination of the amount of attenuation and the amount of interference in the system such that the signal should not be masked appreciably by noise. This also is ordinarily an economic problem depending on the cost of lowering the attenuation or of guarding against external interference. In some cases, however, this limitation is a physical one. A striking case is that of radio transmission in which there is no means of controlling the attenuation of the electromagnetic waves in transit to the receiving station. They may arrive at levels below those of thermal[3,4] noise in the antenna and other receiving apparatus. Thus, even in the absence of static, there is a definite useful lower limit to the received and hence the transmitted volume. In such cases the problems raised by the spread in signal intensities become a matter of particular importance. Radio telephony, therefore, was one of the fields of use particularly in view for the development of the device to be described.

Effect of Volume Control

Until recently the only method in use for reducing the range of signal intensities on radio circuits was a special operating method for constant volume transmission. At each terminal the technical operator, with the aid of a volume indicator, adjusted the speech volume going to the radio transmitter to that maximum value consistent with the transmitter load capacity.

In Fig. 2 is shown the normal relation of input to output intensities of a zero loss transducer as given by the diagonal line. Points A_{max} and A_{min} on this line indicate the extreme values of signal intensities for sustained loud vowels covering a volume range of 40 db. The effect of the volume adjustments made by the technical operator is to bring all the applied volumes to a single value indicated by point B. The value of B could be any convenient intensity. Here it is set at a value determined by transmission conditions in the line between the technical operator's position and the radio transmitter.

As the technical operator has reduced the strongest volumes 5 db and increased the weakest volumes 35 db, the result of this volume control is to increase the volume range which the circuit can handle by 40 db. Through the use of voice controlled switching arrangements[5] which permit transmission in only 1 direction at a time, it is possible to make this adjustment for 2-way transmission in the case of radio circuits without danger of singing. By this method of operation, volumes initially strong or weak are

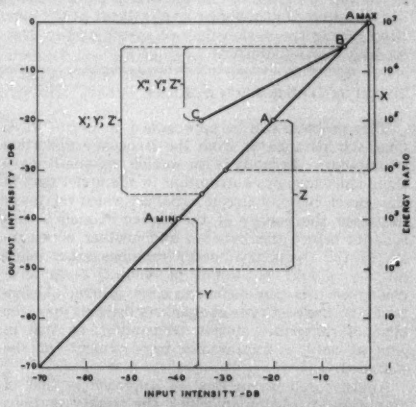


Fig. 2. Range control; the diagonal line indicates normal relation of input to output intensities of a zero loss transducer

delivered to the distant receiving point with equal margins relative to interference and the transmission capacity of the whole system is improved thereby.

Intensity Range at Constant Volume

However, even with speech adjusted to constant volume at the transmitting point, there are large variations in signal intensity from syllable to syllable and within each syllable. For example, the energy of some consonants as compared with the stronger vowels is down about 30 db. The importance of the weaker sounds is brought out by the fact that in the case of commercial telephone sets a steady noise 30 db below the energy in the strongest parts of the speech syllables produces an appreciable impairment in transmission efficiency. Accordingly, it is desirable to maintain transmission conditions such that generally more than this range is kept free from the masking effect of noise. This range of intensities within the syllable also is of importance in the operation of the voice controlled switches used in the radio system. The sensitivity spread between a voice operated relay which just operates on the crests of loud syllables and one which operates sufficiently well not to clip speech also is about 30 db.

Considering that in Fig. 2 the coördinates are in terms of the average rms value over a period of time small compared with the time of a syllable, there is a spread of at least 30 db in signal intensity extending down from the maximum for each talker. Thus for the weakest talker this spread is indicated by the bracket Y and for the strongest, by X. Any other talker, as Z, falls somewhere in between. After manual control of volume this spread of intensities is represented by the bracket X', Y', Z' for all talkers. This residual spread makes desirable a means for further compressing the range of intensities in the speech signals so that the weaker parts of sound are transmitted at a higher level without at the same time raising the peak values of speech and so overloading the transmitter.

Types of Compression Systems

This problem can be approached in several ways. One, for instance, is from the frequency distortion standpoint. As many of the weaker consonants have their chief energy contribution in the upper part of the speech band, a simple equalizer which relatively increased the energy of the higher frequency consonants before transmission and another which restored the frequency energy relations after transmission should be found of value. Tests have confirmed this expectation to some degree. Unfortunately, the best type of equalizer depends upon the type of subscriber station transmitter, so that in general only a compromise improvement can be obtained.

Another general method of approach is that of amplitude distortion in which the weaker portions of the syllable are automatically increased in intensity in some inverse proportion to their original strength. The manual control of volume described may be considered the genesis of this method. Early suggestions[6] included the use of an auxiliary channel such as a telegraph channel for duplicating the control operations in the reverse sense at the receiving end, thus restoring the original energy distribution. Another early suggestion along this line was made by George Crisson of the American Telephone and Telegraph Company.[7] If a voltage be applied to a circuit consisting of a 2-element vacuum tube (with a parabolic characteristic) in series with a large resistance, the instantaneous voltages across the tube are approximately the square root of corresponding voltages applied. Thus a voltage originally 1/100 the peak voltage can be transmitted at an intensity of 1/10 the peak, or 10 times its original intensity. If the instantaneous energy is expressed on the logarithmic or db scale the energy range is then cut in half. Such a device may be called an instantaneous compressor. At the distant end a circuit that is simply the inverse of that at the transmitting end is used. The output voltage is taken off of a low resistance in series with a parabolic element, thus restoring the signal substantially to its original form. This circuit may be called an instantaneous expandor. This scheme was tested successfully in the laboratory, but unfortunately possesses a very serious limitation for practical application in the telephone plant. This is due to the fact that, to maintain properly the characteristics of the compressed signals, a transmission band width without appreciable amplitude or phase distortion of about twice the normal proved necessary.

The "Compandor"

The principle of the present device is the use of a rate of amplitude control for the compressing and expanding devices intermediate between manual and instantaneous control, which may be considered approximately as a control varying as a function of the signal envelope. Such a modulation of the original signal in terms of itself does not appreciably widen the frequency band width of the modified signal as compared with the original signal. The transmitting device is called the compressor; the receiving device, the expandor; and the complete system, the "compandor."

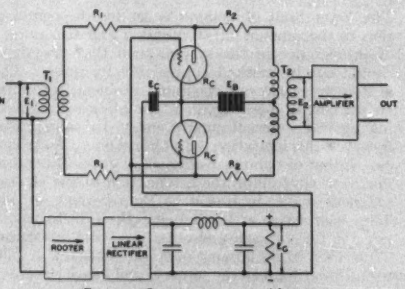


Fig. 3. Compressor circuit No. 1

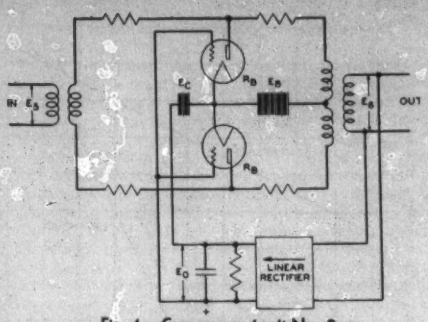


Fig. 4. Compressor circuit No. 2

The functional behavior of a typical compressor may be considered with reference to the simplified schematic circuit No. 1 of Fig. 3. This circuit is of the forward acting type; that is, the control energy is taken from the line ahead of the point of variable loss. The variable loss consists of a high impedance pad connected in the circuit through 2 high ratio transformers T_1 and T_2. The high resistances R_1 and R_2 are shunted by a pair of control tubes connected in push-pull. The push-pull arrangement is desirable for 2 reasons. It reduces the even order non-linear distortion effects caused by the shunt path on the transmitted speech and it balances out the control impulse and unfiltered rectified speech energy from the control path which might otherwise add distortion to the speech. The impedances of these tubes are controlled by the control voltage E_G which is roughly proportional to the envelope of speech energy and which is derived from the line through a non-linear or "rooter" circuit (so-called because the output is proportional to a root of the input, see eq 4), a linear rectifier and a low-pass filter which may have a cutoff frequency in the range 20 cycles to 100 cycles. In the following analysis it is assumed that the delay due to this filtering is negligible.

Let E_1 = rms speech voltage at input
and E_3 = rms speech voltage at output in same impedance
R_C = a-c impedance of control tubes.

Now if R_C is kept small compared to the pad impedance, we have approximately

$$E_3 = k_1 E_1 R_C \tag{1}$$

Let E_G be the control voltage applied to the grids of the control tubes. With the plate voltage E_B just neutralized by the steady biasing grid voltage E_C, then only E_G may be considered as determining the space current and we may assume ideally that the space current

$$I_B = k_2 E_G^s$$

$$\text{Then } R_C = \frac{dE_B}{dI_B} = \mu \frac{dE_G}{dI_B} = \frac{1}{k_3 E_G^{s-1}} \tag{2}$$

where s is determined by tube design and the k's are constants for constant μ tubes. For variable μ tubes eq 2 can be used to set requirements on the tube design. From eqs 1 and 2

$$E_3 = \frac{k_1 E_1}{k_3 E_G^{s-1}} \tag{3}$$

Now let the rooter be a non-linear circuit such that the instantaneous voltage is the tth root of E_1. After rectification and filtering we will have approximately

$$E_G = k_4 E_1^{\frac{1}{t}} \tag{4}$$

From eqs 4 and 3 we have

$$E_3 = \frac{K E_1}{E_1^{\frac{s-1}{t}}} = K E_1^{\frac{t-s+1}{t}} \tag{5}$$

If $t = s = n$

$$E_3 = K E_1^{\frac{1}{n}} \tag{6}$$

Now if the input voltage be increased by a factor x, the input increment in db will be 20 log x. The new output will be

$$E_3' = K(xE_1)^{\frac{1}{n}}$$

The increment in output in db will be

$$20 \log \frac{E_3'}{E_3} = 20 \log x^{\frac{1}{n}} = \frac{20}{n} \log x$$

The ratio of the output increment to the input increment in db is $\frac{1}{n}$ and the device is said to have a compression ratio of $\frac{1}{n}$. In other words, the per cent change in relative speech voltages in passing through the compressor is the same at all points in the intensity range. In the general form of this circuit t and s need not be equal to secure a particular value of $\frac{1}{n}$.

In Fig. 4, compressor circuit No. 2 is shown, a backward acting type of circuit. In this circuit the control tubes can be used to perform the function of the rooter in circuit No. 1 when $s = t = n$. We may write for this circuit

$$E_4 = k_1 E_3 R_B$$

$$E_G = k_2 E_4$$

$$R_B = \frac{1}{k_3 E_G^{n-1}} = \frac{1}{k_4 E_4^{n-1}}$$

$$E_4 = \frac{k_1 E_3}{k_4 E_4^{n-1}} = K E_3^{\frac{1}{n}} \tag{7}$$

which is the same as eq 6 for circuit No. 1.

In Fig. 5 is shown the expandor circuit. If the resistances r are kept small compared with those of the control tubes, we may write

$$E_3 = \frac{k_1 E_7}{R_x}$$

$$E_x = k_2 E_7$$

$$R_x = \frac{1}{k_3 E_x^{n-1}} = \frac{1}{k_4 E_7^{n-1}}$$

$$E_3 = K E_7 E_7^{n-1} = K E_7^n \tag{8}$$

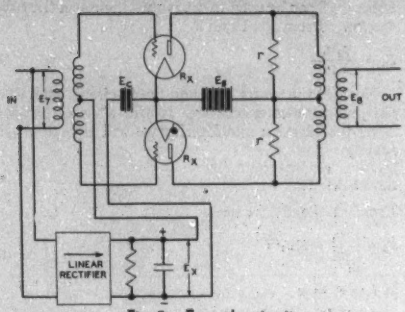


Fig. 5. Expandor circuit

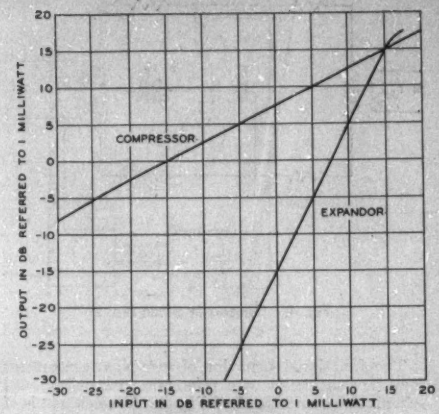


Fig. 6. Experimental input-output characteristics; 1,000 cycles steady state

This relation is just the inverse of that given in eqs 6 and 7. The increment ratio in db of output to input is n and the expansion ratio may be said to be n. When a compressor and expandor having the same value of n in their indices are put in tandem, the final output and input intensity ranges are the same. However, between the compressor and expandor the range of signal intensities, whose rate of change is not faster than the usual syllabic envelope, is $1/n$ in terms of db. In terms of voltage ratios the intermediate signal intensities are proportional to the square root of their original values if $n = 2$, the cube root if $n = 3$, etc.

The ideal relations postulated above cannot all be met in the physical design of the circuits. The indices s and t must be the dynamic characteristics of the tube and circuit and can be held to constant value only over limited ranges of operation. Equation 2 is only approximately true as some space current is permitted to flow when no speech is passing; otherwise, impractical values of control impedances would be involved. However, they do serve to illustrate the functional operation and can be approximated sufficiently well in commercial equipment for useful amounts of compression and expansion. Fig. 6 shows experimental steady-state input versus output characteristics for devices built to have a compression ratio of $^1/_2$ and an expansion ratio of 2.

The compressor is seen to operate substantially linearly over a 45-db range of inputs and the expandor over a 22.5-db range. This is about as much range as can be secured conveniently from a single stage of vacuum tubes. As such ranges would be entirely insufficient to handle the seventy odd db range at speech intensities, it is necessary to control volumes to a given point before sending through these devices, rather than compress or expand first and then control. The range is adequate, however, to take care of the range of signal intensities for commercial speech at constant volume.

Effect of Compandor

The compressor curve of Fig. 6 indicates that, when the input is 15 db above 1 milliwatt, the compressor gives no gain or loss. If the levels are adjusted so that this point corresponds to the intensity at point B on Fig. 2, then the line BC indicates the compressed intensities corresponding to the assumed 30 db spread of speech controlled to constant volume. The new range of intensities as indicated by the bracket X'', Y'', Z'' is now finally reduced to about 15 db. Tests show that a volume indicator on the output of the compressor reads from 1 to 2 db higher than on uncompressed speech at its input. Compressed speech sounds slightly unnatural but the effects of compression upon articulation in the absence of noise are negligible.

In considering the action of the expandor it is important to note that all of the improvement in signal-to-noise ratio is put in by the compressor. Considering any narrow interval of speech the insertion of the expandor does not change the signal-to-noise ratio. The desirability of using it depends on other reasons. First, it restores the naturalness of the speech sounds. Second, the apparent magnitude of the noise is greatly reduced since noise comes in at full strength only when speech is loudest and is reduced by the loss introduced by the expandor at times when the energy is low between syllables. When no speech is being transmitted, noises up to a certain limit, which corresponds to the maximum energy in received speech, are reduced in varying amounts from about 20 db to zero depending on their value.

When speech is present the effect of the expandor is determined by the sum of the instantaneous speech and noise voltages, so that the effect on the noise, whether it is large or small, is determined largely by the existing speech intensity. For a circuit having somewhere near the limit of static, the use of the compandor allows on the average 5 db more noise than when it is not used. When the noise is less than this limit, somewhat greater improvements are

obtained from the compandor, ranging up to at least 10 db.

The particular values of compression and expansion ratio were chosen initially for the relative ease in the design of the system with commercially available vacuum tubes whose characteristics closely approximated a parabola. Tests of the equipment have shown that this degree is sufficient for present telephone circuit intensity range requirements. Increasing the amount of compression is limited by ncrease in quality distortion and by increased variation in the intensity of radio noise as heard by the listener A noise which is constant at the nput to the expandor varies on the output as the speech intensity changes. Also variations in attenuation equivalent between the compandor terminals are multiplied by the expandor. Herein lies a reason

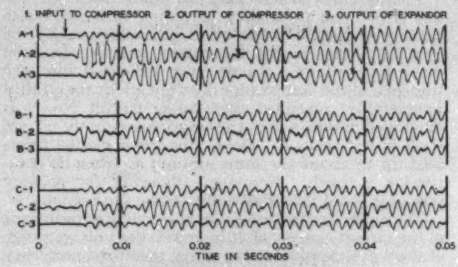


Fig. 7. Oscillograms showing operation of compandor on beginning of word "bark"

A—Compressor circuit No. 1
B—Compressor circuit No. 2 with low pass filter in control circuit
C—Compressor circuit No. 2 without filter

for having a constant compression and expansion ratio over the working range. If it were different at different intensities, attenuation changes would distort the reproduced speech as well as appearing as a somewhat increased change in intensity. This change in intensity is n times the attenuation change in front of the expandor in db.

The degree of compression obviously may be controlled in a variety of ways; such as using different values for the indices s and t, applying control voltages upon more than one variable stage in tandem, the use of variable μ vacuum tubes, etc. The circuits as shown use variable shunt control for the compressor and variable series control for the expandor. Either or both may be changed to the other by inverting the polarity of the control potential and properly designing the rectifier characterist cs of the control circuits.

There are 2 major sources of possible speech distortion that must be considered in the design and use of these devices in addition to those ordinarily present. The first is due to the non-linear characteristics of the vacuum tubes used for controlling. The even order distortion terms are largely balanced out by using 2 tubes in a push-pull arrangement. The remaining distortion is minimized by having speech pass through the control tubes at a sufficiently low level. In the operating ranges for the device shown in Fig. 6, the harmonics of a single-frequency tone are 30 db or more below the fundamental.

The second major source of distortion is the time lag in the control circuits due to the presence of the filters after the linear rectifier. However, with a complete compandor circuit using the compressor circuit No. 1, it was found on careful laboratory tests with expert listeners that it was almost impossible to distinguish whether the device was in or out of circuit. Furthermore, distortion of this type is largely eliminated when compressor circuit No. 2 is used. In that case it may be noted that, if both terminals are connected by a substantially distortionless transmission system, the identical control circuits of both devices receive identical operating voltages. As the gain changes put in are reciprocal and occur now with equal time lag, the deviations from ideal compression are virtually counterbalanced by the inverse deviations from ideal expandor action. In Fig. 7 are shown oscillograms taken of the first part of the word "bark." Each record shows the intensity changes before the compressor, between the compressor and expandor and on the output of the expandor.

Fig. 8. Experimental installation of compandor at New York

Application to Transatlantic Circuit

A compandor system has been in service on the New York-London long wave radio telephone circuit since about July 1, 1932. At first compressor circuit No. 1 was used, and later a change was made to compressor circuit No. 2. In Fig. 8 is shown the experimental installation at New York. It occupies about 5 ft of standard relay rack space. The blank panel shown indicates the saving of apparatus resulting from the change to compressor circuit No. 2.

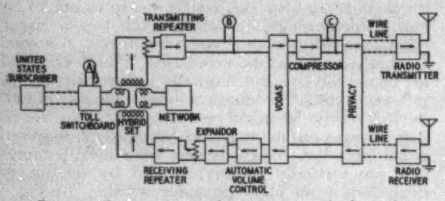


Fig. 9. Compandor applied to one end of a radio telephone circuit

The schematic diagram of Fig. 9 shows the method of inserting the compressor and expandor in the radio telephone terminals at each end of the circuit. Since the 2 ends are similar, only one end is shown. The compandor circuits are indicated in their relation to the subscriber, the toll switchboard, the vodas and privacy apparatus, and the radio transmitter and receiver.[5] A meter located at the point designated A would indicate the full range of applied volumes, at B, the controlled volumes and at C, the compressed speech signals.

When the United States subscriber talks, electrical waves set up by his voice pass over a wire line to the toll switchboard. They then divide in a hybrid set; part of the energy is dissipated in the output of a receiving repeater and part is amplified by a transmitting repeater whose gain is controlled by noting the reading of a volume indicator at B and adjusting a potentiometer ahead of the transmitting repeater. The waves then act on the vodas which consists of amplifier-detector, delay circuit and relays for switching the transmission paths in such a manner as to prevent echoes, singing, and other effects. When in the transmitting condition, the vodas is arranged to have zero loss so that the waves impressed on the compressor are practically the same as at B. The waves put out from the compressor are then sent through the privacy apparatus, the output of which is then sent over a wire line to the radio transmitter. The radiated waves are picked up by the distant radio receiver, amplified and transformed into voice-frequency energy which passes over a wire line to the terminal at the distant end.

The path of received waves in either terminal may be traced in the lower branch of the circuit shown in Fig. 9. After being made intelligible by passing through the receiving privacy device, the compressed incoming waves are sent through the vodas into an automatic volume control and then into the expandor. The expanded waves are sent through a receiving repeater from whose output the amplified waves pass into the hybrid set, part being dissipated in the network and the other part going through the toll switchboard to the subscriber. Due to imperfect balance between the subscriber's line and the network, a portion of the received energy is transmitted across the hybrid set and amplified by the transmitting repeater. This echo might operate the transmitting vodas under certain conditions. For this reason a potentiometer is inserted in the receiving branch of the circuit so as to reduce the echo, and consequently the received volume, so that false operation of the transmitting vodas is prevented.

Results of Compandor Operation

Effectiveness of the compandor in service depends not only upon its ability to reduce noise, but also upon its relation to the other characteristics of the circuit. Tests in the laboratory and on the long wave transatlantic circuit have indicated that the presence of the compandor does not affect the quality appreciably, provided compressor circuit No. 2 is employed and provided the compression in the circuit itself is not serious. Delay distortion can be tolerated up to about the same amount as when no compandor is used. Frequency changing for privacy purposes is not materially affected by the compandor.

The expandor increases the transmission variations in the circuit exactly as it increases the voltage range of the waves applied to it. It is, therefore, necessary to guard against excessive variations in the over-all circuit including the wire line extensions as well as the radio links. At the New York terminal there has been installed an automatic volume control operated from received speech signals which performs this function.

The received volume is limited by waves which do not operate the receiving side of the vodas, but which return as echoes to cause false operation of the transmitting side. The compressor increases these weak waves so that they are better able to operate the receiving side of the vodas, and the expandor effectively increases the stronger waves relative to the weak. This results in more received volume being delivered to the 2-wire terminal than when the compandor is not used. The overall improvement in volume delivered to the subscriber varies with the noise, being greatest when the noise is low.

References

1. The New York-London Telephone Circuit, S. B. Wright and H. C. Silent. *Bell System Tech. Jl.*, v. VI, p. 736–49, Oct. 1927.
2. Speech Power and Its Measurement, L. J. Sivian. *Bell System Tech. Jl.*, v. VIII, p. 646–61, Oct. 1929.
3. Thermal Agitation of Electricity in Conductors, J. B. Johnson. *Phys. Rev.*, v. 32, p. 97–109, July 1928.
4. Thermal Agitation of Electric Charge in Conductors, H. Nyquist. Presented before the American Physical Society, Feb. 1927; pub. *Phys. Rev.*, v. 32, p. 110–13, July 1928.
5. Two-Way Radio Telephone Circuits, S. B. Wright and D. Mitchell. *Bell System Tech. Jl.*, v. XI, p. 368–82, July 1932; *Proc.* of the Inst. of Radio Engrs., v. 20, p. 1,117–30, July 1932.
6. U. S. Patent 1,585,548; Dec. 15, 1925; issued to A. B. Clark.
7. U. S. Patent 1,737,830; Dec. 3, 1929; issued to George Crisson.

Recent Developments in Suspension Insulators

A recent development in the design of the cap and pin of suspension insulators, to enable compression principles of stress distribution to be incorporated, has made possible an increase from 6,000 lb to 11,000 lb in load as determined by time-load tests covering a period of 2 years. Also, fatigue failure caused by vibration has been found to occur in the metal part before the porcelain is affected.

By
G. M. BARROW
ASSOCIATE A.I.E.E.

Westinghouse Elec. & Mfg. Co., Derry, Pa.

THE EVOLUTION of the suspension insulator has been reviewed recently before the Institute so that it is unnecessary to discuss again here the early developments and the changes in design that have produced a type of insulator embodying compression principles of mechanical load distribution for improved performance. ("Development of Porcelain Insulators," K. A. Hawley, A.I.E.E. TRANS., March 1931, p. 47.) In the design described in the following paragraph, the details of the cap and pin are so shaped as to resolve the mechanical load into compressive stresses in the porcelain, in contrast to the shear and tensile stresses in the older designs.

Design developments during recent years have notably improved the compression loading features of the porcelain and are, therefore, of general interest. The older shear and tension type of design is shown in Fig. 1a and the latest compression type is illustrated in Fig. 1b. In the latter the keystone arch and buttress principles of construction are evident, with the cap acting as the buttress, the pin as the keystone, and the porcelain as the arch. This construction offered such a decided improvement in mechanics that extensive tests were conducted over a 2-year period to determine its merits and to compare it with the previous designs. The tests and results are especially significant in view of A. O. Austin's discussion of Mr. Hawley's paper, in which he said: "Where long life and reliability are desired, low stress in the dielectric, due to the combined working load and differential expansion, is far more important than a good factor of safety for the working load based on the maximum or ultimate [strength] on test . . . the time lag before defects are apparent, together with the wide variety of conditions encountered in service, make it exceedingly difficult to predict results from design or accelerated tests."

MEASUREMENT OF INSULATOR STRENGTH

It is generally recognized that, with good porcelain, the service life of the suspension insulator depends upon the mechanics of the design in distributing the stresses of loads and thermal changes. As a check on the distribution of load stress, etc., there are the ultimate strength, the combined mechanical-electrical strength, and the time-load performance. The ultimate strength, as such, has long been superseded by the combined mechanical-electrical strength, which is a better measure of expected performance. It is used as a reference base for the latter, their ratio giving an indication of the stress balance, and in determining the mechanical factor of safety, but this is secondary to the combined mechanical-electrical strength that determines the effective limit of the insulation. In the combined mechanical-electrical strength test the time element is an important factor, as was recognized some 10 years ago by a customer's specification that called for this test at 11,000 lb for 1 min. Time and load increments similar in proportion to accelerated service conditions furnish a more comprehensive evaluation of performance and lead to the so-called time-load test.

The performance values for these characteristics are given in Table I, which also shows the comparison of the 2 designs in Fig. 1.

This improved performance with the same or slightly smaller dimensions of the porcelain head is an ample demonstration of the superior distribution of stress in the compression type. It also confirms the theory of the design and the results of the preliminary photo-elastic study of various models. The insulator has the well-known and proved resilient

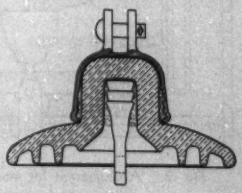


Fig. 1a. Tension and shear type design

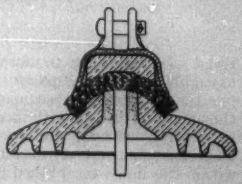


Fig. 1b. Compression type design

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Virginia, June 25–29, 1934. Manuscript submitted March 5, 1934; released for publication March 16, 1934. *Not published in pamphlet form.*

Table I

Types of Test	Shear Type	Comp. Type
Ultimate strength	14,000 lb	15,000 lb
Comb. mechanical-electrical	12,000 lb	15,000 lb
Time-load for 1 week	8,000 lb	13,000 lb
Time-load for 1 month	7,000 lb	12,000 lb
Time-load for 1 year	6,000 lb	11,500 lb
Time-load for 2 years	6,000 lb	11,500 lb

assembly using the sanded cementing surfaces and cushioning film. The time-load tests through several seasons of normal weather and temperature changes are an indication of the ability of the compression type to take care of thermal stresses, but a much more exhaustive and detailed investigation was made of this feature.

Effect of Thermal Changes

An analysis of the stress action under thermal changes develops the critical points in the design. The coefficient of expansion of the metal parts is approximately $2^1/_2$ times that of the porcelain. The greatest hazard is therefore where the porcelain envelopes the metal, which occurs in the assembly of the pin in the porcelain.

The insulator assembly is steam cured at a temperature exceeding that reached in usual climatic conditions. In returning to normal temperature after assembly, the metal parts shrink more than the porcelain. During subsequent temperature changes the action of the cap with increase in temperature is to expand, relieving the porcelain head of stress. This expansion and any movement of the cap remain within the limits established in the assembly during the steam curing. With decrease in temperature the action is reversed, the shrinkage of the cap tending to place the porcelain head under compression. The great strength of porcelain in compression and the greater mass of the porcelain relative to the metal in the cap, which is in tension, leave the porcelain unaffected by this change in temperature. The reduction in dimension of the cap incident to the shrinkage is compensated by the elongation under the tensile stress developed by the shrinkage against the porcelain, and movement of the cap is, therefore, negligible over the normal temperature range.

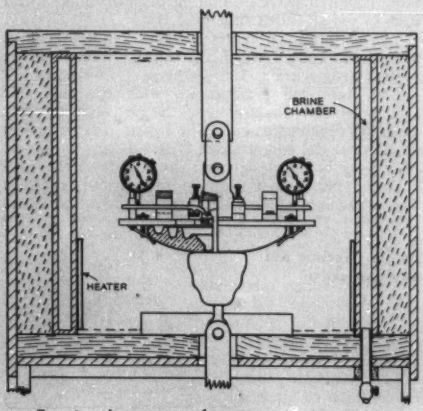


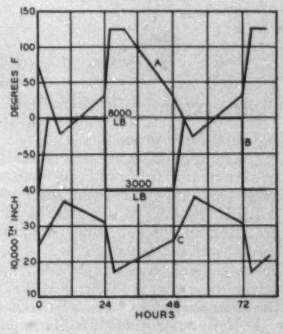
Fig. 2. Arrangement for measuring pin extension and recovery

The combination of the load stress with these thermal stresses does not change the behavior of the cap to any appreciable extent. The reaction of the load between the cap and the porcelain places the head of the porcelain under compression. This action is automatically compensating, any change in load producing a corresponding change in pressure by reason of relative movement between the cap and the cement along their lubricated surfaces. These large surfaces reduce the stress per unit area to a low value and the vertical movement of the cap with normal load changes is therefore small.

The behavior of the lubricating material that is applied to the inside surface of the cap is an important factor, particularly in that it must function properly over wide limits of temperature. A texture and thickness of the material were determined that give the same performance at extreme as at normal temperatures. It is of interest to note that in experimental assemblies where much slippage of the cap occurred, the bell of the cap was ruptured by splitting; the porcelain was not impaired. This demonstrates that the porcelain is immune to any shear component of the cap stress caused by cap movement.

Fig. 3. Pin extension and recovery with changes in load and temperature

A. Temperature
B. Load
C. Movement



Effect of Load on the Pin

Considering the pin without load, it expands with increase in temperature but the temperature and expansion in service do not reach those attained in assembly; with decrease in temperature it shrinks

more rapidly than the porcelain. In either condition the porcelain is free from stress. The addition of load stress restricts this freedom of adjustment and introduces a more complex factor. The area of the pin head is relatively small and the stress per unit area large. The pin is, therefore, more subject to movement than the cap, and it pulls into or nests in the cement in adjusting its position under load. The worst case may be represented by a service condition where reduced temperature shrinks the pin and a sleet load added to the conductor load pulls or tends to pull the head of the pin into the cement. With subsequent increase in temperature it is important that the head recovers its normal position to prevent wedging and the resulting severe stresses.

The controlling factor in the ability of the pin to recover its position is the shape of the working cone. This part is one of the most important in the whole design. Many shapes of single-cone pins have been used in past years, all of which have the advantage of minimum mass, but were made with a straight or,

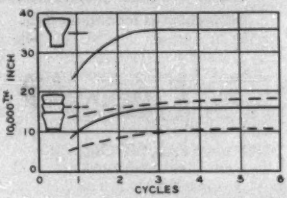


Fig. 4. Maximum and minimum limits for extension and recovery

with respect to the axis, a concave bearing surface. None of these shapes gives a uniform distribution of load stress over the bearing surface. Photo-elastic studies showed clearly that stress concentration occurred at the edge of the cone. This is caused by the greater displacement of that part of the cone as it moves or tends to move into the cement. The convex shape enables the improved cone to give an equal displacement for each increment of bearing surface in order to insure uniform distribution of stress and prevent any wedging action. The recovery of the pin was studied in an investigation of the cone movement between wide limits of load and temperature range. The test was arranged as in Fig. 2, the insulator being enclosed in a thermally insulated container with temperature limits obtained by circulating brine and heating elements. The load was applied by weights and levers and movement of the pin with respect to the porcelain was determined by dial measurements to 0.0001 in. and compensated for elongation and thermal change in dimensions. Starting at normal temperature with a load of 3,000 lb, the temperature was reduced to freezing; there the load was increased to 8,000 lb and the temperature reduced to −20 deg F. The temperature was then increased and at 32 deg F the load was reduced to 3,000 lb; the rise in temperature was continued to 120 deg F, and reduced to normal. This procedure constituted 1 cycle and covered a period of 48 hr. The response of the cone of the pin to the load and temperature changes for 2 cycles is illustrated by Fig. 3. The variation between maximum and minimum points of movement is fairly uniform for successive cycles and equilibrium is reached in several cycles, as indicated by Fig. 4. The leveling off of the curves of extension demonstrates that the effect is not cumulative and that progressive wedging of the pin does not occur. This figure also shows the

Fig. 5. Steam chest for heating insulators on time-load test

behavior of a 3-step pin similar to the design in Fig. 1a. The degree of movement is dependent upon the pin shape, load area, and the thickness of the resilient coating over the load area. The 3-step pin with greater load area has for equal thickness of coating a lower range of movement and permanent deflection than the single cone shape. However, it is less efficient than the latter because of the larger shear component in its distribution of stress. The permanent deflection or set under the 3,000-lb load is represented by the line of minimum extension. This is attributed to the minute migration or compression of the resilient coating against the surface of the cement column by the seating of the cone. Tests on various sizes of the single cone design showed that difference in size does not alter the recovery movement, and that the pin adjusts itself to severe service conditions so that the assembly is protected from injurious stresses.

Recognizing that the seating of the cone imposes additional stress, a further check on the effect of combined load and thermal changes was made by subjecting insulators on time-load test to a wide temperature range. A string of insulators carrying a load of 10,000 lb was enclosed in a steam chest, shown by Fig. 5, in which it was heated to 150 deg F during the day, and then was exposed to freezing and subzero weather conditions at night. Retention of the constant high load over the temperature range imposed caused unusually severe stress conditions, and repeated cycles of this treatment without insulator

failure demonstrated the uniformity of stress distribution and adjustment to differential expansion.

Effect of Vibration

Another feature investigated on time-load test was the effect of vibration and load oscillation. A device shown in Fig. 6 was added to the loading arrangement to oscillate the load at the rate of approximately 115 cycles per min between the limits of 6,500 and 10,500 lb, thus also inducing considerable vibration in the insulator string. This test proved to be more destructive to the equipment and metal fittings than to the insulators. Repeated failures occurred in the fittings as the number of cycles approached 300,000, but there was none in the insulators. This performance has been paralleled in more recent tests made by a cable manufacturer on accelerated cable vibration in which suspension insulators were used to support the cable, and where failure occurred in the metal attachment, the porcelain remaining undamaged. The results of these tests indicate that the porcelain is less susceptible to vibration than the connecting hardware, and they also confirm our research findings that the fatigue strength of porcelain is at least 80 per cent of static strength in comparison to approximately 60 per cent and less for metals.

The results of these tests are believed to be the best indication of service performance available at the present time. The effect of vibration and of wedging of the pin long have been topics of varying opinion and the results of the observations on these therefore are of special interest. The time-load test is inherently a natural basis for measuring service performance, as the degree to which load and temperature variations can be accelerated without insulator failure constitutes a measure of comparative merit. The performance on all of the tests demonstrates the improvement obtained with the latest design development.

Fig. 6. Arrangement for vibrating and oscillating the load on insulators on time-load test

Factors Influencing the

Insulation Coördination of Transformers—II

Supplementing a previous paper, data given here verifies the coördination between transformer major insulation and standard edge gaps for surges of short duration. Insulation deterioration caused by high surge voltages is shown to occur at relatively constant voltages regardless of wave length or polarity. Direct strokes are found to be the cause of principal damage; use of overhead ground wires for apparatus protection is recommended.

By
P. L. BELLASCHI
ASSOCIATE A.I.E.E.

F. J. VOGEL
ASSOCIATE A.I.E.E.

Westinghouse Elec. & Mfg. Co., Sharon, Pa.

In a previous paper,[1] the relationships among impulse characteristics of edge gaps, line insulation, and major insulation (that between winding and core and other windings) of a transformer were shown. For example, it was established that the major insulation of transformers had an impulse ratio of approximately 2.2 and that the time lag curve was practically flat down to time lags of 2 μsec. It was also found that coördination with present standards of transformer major insulation was obtained by edge gaps recommended by the transformer subcommittee of the A.I.E.E.[2] There was some question however whether coördination was obtained between transformer major insulation and the standard edge gaps for extremely short time lags which showed a need for further study of insulation and edge gap characteristics for surges of very short duration.

Additional study of this problem has been made. The time lag curves for insulation and edge gaps previously shown are in agreement with the more recent data, which still indicate that coördination is obtained even for surges of very short duration. The ability of transformers to withstand repeated surges is of great interest in connection with the

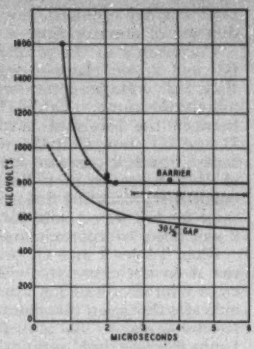
Full text of a paper recommended for publication by the A.I.E.E. committee of electrical machinery, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 4, 1934; released for publication April 18, 1934.

1. For all numbered references, see bibliography at end of paper.

Fig. 1. Results of barrier breakdown tests with single applied surge as compared with results obtained with several surges and with breakdown of coördinating gaps

Points "O" obtained with a single applied surge

Points "X" obtained by applying several surges, starting 10 per cent or more below the breakdown value and increasing in steps up to breakdown. This was the method used in obtaining data presented in the previous paper except at short time lags



The $30^1/_2$-in. gap time-lag values shown indicate the relations that should exist between transformer insulation for a single applied surge and the standard coördinating gap

highest surge voltages. It is well known to all engineers that in testing any material, whether electrically or mechanically, there is found a certain range of values where damage may be done, and where failure may not immediately result. That such damage or deterioration in insulation structures due either to surges or 60-cycle tests might occur is generally believed from previous work, but these opinions as to insulation deterioration from surges are based on puncture tests on small samples not representative of the major insulation of transformers. For these reasons, insulation deterioration due to high surge voltages required investigation. The comprehensive studies here described show that the level at which deterioration can be expected is practically a constant voltage for any one insulation arrangement regardless of wave length or polarity.

The performance of the edge gap at extremely short time lags has been determined and compared with that of the transformer major insulation. Direct strokes are still found to be the source of real danger and overhead ground wires are essential to prevent direct strokes at or near the apparatus. A stroke to the line, however, if several hundred feet away, may be reduced to reasonable limits by the application of suitable protective means.

Conclusions reached as a result of this further study are as follows:

1. Transformer major insulation of conventional types probably is coördinated with the proposed standard coördinating gaps, except that in the case of very high short surges marked deterioration results.

2. Transformer major insulation is shown to have a definite voltage deterioration level, and surge voltages above this level, as permitted by the standard point gaps, definitely result in insulation deterioration.

3. Surge testing as at present recommended by the Transformer Sub-Committee of the A.I.E.E. will not result in any deterioration to the apparatus, providing, of course, the apparatus is properly designed.

4. The best protection that can be afforded to apparatus against damage due to lightning is to provide a protective scheme comprising overhead ground wires, a deion line protector at some suitable distance from the apparatus, lightning arrester at the apparatus, and a ground network.

Insulation Deterioration Indicated by Barrier Tests

While making the surge tests of insulation reported in the previous paper it was noted that the values obtained varied somewhat with the number of tests applied. Accordingly, in obtaining data for the insulation time lag curves, tests were first made in which the insulation was broken down on the first surge applied, this eliminating any effect of insulation deterioration due to repeated tests.

Barriers (similar to Fig. 8 in the previous paper) were made of a similar construction to the major insulation in transformers. Three barriers were tested to determine their maximum 60-cycle, 1 min hold strength. The maximum voltage which these barriers held for 1 min. was 220, 220, and 230 kv or an average of 223 kvrms. The results of the surge test are as shown in Fig. 1. For comparison the time lag curve for a $30^1/_2$-in. edge gap, which would correspond to a 1-min insulation test of 223 kv is shown. It may be noted that these barriers with a 223-kv "hold strength" are not quite equivalent to the major insulation for the 115-kv class even if there were no factor of safety in the one minute test, as the 60-cycle test voltage for this class is 231 kv and the corresponding gap is $31^1/_2$ in.

For further comparison to show the effect of deterioration the results of tests at from 2- to 6 μsec time lag, when several previous tests had been applied, are also shown. It is seen that the insulation and edge gap characteristic curves are closest at

Fig. 2. Typical appearance of barrier after surge breakdown

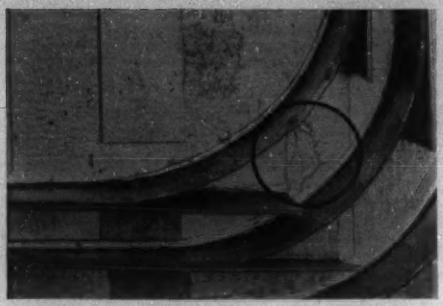


Fig. 3. Typical appearance of deterioration marks from repeated high voltage surges applied to barrier

about 2 μsec. It was the results of such tests as these that led to the adoption of 2 μsec as a critical time lag in the previous study of impulse coördination.

The earlier work in obtaining the shape of the time lag curve indicated that the flat part might be termed the true dielectric strength of the barrier and that the apparent greater dielectric strength shown by the extremely steep rising part of the curve was due to the fact that a certain length of time is required to cause insulation breakdown. It appeared that deterioration results from all voltages above some critical level. Accordingly the deterioration level for impulse voltages for certain barriers, completely representative of transformer major insulation, was fully determined.

The larger barrier (barrier A, reported in the previous paper) had an average 1-min 60-cycle hold strength of 345 kv rms. Barriers of this type have been given repeated surge tests using full $1^1/_2 \times 40$-μsec positive and negative waves. Inspections for evidences of visual deterioration were made and the tests in some instances were continued to failure. The procedure of these tests was to apply at least 100 surges of predetermined value and inspect the barrier at each voltage step up to the point where visual deterioration or marking was first established. The results of the tests are as shown in Table I.

Similarly, tests were made with the same type of barrier (A) and with surges chopped by an edge gap after from $2^1/_2$ to 4 μsec. The results of these tests are shown in Table II along with similar tests on a smaller barrier (B). The smaller barrier had an average 60-cycle 1-min hold strength of 223 kvrms. These barriers are exactly similar to the ones used in obtaining the data shown in Fig. 1

For very short surges, waves were used that rose at a rate of 1,500 kv per μsec and which were chopped on the front by edge gaps. These tests were made only on barrier B. The procedure was to use a given gap setting, apply 100 surges, and then increase the gap setting. Inspection of some of the barriers indicated that marking as in the previous tests was not obtained, but failure was the first indication of deterioration.

Comparison of the results in Tables I and II for full and 2-μsec chopped waves for barrier A show that the voltage deterioration level is approximately the same. Table II shows the relationship between the levels of barriers A and B. Tables II and III show that the deterioration level is the same at both 2 μsec and for very short times. All of this indicates that the deterioration level for barriers representing transformer insulation is the same for full waves, and for waves chopped at from 2 μsec down to approximately 0.4 μsec.

From Tables I and II, tests up to 870 kv on barrier A do not cause any visible deterioration. The large number of surges applied above this voltage indicates that even visual marking does not constitute serious damage. As stated before, the maximum 1-min 60-cycle hold strength of barrier A was 490 kv crest. This gives a ratio of 870/490 or 1.78. For barrier B, this ratio is approximately 565/316 or 1.79, where 316 kv is the maximum 1-min 60-cycle hold strength of barrier B.

It should not be inferred from these tests that the ratios and data above apply either to all types and arrangements of barriers, or to all transformers as actually constructed. The ratio may vary over a wide range with different barriers or the arrangement of insulation in different designs. The principle of a constant voltage deterioration level however does apply to all transformers. Where the transformer winding insulation is as strong or stronger than the major insulation, as in a surge proof transformer, and proper design methods and adequate factors of safety are used, impulse tests can be made without fear of deterioration. From these tests it is possible to draw the following conclusions:

1. The strength of these barriers is independent of polarity.

Table I—Results of Repeated Applications of Full $1^1/_2 \times 40$-μsec Waves

Barrier	Surge Voltages (kv) Held 100 Times Without Marking	Total Number Surges Applied Without Marking	Surge Voltage (kv) at Which Marking Occurred	Number of Surges at Marking Voltage	Total Surges Applied
Barrier A—positive waves					
1	580–615–675–735–790–850–910	700	965	100	800
2	705–760–820–880	400	940	100	500
Average voltage held without marking, 895 kv					
Barrier A—negative waves					
3	720–760–805–850	400	900 945 (failed after 2 shots)	102	502
4	720–760–805–850–900	507	945–990 1030 (failed after 24 shots)	224	731
5	720–760–805–850–900–945	605	990 1030 (failed after 8 shots)	108	713
Average voltage held without marking, 900 kv					

2. Marking and insulation deterioration occurs at a voltage level constant for any given design of barrier from full $1^1/_2 \times 40$-μsec waves down to short chopped waves of 0.4 μsec. With these data, it is reasonable that this same level would hold for still shorter chopped waves.

The above conclusions are based on tests on barriers. To demonstrate that they apply to complete transformer designs, a particular 230-kv design has been tested 100 times with impulse voltages at 1,430 kv. This shows that when the design is made properly and the deterioration limit is not exceeded, deterioration does not accompany impulse testing.

Short Wave Surge Breakdown of Edge Gaps

To view the general coördination problem from a broad and scientific aspect, the breakdown strength of edge gaps was investigated with extremely short surges, of such duration as would be associated with lightning in case there was a direct stroke at the apparatus. Inasmuch as very little, if anything, has hereto been published on the edge gap characteristics for such very short surges, in addition to the test data reported below, there is also described briefly the technique of test as well as the difficulties besetting testing of this kind.

Table II—Results of Tests With $1^1/_2 \times 40$-μsec Waves Chopped by Point Gap After From $2^1/_2$ to 4 μsec

Barrier	Surge Voltages (kv) Held 100 Times Without Marking	Total Number Surges Applied Without Marking	Surge Voltages (kv) Applied 100 Times After Marking Occurred, and Failure Voltage	Number of Surges Above Marking Voltage	Total Surges Applied
Barrier A—positive waves					
1	790–830–865	307	900	128	435
			940 (failed after 28 impulses)		
2	790–825–865	307	900	105	412
			940 (failed after 5 impulses)		
Average voltage held without marking, 865 kv					
Barrier A—negative waves					
3	785–825–860	302	910	125	427
			950 (failed after 25 impulses)		
4	785–820–855	305	890 (failed after 98 impulses)	98	403
5	790–830–860–905	406	940 (failed after 32 impulses)	32	438
Average voltage held without marking, 870 kv					
Barrier B—positive waves					
6	468–510–555	300	610 (failed after 56 shots)	56	356
Barrier B—negative waves					
7	540	100	585	100	200

Table III—Results of Tests Made With Short Chopped* Surges

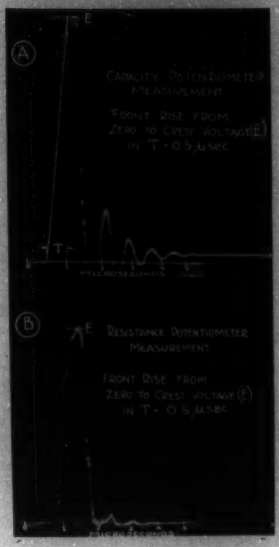
Barrier	Surge Voltages (kv) Held 100 Times Without Marking	Surge Voltages (kv) at Failure	Gap Length at Failure	Surges Applied Up to Time of Failure
Barrier B—positive waves				
1	470–540–630	675	17"	315
2	540	600	14	143
3	540	600	14	156
Average	570	625		
Barrier B—negative waves				
4	470–540	600	14	300
5	540	600	14	120
6	540–600	650	16	314
Average	560	617		

* The time from the start of the wave to the time of failure was between 0.4 and 0.5 μsec.

Fig. 4. Oscillograms of point gap flashovers on the fronts of steep waves

Oscillogram A shows the method of analysis of oscillograms to obtain time T to beginning of flashover

Oscillograms A and B show a comparison of similar waves as recorded by the capacity and resistance potentiometer. The rapid response of the capacity potentiometer is indicated by the sharp break in voltage at the beginning of flashover. The flat part at the crest of oscillogram A is due to streamer formation, length of lead, and possibly reactance drop of surge current flow across gap



The gaps tested were in agreement with the proposed rules for standard coördinating gaps and furthermore they were located immediately adjacent to the surge generator, as close to it as physically possible. The surge generator was set to a sufficiently high voltage to produce breakdown of the gap on the rising front. As indicated by the oscillograms in Fig. 4 the front rises substantially at a constant rate from 10 per cent to 90 per cent of the crest voltage. The rounding up near the crest is due, partly, to the capacity load produced by the heavy streamer discharge, as breakdown of the gap is in progress; partly, to the combined arc and inductive drop which is maintained across the gap at complete breakdown until the full surge generator current is discharged through the gap; and in some measure, this rounding is partly due to imperfect response, which is inherent even in the best potentiometers available when measuring extremely short voltage-time variations.

It seemed then logical for the special investigation at hand to plot the crest voltage E of the gap breakdown against the time duration T on the rising front, as indicated in oscillogram A (Fig. 4). Accordingly the surge voltage breakdowns of $9^1/_4$ in., $18^3/_4$ in., and other gaps for fronts rising uniformly to crest in times ranging from 1.0 to 0.2 μsec have been

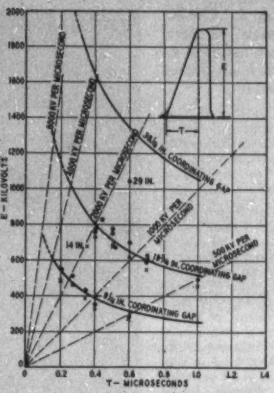


Fig. 5. Experimental data for breakdown of coordinating gaps on the fronts of steep waves

- ⊙ Data taken with capacity potentiometer, positive waves
- × Data taken with resistance potentiometer, positive waves
- ⊡ Data taken with capacity potentiometer, negative waves
- △ Data taken with resistance potentiometer, negative waves

Data taken with capacity potentiometer may be slightly high due to length of potentiometer lead; data taken with resistance potentiometer may be low due to slow response. True values should be within these limits where data by both potentiometers are given. Dashed lines show voltages at flashover for different rates of voltage rise or steepness

plotted in Fig. 5. They furthermore may be replotted as a family of curves for constant rates of rises as indicated in Fig. 6. The relationships indicated in Fig. 6 make it appear that extrapolation is fairly safe even over considerable range. One significant finding from these data is the fact that the breakdown strengths to positive and negative waves are substantially the same for all purposes of any importance in this paper.

Following are some of the difficulties and limitations encountered in securing the data in Table III and in Fig. 5:

1. The capacity load permissible was very small. In a case of this kind it cannot exceed the stray capacity of the generator proper if steep wave fronts as indicated are to be obtained with a reasonable size of surge generator. In addition, the surge generator must be designed for and have a voltage rating at least from double to several times the breakdown voltage of the gap on the rising front.

2. To secure reasonably correct measurements of gap or insulation breakdown in the tests made a potentiometer had to be located right at the terminals of the gap or at the electrodes of the insulation. The capacity potentiometer inherently is the type of potentiometer most capable of very rapid response. Unfortunately the capacity potentiometer available during the tests, being fixed in position, would have entailed a part of the discharge circuit drop so that it could not be used directly in these particular tests. A resistance potentiometer accordingly was connected with short potential leads directly across the terminals of the test piece, thus eliminating a voltage drop in part of the surge generator discharge circuit. The resistance of the potentiometer was reduced to the lowest permissible value compatible with its own insulation requirements, in this way securing the best fidelity possible in voltage response even at the very short times. As a further confirmation the resistance potentiometer was checked directly against the capacity potentiometer.

Accounting for the lead drop measured by the capacity potentiometer during the tests, the resistance and capacity potentiometer give substantially the same voltage and wave form, as indicated in both oscillograms of Fig. 4 and also the experimental points on Fig. 5. Briefly stated, although the data on very short waves here presented may not be extremely accurate, all precautions were taken so that it may be considered the best data at present available and amply good for the theoretical and practical purposes proposed in this paper.

The Coördination Problem: Direct Strokes and Short Waves

It is now apparent that there is a definite limit to coördination of transformers with edge gaps. The results show that transformer insulation might be able to withstand exceedingly high short surges, such as might be associated with direct strokes, once or twice, based on the results of Fig. 1. It is equally clear, based on the results of the endurance tests, that injury results, and will lead to eventual failure if such exceedingly high voltage surges are repeated.

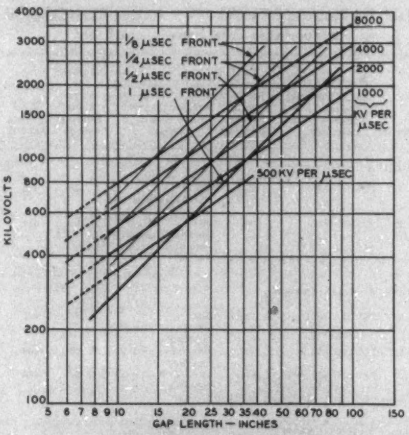


Fig. 6. Breakdown voltages for coördinating gaps on the fronts of steep waves

In high voltage work it often is found that the use of log-log coördinate paper shows interesting relationships and provides means for easy extrapolation. The data for constant rates of voltage rise or steepness and for different values of time to breakdown are plotted. It may be seen that both are pure exponential relationships, are in remarkable agreement with the experimental data, and also appear to determine laws of breakdown which are readily extrapolated

The question of transformer protection against direct strokes then becomes one of economics, in that it may either be decided:

1. To run the risk of failure due to direct strokes;

2. To attempt to so coördinate the transformer insulation that it will withstand direct strokes; or

3. To avoid any possibility of direct strokes at the apparatus.

In many cases undoubtedly the first procedure is

reasonable, as the possibility of a direct stroke may not be great due to the location of the apparatus, and protection other than arresters may be relatively too costly in comparison with the cost of the apparatus or the value of the service. The second procedure is not sound at all if edge gaps are used. The actual steepness of lightning voltages can only be surmised, and even with an estimated rate of rise of 4,000 kv per microsecond, direct strokes would result in such high voltages as to be prohibitive for the lower voltage classes (see Fig. 6). For estimated rates of rise of 8,000 kv or more per microsecond, it is prohibitive for any voltage class. It is evident that the desirable thing to do is to prevent direct strokes to the apparatus in so far as possible, and to provide protection only against traveling surges.

Many have been the suggestions made to limit the abnormally high voltages that would result from a direct stroke at the apparatus. The use of sphere gaps would have certain merits were it not for the clumsiness of this types and of similar types of gaps, the fact that provisions have to be made to protect the spheres from the weather, dirt, etc., and also the need of setting the gap at less than half-diameter spacing in order that it operate at very short time lag without exceeding substantially unity impulse ratio. Limiting devices to fix the voltage to a constant value are no doubt desirable whether these be in the form of sphere gaps, lightning arresters or what not, but full assurance of their characteristics is essential to apply them properly.

Any scheme or method of protection that is to receive consideration must have at least 2 essential requirements:

1. Practicability, in the sense that it can readily be incorporated with the normal design of the line and station, an advantage being to apply a method of protection that has already been well established through past developments and practical experience.

2. Economy.

Briefly Fig. 7 illustrates an ideal arrangement which conforms in a good measure with the foregoing 2 requirements. It consists of a ground wire protection covering the substation and extending over the line for several hundred feet, where ground wires are not provided on the entire line. For the stations of higher voltage class, the regular ground wire protection with 2 or more ground wires, ample line insulation, spacing between ground wires and line wires, and low ground impedance (not exceeding a few ohms or where necessary a counterpoise) are found from experience to furnish good shielding.

The substation and apparatus as well as a length of line, L feet, can now be considered well shielded from most direct strokes. This complete shielding is secured according to the modern technique of ground wire protection, low ground resistance at the tower footings, as well as the use of the counterpoise. However, for low voltage circuits, sufficiently low ground resistances at tower footings to obtain ideal conditions are difficult to secure. To overcome this difficulty, the use of diverters has been recommended, but this does not appear to be entirely effective except as a shield from direct strokes to the line in the region of the diverter. However, a direct stroke to the line beyond the diverter would discharge over gap No. 1, still requiring very low ground resistance. Therefore a ground cable system extending from the station parallel to the line and solidly connected successively to the first 2 or more towers and beyond the first gap is here recommended to avoid this difficulty.

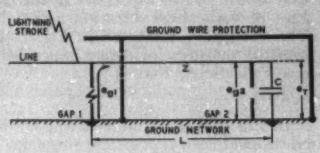


Fig. 7. Effective method of protecting apparatus against direct strokes at or near substation

It is beyond the scope of this article to restate the fundamental principles of ground wire protection,[8] so it is immediately assumed that the salient features of shielding against direct strokes have been incorporated as outlined diagrammatically in Fig. 7. Direct strokes to the line at a distance greater than L feet are intercepted and discharged at the coördination gap No. 1. Due to the time-lag phenomena (curves of Fig. 6) a surge voltage e_{g1} is bypassed to the line. This surge travels over the segment of line L and builds up a voltage across the capacity C of the apparatus, which we shall denote as e_T. There are reflections back and forth between the two ends of the line segment L. The following analysis summarizes the traveling wave phenomena and enables readily the computation of e_T from any set of circuit conditions and voltage e_{g1} considered.

The voltage built up across a condenser C connected in series with an infinite line of surge impedance Z, in the case of a unit rectangular wave, is $e_1(t) = 2\,(1 - \epsilon^{-\frac{t}{ZC}})$. Then by superposition, the voltage built up across the condenser C by any voltage (a function of t) e_{g1} (t) (see Fig. 7) is for the first incidence

$$e_{T1} = \int_0^t e_1\,(t - \lambda)\, e'_{g1}\,(\lambda)\, d\lambda \qquad (1)$$

where e'_{g1} (λ) is the derivative of e_{1_g} (λ) and is considered to rise from zero to crest and back to zero.

Simply stated, this integration process is nothing more than dividing the incoming voltage wave e_{1_g} (t) into a series of rectangular components, each component producing a resultant voltage at the condenser similar to that of a simple rectangular wave. All these components can then be summed up to obtain the combined effect of all, thus giving the voltage e_{T1} at the condenser. This summing up may be done mathematically, as stated in equation 1, or often more conveniently graphically, as in the case considered later in Fig. 8.

A voltage is then reflected back to gap 1 as indicated below

$$e_{g2} = e_{T1} - e_{1_g} \qquad (2)$$

This reflected voltage is reversed in polarity (nega-

tive reflection) at the grounded end (gap 1, inasmuch as gap 1 is still discharging) and returns to the terminal apparatus at time $t = \frac{2L}{1{,}000}$ μsec. Much the same as indicated in equations (1) and (2), a second reflection is produced, setting up a voltage e_{r2} across the capacity. Subsequently, third, fourth, and other reflections are produced, but account should be taken in the computation of the fact that rapid attenuation would result, especially in the case of high voltages of very short duration as are here considered. The voltage e_T indicated in Fig. 7 then is the sum total of the first incidence plus effect of the successive reflections, that is

$$e_T = e_{r1} + e_{r2} + \ldots \tag{3}$$

In Fig. 8 is illustrated an application of the above relationships to a practical problem, where the voltage e_{g1} by-passed is represented as rising uniformly and chopped instantly to zero at the crest value E. The duration $T = 0.4$ μsec and the parameters for the line and apparatus are $Z = 200$ ohms, $C = 5{,}000$ μμf and $L = 500$ ft. For a $38^1/_4$-in. gap and a rising front of 4,000 kv per microsecond the maximum voltage E would be 1,600 kv (curves of Fig. 6) and the maximum voltage, e_T (max) across the apparatus would be limited to approximately 500 kv, which would be a safe value for coördinated apparatus.

Had the length of shielded line been considered as $L = 1{,}000$ ft the second reflection would have occurred at a time $t = 2.5$ μsec instead of approximately 1.5 μsec. It should be noted as a matter of general importance that the length of the line (time $= \frac{2L}{1{,}000}$) relative to the time constant of the line impedance and the apparatus ($t = ZC$) and also taking into consideration the duration of the voltage e_{g1} should be such as to avoid any appreciable adding up of the reflections.

It is well appreciated that due to the lead connecting the line to gap 1, the voltage e_{g1} would not drop abruptly at the crest E to zero, but remain flat and decay gradually to zero value in 0.2 μsec or more depending on the height of the tower. The oscillograms in Fig. 4 illustrate clearly the type of wave passed on to the apparatus. This consideration does not change the principle although it would modify the results obtained in Fig. 8.

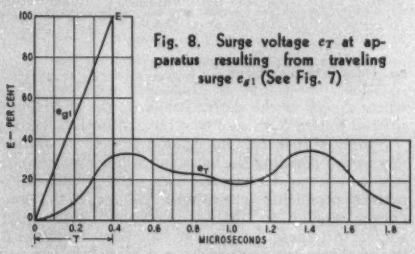


Fig. 8. Surge voltage e_T at apparatus resulting from traveling surge e_{g1} (See Fig. 7)

Unless unusual care is taken to reduce the effective tower footing impedance the voltage e_{g1} instead of reducing to zero value would remain at a value IR for some time, this drop being equal to the product of the lightning stroke discharge current I and the tower footing resistance R. Since the currents are known to reach values of from 100,000 to 150,000 amp it is desirable that the ground resistance be reduced to a very few ohms. In fact the desirable arrangement is to extend several cables in the ground from the station to the first 2 or more adjacent towers. This requirement in the station and apparatus shielding is very essential for the medium and low voltage classes.

This paper does not propose to treat in full detail and in its full ramifications the subject of shielding substations and apparatus from direct strokes. The general problem can readily be analyzed in its full detail following the method of attack outlined above. For a given condition of voltage class, apparatus capacity and line impedance, an economical layout of ground protection can be determined.

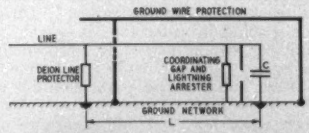


Fig. 9. Suggested method of protecting apparatus and substation against both damage and outage due to direct strokes at or near substation or due to traveling waves

It can be readily seen that with this scheme of protection apparatus may be furnished a substantial measure of protection against direct strokes and high voltage traveling surges. In fact, longer surges, in the order of 1 μsec chopped at gap 2 are much more to be feared. Such conditions may occur from lightning strokes a long distance out on the line and reflecting at the apparatus. In such a case, a voltage limiting device such as the arrester in parallel with gap 2 will provide a considerably increased factor of safety as well as protection against outage. Furthermore, since discharges at gap 1 also may entail service outages, deion line insulator protectors may be used in place of gap 1 as shown in Fig. 9. This arrangement has the merits of eliminating service outages and furnishing a far greater margin of protection than could be obtained with coördinating gaps alone.

References

1. Factors Influencing the Insulation Coördination of Transformers, F. J. Vogel, A.I.E.E. Trans., v. 52, 1933, p. 411.
2. The Coördination of Transformer Insulation With Line Insulation, V. M. Montsinger and W. M. Dann, A.I.E.E. Trans., v. 51, 1932.
3. Lightning and Its Effects on Transmission Lines, C. L. Fortescue, Internl. Elec. Congress, Paris, 1932.

Transmission Line Design Estimates—Simplified, A. C. Monteith, Elec. Jl., Feb. 1934.

Electronic Regulator for A-C Generators

This paper describes circuits and operating details of an electronic device designed to provide, through field excitation control, a regulation of a-c generator voltage within a range of $\pm^1/_{10}$ per cent.

By
F. H. GULLIKSEN
ASSOCIATE A.I.E.E.
Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

IN THE MAJORITY of voltage regulator applications a regulator sensitivity of $\pm$ from $^1/_2$ per cent to $\pm$ 1 per cent is entirely satisfactory, and the various types of electromagnetic voltage regulators may, therefore, be applied successfully. In applications where very close voltage regulation is needed, electromagnetic type regulators do not prove adequate. Particularly in connection with testing equipment for forced life test for lamps there has been a definite need for faster acting and more sensitive voltage regulators, and to meet this need the type of electronic voltage regulators have been developed as described in this paper.

Operation of these regulators during a period of up to 16 months indicates that electronic type voltage regulators will give a consistent regulation within a range of $\pm^1/_{10}$ of one per cent, and oscillographic tests prove that the speed of response of the electronic type regulators is higher than obtained with the best of the electromagnetic type of regulators.

The performance and reliability of the electronic type voltage regulators have been so satisfactory that it seems safe to predict that during the next few years electronic type voltage regulators will find wide application in the industrial and the central station field. For industrial and central station application the extreme sensitivity of the type *AT* regulator as described in this paper is not needed, and therefore for such applications simplified electronic regulators have been developed. These regulators compare favorably with the vibrating type voltage regulator in respect to sensitivity and speed of response, and due to the simplicity of adjustment and the absence of maintenance, they should appeal strongly to operating engineers.

An electronic voltage regulator recently developed for general industrial applications does need any dry cell battery, is equipped with 2 detector tubes operating in parallel and 2 pairs of grid glow tubes also operating in parallel, and the circuits are so designed that failure of any one tube in the detector circuit or in the power circuit will not cause any change in the regulated voltage.

Full text of a paper recommended for publication by the A.I.E.E. committee on automatic stations, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 26, 1934; released for publication April 16, 1934. *Not published in pamphlet form.*

Regulator Circuit Design

Two slightly different circuits have been used as shown in the schematic diagrams in Fig. 1 and Fig. 2. These circuits are similar except for the voltage indicating tube and the connections to this tube. In the type *AT* regulator shown in Fig. 1 a type *RO-587* full wave rectifier is applied as the voltage indicating element, while with the type *AT-1* regulator shown in Fig. 2, an *RO-585* diode type rectifier tube is applied. While the *RO-587* rectifier tube is a conventional rectifier where the d-c output voltage is proportional to the anode voltage, the *RO-585* rectifier, which has a tungsten filament, operates at an anode voltage exceeding the saturating voltage so that the anode current will be controlled by the filament temperature, and therefore by the filament voltage.

The basic difference between the two voltage indicating schemes is that the *RO-587* detector gives an indication of the average a-c voltage, while the *RO-585* detector indicates the rms value of the a-c voltage. The *RO-587* scheme is slightly superior to the *RO-585* scheme in respect to the response because there is a small amount of thermal lag in the *RO-585* filament, so the *RO-587* scheme should, therefore, be preferred in applications where the generator wave form remains approximately constant with varying load conditions, that is, when the ratio between the average a-c voltage and the rms value of the a-c voltage does not vary more than the required regulator sensitivity. If the generator wave form is changing, as would be the case if a standard 3-phase generator is operating with single phase load, the *RO-585* scheme, which always regulates for the rms value of voltage, should be used.

Referring to Fig. 1 it will be seen that the generator voltage is applied to the No. 1 *RO-587* tube, and the d-c output is filtered and fed to the voltage adjusting potentiometer P_1. The output circuit of potentiome-

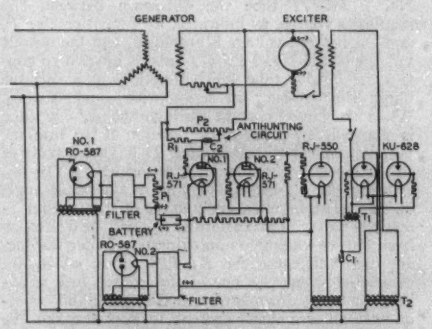


Fig. 1. Schematic diagram of type AT electronic voltage regulator

Fig. 3. Oscillogram showing response of type AT voltage regulator as load is switched on

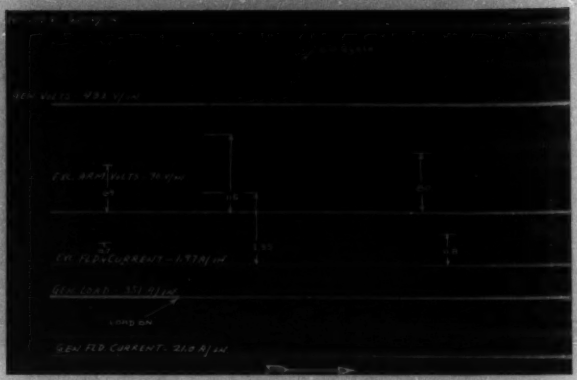
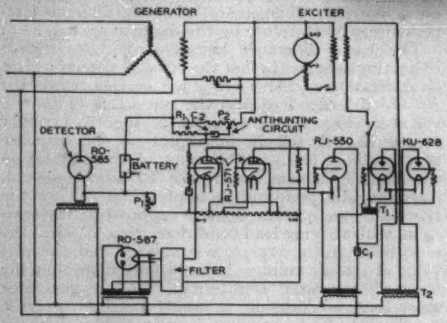


Fig. 2 (below). Schematic diagram of type AT-1 electronic voltage regulator



ter P_1 is bucked against a 90-volt dry cell battery, and the voltage difference is connected in series with the antihunting resistor R_1 between the cathode and the control grid of the No. 1 *RJ-571* screen grid type detector tube so that the No. 1 *RJ-571* control grid voltage is approximately -2 v. By means of the No. 2 *RJ-571* tube the difference between the regulated voltage as indicated by potentiometer P_1 and the battery voltage is amplified, and the output voltage of the No. 2 *RJ-571* tube is applied to control the *RJ-550* tube which functions as a variable phase shift resistor in series with condenser C_1. When the anode current through the *RJ-550* tube is changed, the phase angle position of the primary voltage applied to transformer T_1 is varied relative to the secondary voltage of transformer T_2. By increasing the *RJ-550* anode current the phase angle displacement between the voltage of transformer T_1 and the voltage of transformer T_2 will be decreased from 180 deg leading to approximately 70 deg leading, and this will cause the *KU-628* tubes, which are connected to energize one of the excited field windings, to break down earlier in the cycle, and consequently allow a higher current to flow through the exciter field.

The antihunting action is obtained from the effect of variation in exciter armature voltage acting upon the antihunting circuit consisting of potentiometer P_2, resistor R_1, and condenser C_2. When the exciter armature voltage is constant, the voltage drop across R_1 is zero. If the exciter armature voltage is changing due to the correcting action of the regulator, a charging current will flow into, or a discharging current will flow out of condenser C_2. This current will produce a voltage drop across resistor R_1, with a polarity so as to oppose and diminish the unbalanced voltage conditions in the grid circuit of the No. 1 *RJ-571* tube which caused the corrective action of the regulator.

Assuming that load is applied to the generator with a resulting drop in generator voltage, the No. 1 *RJ-571* grid voltage will become less negative and the current through the *KU-628* tubes, and consequently the exciter field current, will increase, thus tending to bring the generator voltage back to normal. As soon as the exciter armature voltage is increased a voltage drop will appear across resistor R_1, tending to make the No. 1 *RJ-571* grid more negative, and the exciter field current, which at this instant will be considerably higher than prescribed by the new generator load condition, will start to decrease before the regulator voltage is back to normal. This anticipatory action of the antihunting element is imperative in order to obtain stable operation as well as quick response action.

The operation of the antihunting circuit can be clearly visualized from the oscillograms in Fig. 3 and Fig. 4. These oscillograms were obtained with a 50-kva single phase generator, and during the oscillographic tests full load at 0.95 power factor was applied to the generator (Fig. 3), and full load was disconnected from the generator during oscillogram Fig. 4. It may be seen from Fig. 3 that within 5 cycles after the load had been applied to the generator, the exciter field current had increased from 0.7 to 2.35 amp. At this point on the oscillogram the exciter field current starts to decrease due to the action of the antihunting circuit, even though the regulated voltage is still below normal. The

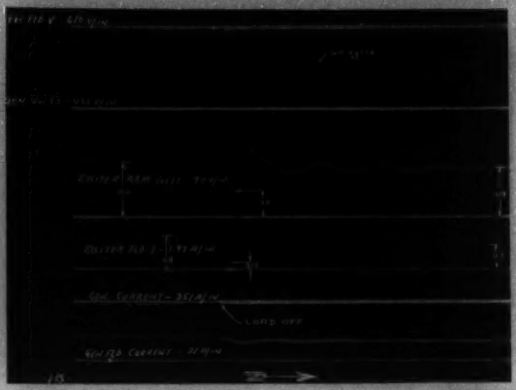
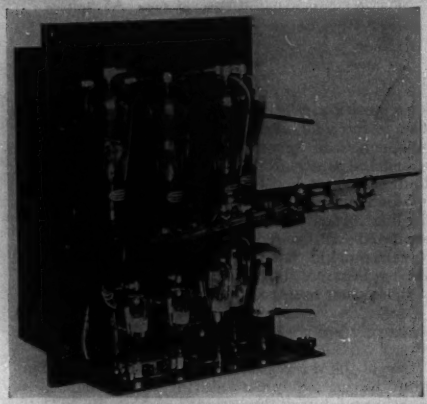


Fig. 4. Oscillograms showing response of type AT voltage regulator as load is switched off

Fig. 5 (below). Type AT voltage regulator with front cover off



quick response characteristic of the electronic regulator is apparent from this oscillogram, and it may be seen that the regulated voltage is back to normal in approximately 10 cycles after full load was applied to the generator.

The *AT-1* electronic regulator shown in Fig. 2 operates on the same general principle as the regulator shown in Fig. 1. When the regulated voltage is increased the current through the *RO-585* tube will increase and the negative bias on the grid of the No. 1 *RJ-571* tube will decrease. Since the cathode-grid connections of the *RJ-550* tube in this circuit is reversed as compared to Fig. 1, the effect of increasing regulated voltage will be a decrease in exciter field current. To obtain the correct polarity of the antihunting resistor, the polarity of the connections between the antihunting potentiometer P_2 and the exciter armature have been reversed as shown in the figure.

Applications of the Regulator

From the photograph in Fig. 5 it may be seen that the electronic regulator is equipped with a total of 4 *KU-628* grid glow tubes, while for the sake of simplicity only 2 *KU-628* tubes were shown in Figs. 1 and 2. In order to use all 4 *KU-628* tubes the exciter field winding should be split into 2 circuits and one field circuit should be connected in series with each pair of *KU-628* tubes, as shown in Fig. 6, which gives the connections for the electronic regulator applied to control the output voltage of synchronous booster equipment. The equipment is started by having one exciter field winding self-excited. When the generator voltage is approximately normal, a-c voltage is applied to the electronic regulator in order to heat up the tube filaments. After approximately one minute switch No. 2 of Fig. 6 may be closed and the exciter field rheostat may be turned in until the *KU-628* tubes assume their share of the exciter field current. Switch No. 1 is now thrown from the self-excited to the separately excited position and all 4 *KU-628* tubes will now be in control. The regulated voltage may then be adjusted by means of potentiometer P_1 shown in Fig. 1 and Fig. 2.

The booster circuit shown in Fig. 6 is of considerable interest due to the difficulties encountered on account of the many variables affecting the regulated voltage in such a circuit. Because quick response regulator action was the predominating regulator requisite in this application, it is doubtful whether any other type of regulator but the electronic regulator could have handled this problem successfully. The booster generator, which had a capacity of 30 kw, was synchronously driven from a 220-volt 60-cycle line, the voltage of which was varying within a range of 10 per cent. Since this equipment was used for life tests of lamps, it was imperative to maintain the regulated voltage, 126 volts, within a range of ± 0.1 per cent, when the booster generator load was changing from zero to 2,500 amp and voltage E_L was changing from 114 to 126 volts.

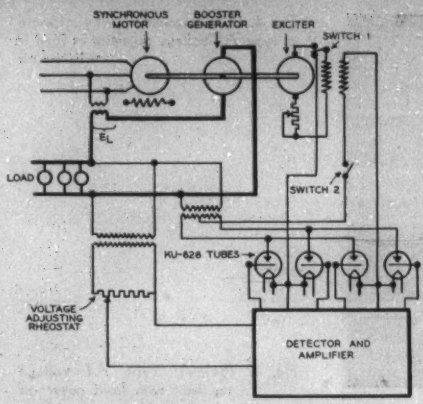


Fig. 6. Schematic diagram of type AT voltage regulator arranged for synchronous booster application

Due to the 25-deg change in the synchronous motor rotor position relative to the line voltage, from no load to full load, and due to a similar change in the phase angle of booster voltage, it was necessary to adjust the position of the booster armature to give a 25-deg leading booster voltage at no load. With full load on the booster, the booster voltage would lag the line voltage by 25 deg. In order to maintain the regulated voltage constant, the regulator had to correct quickly, not only for changes in line voltage and load current, but also for changes in the position of the booster rotor relative to the line voltage.

Notes on Performance

One of the AT regulators has been in operation on lamp testing equipment during approximately 16 months and during the period from Nov. 10, 1933, to Dec. 18, 1933, the equipment was in service a total of 34 days. This particular equipment is used for forced voltage lamp testing and is started up every morning at 8:15 with full lamp load, and continues to operate until 4 o'clock in the afternoon when all lamps will be burned out. During this period from 8:15 a.m. to 4:00 p.m. the generator load will be tapering off to zero as the lamps gradually burn out. In the following table is shown a résumé of the voltage readings taken every 15 minutes from 8:15 a.m. to 4:00 p.m. The first column gives the number of days during which the regulator voltage remained within a definite zone during the 8:15 a.m. to 4:00 p.m. period. The second column gives the same data covering the period from 10:00 a.m. to 4:00 p.m. The reason why the second column is better must be ascribed to the time required to bring the regulator up to a constant temperature, after being started up from the cold condition.

Regulated Voltage Range ± Per Cent	Days During Which Regulated Voltage Did Not Exceed Range: 8:40 a.m. to 4:00 p.m.	Days During Which Regulated Voltage Did Not Exceed Range: 10:00 a.m. to 4:00 p.m.
0.05	7	17
0.08	17	24
0.125	21	30
0.2	28	34
0.25	33	
0.33	34	

From the second column of the table may be seen that on 24 out of 34 operating days, the sensitivity of the regulator was ±0.08 per cent or better, during 30 days the sensitivity was ±0.125 per cent or better, and never during the 34 days of operation was the sensitivity less than ±0.2 per cent.

Design of Electronic Type Monitor

In order to eliminate the temperature effect of the type AT electronic regulator during the warming up period an electronic type monitor as shown in Fig. 7 has been designed. This equipment is arranged so that the indicating element, which consists of 2 Mazda lamps and 2 resistors, is connected directly to the generator bus without any intermediate transformers which would introduce a temperature error.

When the regulated voltage is normal, the voltage across the grid transformer T_1 connected across the bridge circuit is zero. If the regulated voltage departs from normal there will be a definite voltage across this grid transformer. This voltage will

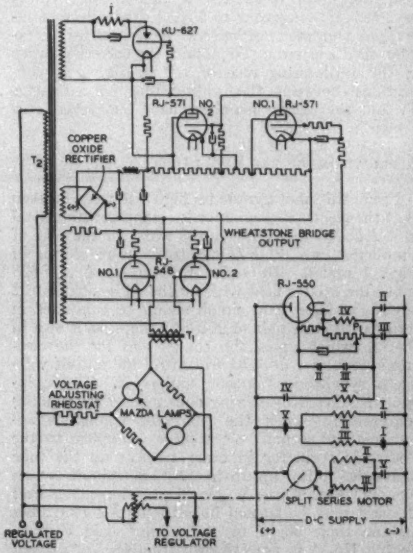


Fig. 7. Schematic diagram of electronic monitor

either be in phase with the regulated voltage or 180 deg out of phase, depending upon whether the regulated voltage is too high or too low. The operation of the voltage balancing bridge is based on the fact that the resistance of a Mazda lamp will increase with increasing lamp voltage, while the resistance of the Ward Leonard tubes connected in series with the lamps is practically independent of the applied voltage. In this connection may be mentioned that special type resistor tubes wound with copper nickel wire were used. This wire has a lower temperature coefficient than the nichrome wire used with the standard type resistor tubes.

The secondary winding of the grid transformer is connected to control a pair of *RJ-548* amplifier tubes energized from the main transformer, T_2, so that the current through the No. 2 *RJ-548* tube will increase and the current through the No. 1 *RJ-548* tube will decrease if the regulated voltage is increased. The 2 *RJ-548* tubes in combination with their anode resistors are connected in a wheatstone bridge circuit and the output of this bridge is applied in the grid circuit of the No. 1 *RJ-571* amplifier tube, which through the No. 2 *RJ-571* amplifier tube controls the *KU-627* tube which is connected in series with relay No. 1.

For an increase in regulated voltage the operation of the equipment is therefore as follows: The current through No. 2 *RJ-548* is increased. This causes an increased negative bias on the control grid of the No. 1 *RJ-571* tube, and the anode current of the No. 1 *RJ-571* tube will decrease. Decreasing No. 1 *RJ-571* anode current will decrease the negative bias

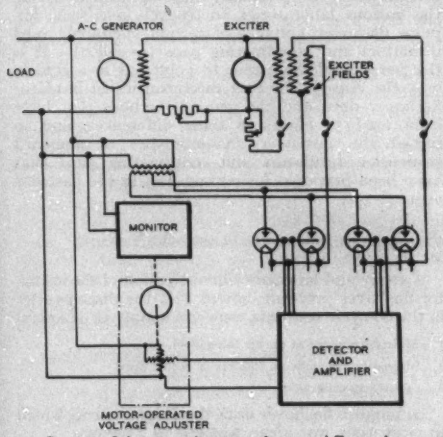


Fig. 8. Schematic diagram of type AT regulator with monitor

on the control grid of the No. 2 *RJ-571* tube which will produce an increase in the No. 2 *RJ-571* anode current with a consequent increase in the negative bias on the grid of the *KU-627* so that the current

Fig. 9. Switchboard with equipment shown in Fig. 8

flow through the *KU-627* will be stopped and the No. 1 relay deënergized.

If the regulated voltage is decreased, the opposite conditions obtain, and the *KU-627* tube will break down and energize relay No. 1.

When the voltage is normal, relay No. 1 will alternately close and open, and will energize either relay II or relay III, but no further relay action will take place. If, however, the regulated voltage remains too low or too high during a definite time interval of from 1 to 24 sec, dependent upon the adjustment of potentiometer P_1, relay IV will be energized. Supposing the voltage is too high, relay I would be deënergized and relay III energized. "Make" contacts of relay III now energize the time delay circuit, consisting of the *RJ-550* amplifier tube, relay IV, potentiometer P_1 and the condenser discharge circuit, and also close the control circuit for the motor operating the voltage adjuster which is connected to recalibrate the *AT* regulator as shown in Fig. 8. After a definite time interval, dependent upon the adjustment of potentiometer P_1, the current through the *RJ-550* tube is high enough to energize relay IV. "Make" contacts of relay IV energize relay V which completes the motor control circuit and the voltage adjusting motor will start to operate to increase the voltage applied to the detector terminals of the *AT* regulator, and thus decrease the regulated voltage. When relay V operates, "break" contacts of relay V deënergize relay III; but, being a slow releasing type relay, relay III will remain closed during an interval of from approximately $^1/_2$ to 1 sec. When relay III opens, the motor circuit is interrupted and the voltage adjusting motor stops. If the regulated voltage still is too high the sequence of relay operation will be repeated, and the motor will continue to operate during a period of from $^1/_2$ to 1 sec with intervals dependent upon the adjustment of the time delay potentiometer P_1.

Flashover Voltages of Insulators and Gaps

In an effort to clarify the confusion that has existed during past years regarding the flashover strength of insulators, the A.I.E.E. lightning and insulator subcommittee* has been engaged, jointly with high voltage laboratories of several insulator manufacturers, in an investigation to determine and eliminate differences in insulator flashover data from different sources, and to obtain reliable flashover data for standard insulators and gaps. In this latest report, the subcommittee presents average 60-cycle and impulse flashover voltages for suspension insulator strings consisting of 10-in. units with $5^3/_4$-in. spacing, and for coördinating gaps with various spacings.

IT IS WELL KNOWN that a knowledge of the safe dielectric strength of insulation and the relative flashover characteristics of line and station insulators, bushings, and air gaps is essential to a coördinated design of an electric power system if it is to be free from major interruptions. A realization of the importance of this coördinated design (largely a problem of determining the insulation strength of porcelain insulators where the dielectric breakdown is in air) may be gathered by referring to some of the work already done on the problem (see bibliography at end of paper).

The situation confronting the station and line designer until some 5 years ago was a complete lack of reliable flashover data on insulators, actual values given by manufacturers on what were, or appeared to be, similar insulators differing by as much as 25 to 30 per cent for 60-cycle flashovers and some 60 per cent for impulse flashovers. This condition, as well as the general principles of insulation coördination, were pointed out as early as 1928[1]; and shortly thereafter the problem of insulator flashover strengths and characteristics was given intensive study and investigation.

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 13, 1934; released for publication April 16, 1934. *Not published in pamphlet form.*

1. See bibliography at end of paper for all numbered references.

* Personnel of lightning and insulator subcommittee of A.I.E.E. committee on power transmission and distribution: Philip Sporn, *chairman;* I. W. Gross, *secretary;* C. L. Fortescue, K. A. Hawley, J. Allen Johnson, W. W. Lewis, J. T. Lusignan, and F. W. Packer.

In the early work of the lightning and insulator subcommittee, it was realized that impulse data must be made available on a basis both comparative and representative of natural lightning conditions that might be expected in the field. Intensive field investigations on natural lightning that were in progress in 1927 were supplemented in 1929 by the subcommittee's efforts to clarify the rather confused situation in the data then available on the flashover strengths of insulators. The first step was the establishing of preferred impulse test waves or yardstocks of measurements, the latest recommendations on which are covered by a subcommittee report published in 1933.[17] The situation in the field of 60-cycle flashover voltages of insulators, while less confused than the impulse voltages, presented a problem that also required attention.

Through the efforts of the subcommittee members associated with company laboratories where flashover tests of insulators were made, slow but sure progress so far has been made in reaching generally agreed upon flashover voltages of suspension insulators and one form of air gap. The carrying on of this work in the laboratory has been stimulated by other agencies. The transformer subcommittee of the A.I.E.E. committee on electrical machinery, as well as the National Electrical Manufacturers' Association and the Edison Electric Institute, through their committees on insulation coördination, have contributed their support to this work.

Results of this work have brought about a much clearer understanding of insulator flashover characteristics and the factors affecting them, so that at present there is reasonably close agreement among the various laboratories on 60-cycle and some impulse flashover voltages of certain commonly used insulators and coördinating gaps (so-called). It is the purpose of this paper to point out in a general way the reasons for past discrepancies in insulator flashover data and the general methods that have been used to eliminate these differences, and to record the flashover characteristics of standard suspension insulators and coördinating gaps that have been proposed for certain uses in the past few years.

Progress in Insulator Flashover Testing

A study and laboratory investigation of the insulator flashover problem showed that the discrepancies in the 60-cycle test data were due mainly to 3 factors:

1. Moisture content of the air (humidity).
2. Measuring instruments (spheres or needle gaps).
3. Sphere gap calibration.

In impulse flashover data the disagreement, which in most cases was great, was due to 7 factors:

1. Use of different test waves and of different definitions for a designated wave.
2. Failure to designate flashover as front, crest, or tail of wave flashover.
3. Failure to observe polarity (positive or negative) effect of test wave.
4. Presence of oscillations in the test wave.

5. Inaccuracies in measuring test voltages.

6. Questionable reproduction of the actual applied voltage wave due to different types of potentiometers, and oscillations in the test circuit.

7. Air conditions (air density and humidity).

In the attempt to reach a satisfactory solution of this problem, 4 of the major laboratories of etectrical manufacturers which were best equipped to make 60-cycle and impulse tests (General Electric Company, Westinghouse Electric and Manufacturing Company, Ohio Brass Company, and Locke Insulator Company) coöperated in a study of insulator and gap flashover. To show how carefully the work was conducted during its early stages, a given string of insulators was sent in turn to each of the 4 laboratories for test, and on the basis of the results obtained alterations in test conditions or equipment were made to eliminate such variables as were found or suspected. In this way most of the factors affecting the discrepancies were discovered and eliminated, and a means of reducing test data to a common basis was established.

Progress in the investigation of the causes of past discrepancies in suspension insulators flashover data has been so great in the past 2 years that the prominent laboratories are now in close agreement and are in a position to check these agreed upon values within close limits on standard suspension insulators with their regular test equipment. Correction factors for both 60-cycle and impulse voltages have been determined for certain types of insulators, and are applied to reduce test data to a common basis of humidity; this has eliminated one of the most troublesome factors in the past. Test circuits have been calculated and checked, and measuring spheres and methods have been cross checked.

The coördinating of test results between laboratories, which has been confined almost wholly to suspension insulators and gaps, to 60-cycle dry flashovers, and to positive impulse waves, is expected to be extended gradually to other types of insulators, such as pin and switch insulators and bushings, and to 60-cycle wet flashover data, impulse waves of negative polarity, and various voltage-time characteristics. Now that the ground work for the basic test data has been laid, it is expected that progress in securing these much needed data will be more rapid.

Basis of Present Data

As an outgrowth of the coöperative work of the 4 major laboratories mentioned, the basis to which the flashover data were referred, or corrected, was as follows:

Temperature.....25 deg C.
Barometric pressure.....760 mm of mercury.
Humidity.....6.5 grains of water per cubic foot, corresponding to a vapor pressure of 0.6085 in. of mercury.

Voltage measurements were made with the sphere gap as a primary standard, although the transformer voltmeter coil sometimes was used in 60-cycle testing and calibrated voltage dividers in impulse testing. In the use of the sphere gap, some discrepancies appeared where the calibration of different sized spheres overlapped, and also where sphere sizes and spacings exceeded those given in A.I.E.E. Standards No. 4. Since these sphere gap deviations, within the voltage range covered by standards No. 4, showed relatively small voltage variations they have been ignored mostly in the results presented herein. In the higher voltage range it is planned later to investigate the field of sphere gap calibration further, the values in this higher range given here being the best agreement possible at the present time.

As regards the accuracy of test results given for impulse flashover voltages, it is believed they can be relied upon within approximately plus or minus 5 per cent. The data on insulators were obtained from laboratory tests, each laboratory presenting its average curve of flashover voltages; the average curves of the 4 laboratories then were averaged and this one curve taken as the agreed upon set of values for the insulators tested. By this method, it was found that the spread of the average curves for insulators was not in excess of 5 per cent total, thus bringing any laboratory's curve within about plus or minus $2^1/_2$ per cent of the average curve. Although the agreement between laboratories is quite close on these average flashover voltages, single tests on a given insulator string may deviate from the given data in the order of $7^1/_2$ per cent.

In the case of 60-cycle flashover voltages, it might be expected that the problem of tracing the causes of discrepancies and reaching an agreement could be solved much more easily than with the impulse tests. While this may be the case, impulse tests, because of their importance in insulation coördination, have been given precedence in the investiga-

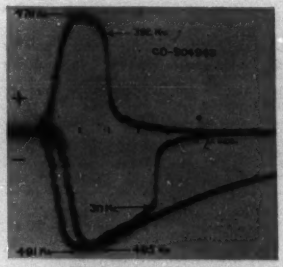


Fig. 1. Cathode ray oscillogram of flashover test on an insulator string consisting of 4 10-in. disk units spaced $5^3/_4$ in., with a 1 x 5-μsec wave

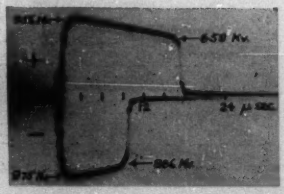


Fig. 2. Cathode ray oscillogram of flashover test on an insulator string consisting of 8 10-in. disk units spaced $5^3/_4$ in., with a $1^1/_2$ x 40-μsec wave

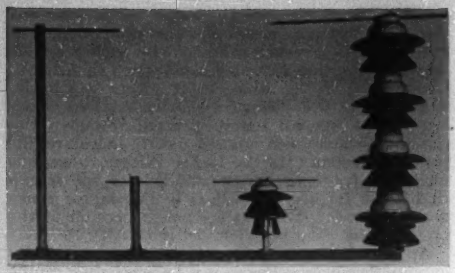


Fig. 3. Coördinating gap of the type used in obtaining the data given in this paper

The large gap is rated 138 kv and its spacing is 38¼ in.; the small gap is rated 46 kv and its spacing is 12¼ in.

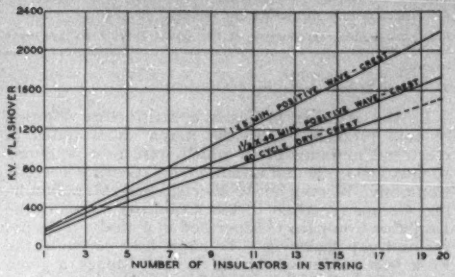


Fig. 4. Flashover voltages of suspension insulator strings consisting of 10-in. units spaced 5¼ in.

Humidity, 6.5 grains per cubic foot; barometric pressure, 760 mm.; temperature 25 deg C

tion work; as a result, there is closer agreement today between various laboratories on impulse test data of suspension insulators and gaps than on 60-cycle test data. The 60-cycle data given herein were obtained from the individual laboratories and, although not as yet definitely agreed upon, are the best representative average data available. The 60-cycle flashover situation, however, is being studied and it is expected that closer agreement soon will result. At the present time many of the average 60-cycle flashover voltages of insulators and gaps are already within the plus or minus 5 per cent mentioned for impulse tests, although some of the 60-cycle voltages may have a tolerance in the order of plus or minus 10 per cent.

While the general procedure in making 60-cycle flashover tests is well understood, the situation is vastly different in impulse testing. Because of the various methods used in the past in making impulse tests and reporting the data, a brief explanation of the methods used in securing the data presented in this paper will be given.

Table I—Flashover Characteristics of Suspension Insulator Strings Consisting of 10-In. Units With 5³/₄-In. Spacing

Barometer 760 mm; temperature 25 deg C; humidity 6.5 grains per cubic foot; vapor pressure 0.6085 in. of mercury

Number of Units in String	Flashover Kv (to nearest 5 kv) 60-Cycle Crest, Dry†	Minimum Positive Impulse Waves 1×5-μsec	1½×40-μsec
1	110*	170**	160**
2	205*	285**	255**
3	300	390	355
4	370	500	440
5	455	610	525
6	525	715	620
7	605	820	695
8	685	930	780
9	760	1,040	860
10	830	1,145	945
11	895	1,250	1,025
12	960	1,355	1,105
13	1,035	1,460	1,185
14	1,105	1,565	1,265
15	1,175	1,670	1,345
16	1,240	1,775	1,425
17	1,305	1,880	1,505
18	1,370	1,985	1,585
19	1,435*	2,090	1,665
20	1,490*	2,200	1,745

* Average values from 3 laboratories.
** Actual values reported by one laboratory only—subject to revision.
† Average values; not definitely agreed upon.

Test waves used were the preferred test waves recommended by this committee,[17] namely, 1×5 and 1½×40-μsec waves. The first number in the wave designation represents the time in microseconds from the origin of the wave to the crest, and the second number the time from origin to half the crest voltage on the tail. The minimum impulse flashover voltage recorded is the crest value of the lowest magnitude wave of the specified type that will cause flashover. With this method of testing, flashover of the test specimen invariably takes place on the tail of the wave. Typical test oscillograms are shown in Figs. 1 and 2.

In Fig. 1, which depicts a test on an insulator string consisting of 4 10-in. disk units spaced 5¾ in. with a 1×5-μsec wave, flashover is shown taking place in 2 μsec on the positive wave and in 3½ μsec on the negative wave. The "minimum voltage flashovers" are 478 kv and 491 kv, respectively, although the actual voltages at the instants of flashover were 392 kv and 317 kv, respectively. The full negative wave to which the insulator string was subjected without flashover, as shown below the zero line, had a crest value of 485 kv. Similar tests on an 8-unit string where the 1½×40-μsec wave was used are shown in Fig. 2. All impulse test voltages given in this paper are "minimum impulse" test values as just described, and, as before noted, of positive polarity only.

The coördinating gaps on which flashover data are given here were constructed according to the A.I.E.E. transformer subcommittee's recommendations, the general details of the gaps being given in past A.I.E.E. papers.[2,18] Figure 3 shows a photograph of typical 46-kv and 138-kv gaps such as used in securing these data in the laboratory. In making tests, however, only one gap was present at a time, although both gaps are here shown on a common base.

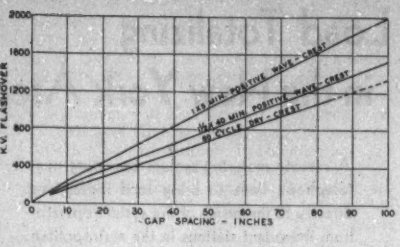


Fig. 5 (Left). Flashover voltages of coördinating gaps

Humidity, 6.5 grains per cubic foot; barometric pressure, 760 mm.; temperature 25 deg C

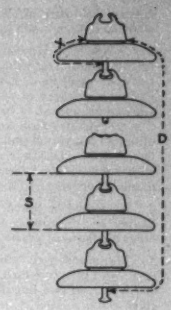


Fig. 6 (Right). Diagrammatic sketch of insulator string

Test Data

The flashover voltages of $5^3/_4$-in. spaced 10-in. disk insulators are given in Table I for insulator strings containing up to 20 units. These data, which have been given in tabular form to eliminate inaccuracies in reading the values from a curve, have been plotted in curve form in Fig. 4 for comparison. Similar data for coördinating gaps are given in Table II and plotted for comparison in Fig. 5 for gap spacings up to 100 in.

As stated before all these values in Tables I and II have been corrected to standard conditions of humidity, temperature, and barometric pressure. They represent flashover voltages that (except as noted) are the averages of results obtained in 4 different recognized laboratories which coöperatively have checked these data. It should be possible in any one of these laboratories to check these given data, at any time with an error not exceeding approximately 5 per cent.

In addition to the 10-in. disk suspension insulator unit with $5^3/_4$-in. spacing, there are in use today many similar units having $4^3/_4$, 5, and $5^1/_8$-in. spacing on which accurate and generally accepted flashover data are not available. The extent of the work necessary by the laboratories and coördinating groups to obtain the data for the $5^3/_4$-in. spaced units and the gaps presented in this paper has made it impossible, so far, to obtain and correlate data on the shorter spaced units. To apply the data for the $5^3/_4$-in. spaced units to shorter spaced units, the following procedure is suggested:

Referring to Fig. 6 which represents any standard insulator string having 10-in. diameter disks, let:

N = Number of insulators in the string.
D = Tight string distance between top and bottom hardware on insulator string.
X = Tight string distance of one insulator unit.
S = Spacing of one unit.
E = Flashover of N units, kilovolts.

Let N_s, D_s, X_s, S_s, E_s be corresponding references to any other similar insulator string having 10-in. diameter disks.

$$\text{Then, } E_s = E\left(\frac{S_s(N_s - 1) + X_s}{S(N - 1) + X}\right)$$

This relation should hold very closely both for 60-cycle and long wave impulse voltages *provided D and D_s are roughly equal*, since it is based on the total length of the breakdown path between approximately equal and similar electrodes (cap of one insulator to the pin of the same or another insulator). For short-tail impulse waves, the results to be expected by this method of converting impulse flashovers from insulators of one spacing to another are not so accurate, the error reported in one case being in the order of 10 per cent. It is believed, however, that the indicated method of conversion of impulse flashover voltages will be of value until actual test data on the insulator units with various spacings are obtained.

Summary

1. The confused situation, which was recognized as existing some 5 years ago and previously, in the matter of flashover voltages of insulators has been investigated during the past few years; the

Table II—Flashover Characteristics of Rod Gaps*

Barometer 760 mm; temperature 25 deg C; humidity 6.5 grains per cubic foot; vapor pressure 0.6085 in. of mercury

Gap Spacing, Inches**	Flashover Kv (to nearest 5 Kv above 150) 60-Cycle Crest, Dry†	Minimum Positive Impulse Waves 1×5-μsec	1½×40-μsec
0.5		24	24
1.0		42	42
1.5		53	53
2.0	42	61	61
2.5		67	67
3.0		75	74
3.5		85	82
4.0	78	95	89
4.5		107	98
5.0	84	120	106
6.0	103	148	124
8.0	119	195	160
10.0	145	240	190
15	215		
20	275	440	350
25	345		
30	415	640	505
35	485		
40	550	835	650
45	620		
50	685	1,035	800
55	755		
60	820	1,230	945
65	890		
70	955	1,425	1,095
75	1,010		
80	1,080	1,620	1,240
85	1,130		
90	1,190	1,815	1,385
100	1,315	2,010	1,530

* Rod gaps as referred to in the paper.
** All voltage values for gap spacings of 15 in. and less subject to revision as most of data in this range are from one laboratory only.
† Average values; not definitely agreed upon.

reasons for many of the past discrepancies have been found and steps have been taken to eliminate them.

2. Whole-hearted coöperation on the part of all groups working on this problem, particularly the laboratories of the 4 electrical manufacturers mentioned, has resulted in an agreement on the impulse flashover voltages of standard insulator strings and coördinating gaps which appear to be accurate within plus or minus 5 per cent. The 60-cycle dry flashover voltages for the same insulators and gaps, although not yet officially agreed upon by the 4 laboratories, are believed to be accurate in most cases within plus or minus 5 per cent, with some values indicating discrepancies in the order of plus or minus 10 per cent. These data are given in this paper.

3. A method of converting these agreed upon data on insulators having $5^3/_4$-in. spacing for use on similar insulator strings having other similar unit spacing, such as $4^3/_4$, 5, and $5^1/_2$ in., is given.

4. The meaning of "minimum impulse" flashover voltage of insulators and gaps is explained, and typical actual oscillograms of 1×5 and $1^1/_2 \times 40$-μsec impulse voltages applied to insulator strings are given.

5. Much more data on the impulse characteristics of insulators and insulation are required than the "minimum impulse" flashover data for 2 different test waves as given in this paper.

6. The groundwork that now has been laid for obtaining impulse data on a common basis, and with comparable results, should result in much more progress in obtaining impulse characteristics of insulators and other insulation which are essential to an intelligent application of insulation coördination.

Bibliography

1. Rationalization of Transmission System Insulation Strength, Philip Sporn. A.I.E.E. Trans., v. 47, 1928, p. 998.

2. Recommendations on Balancing Transformer and Line Insulations, Montsinger & Dann. A.I.E.E. Trans., v. 49, 1930, p. 1478.

3. The Coördination of Transformer Insulation With Line Insulation, Montsinger & Dann. A.I.E.E. Trans., v. 51, 1932, p. 923.

4. The Effect of Transient Voltage on Dielectrics—IV, F. W. Peek, Jr. A.I.E.E. Trans., v. 49, 1930, p. 1456.

5. Essential Factors in the Coördination of Line, Station, and Apparatus Insulation, A. E. Silver and H. E. Melvin. A.I.E.E. Trans., v. 49, 1930, p. 1491.

6. Standards of Insulation and Protection for Transformers, J. Allen Johnson and E. S. Bundy. A.I.E.E. Trans., v. 49, 1930, p. 1486.

7. Lightning, F. W. Peek, Jr. A.I.E.E. Trans., v. 50, 1931, p. 1077.

8. Insulator Sparkover, W. L. Lloyd, Jr. A.I.E.E. Trans., v. 51, 1932, p. 669.

9. Rationalization of Station Insulating Structures, C. L. Fortescue. A.I.E.E. Trans., v. 49, 1930, p. 1450.

10. Lightning Discharges and Line Protective Measures, C. L. Fortesque and R. N. Conwell. A.I.E.E. Trans., v. 50, 1931, p. 1090.

11. Impulse Flashover of Insulators, J. J. Torok and W. Ramberry. A.I.E.E. Trans., v. 47, 1928, p. 349.

12. Surge Characteristics of Insulators and Gaps, J. J. Torok. A.I.E.E. Trans., v. 49, 1930, p. 866.

13. Suspension Insulator Assemblies, J. J. Torok and C. G. Archibald. A.I.E.E. Trans., v. 51, 1932, p. 682.

14. Normal Frequency Arcover Values of Insulators, H. A. Frey and K. A. Hawley. A.I.E.E. Trans., v. 51, 1932, p. 690.

15. Relation Between Transmission Line Insulation and Transformer Insulation. W. W. Lewis. A.I.E.E. Trans., v. 47, 1928, p. 992.

16. An Approved Type of Gap for Protecting Station Apparatus, A. O. Austin. A.I.E.E. Trans., v. 51, 1932, p. 676.

17. Recommendations for Impulse Voltage Testing, A.I.E.E. lightning and insulator subcommittee. A.I.E.E. Trans., v. 52, 1933, p. 466.

18. Coördination of Insulation, V. M. Montsinger, W. L. Floyd, and J. E. Clem. A.I.E.E. Trans., v. 52, 1933, p. 417.

19. Influence of Humidity on Surge Flashover, F. D. Fielder. *Elec. J.*, July 1932, p. 348.

20. High Voltage Surge Tests on Standard Air Gaps, F. D. Fielder. *Elec. Jl.*, Oct. 1932, p. 459.

21. Rationalization of Transmission Insulation Strength, Philip Sporn. A.I.E.E. Trans., v. 49, 1930, p. 1470.

Load Totalizing in the New York Area

A remote metering system operating over telephone lines to bring load indications directly to the office of the system operator from important stations in the metropolitan area is described in this paper. A high degree of accuracy has been achieved, and important operating economies are expected.

By
F. ZOGBAUM
MEMBER A.I.E.E.

The New York Edison Co.,
New York, N. Y.

In supervising the electric system in New York, the system operator is principally responsible for having in service at all times sufficient generating, transmitting, and transforming equipment to meet adequately any demands that may be made upon the system. In addition, it is the function of the system operator to subdivide the load among the various generating stations in such a manner that the maximum operating efficiency will be maintained. In order to carry out these duties, the system operator must check continually the amount of load carried by each base load station, and be informed promptly of load changes in the regulating station and important tie lines.

In the past, the information was telephoned to the system operator but recent developments in the art of metering have made it possible to use ordinary telephone channels for the transmission of the metered quantities over considerable distances. On Jan. 19, 1934, indicators and recorders to show the loads carried by the principal generating stations were installed in the system operator's office of the New York Edison Company.

Transmission of Load Indications

The generating stations from which loads are transmitted to the system operator's office are shown on the map (Fig. 1). The system operator's office is located at 41st Street and 1st Avenue. The leased telephone lines over which the 2 indications are transmitted are shown in heavy lines. The load transmitted over the Niagara-Hudson interconnection is metered at Millwood and is trans-

Full text of a paper recommended for publication by the A.I.E.E. automatic stations committee, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 4, 1934; released for publication April 13, 1934. *Not published in pamphlet form.*

mitted directly to the system operator's office, as shown on the map.

On Fig. 2 is shown the system operator's board with the 10 load indicators arranged across the top. These meters indicate the 25-cycle load at Hell Gate, Waterside, and East River, the 60-cycle load at Hell Gate and Hudson Avenue and the load carried on the Niagara-Hudson interconnection. In addition, the total 25-cycle load and the total 60-cycle load are indicated separately, these 2 indications being combined on another indicator to show the total system generation. This total is again combined with the Niagara-Hudson interconnection load to give on the remaining indicator the total power consumed on the New York system. The last 3 indications, namely, the Niagara-Hudson interconnection, the total system generation, and the total system consumption, are recorded on 3 instruments mounted in a separate panel at the rear of the room, shown on Fig. 3.

At each generating station a polyphase thermal converter is connected to potential and current transformers of each generating unit. The converter develops a d-c voltage directly proportional to the a-c power output of the generator. By connecting the d-c terminals of the thermal converters in series as shown in the diagram, Fig. 5, the total voltage developed is proportional to the total power output of the station. This voltage is impressed on 2 wires (a telephone pair) connecting the terminals of the converters in series with a load indicator in the system operator's office, as shown.

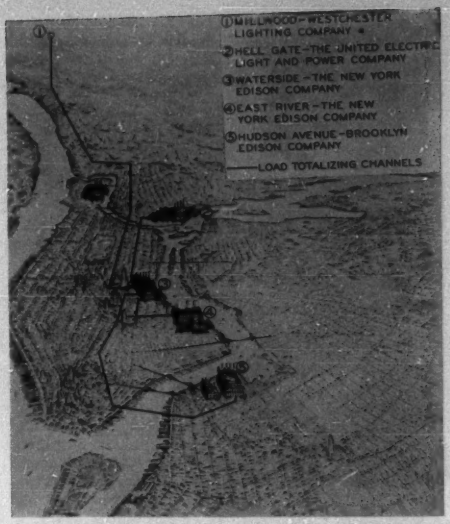


Fig. 1. Map showing locations of generating stations, system operator's office, and telemetering channels

Conversion

The calibration is not affected by normal ambient temperature changes as the temperature of the 2 thermocouple junctions which are located near each other are changed equally, and the difference in temperature, which is the measure of the power, is unchanged. The operating principle of the thermal converter is well known. (A detailed description may be found in P. M. Lincoln's paper, "Totalizing of Electric System Loads," A.I.E.E. Jl., v. 48, Feb. 1929, p. 129.)

Each station load indicator on the system operator's board is equipped with a circuit for transmitting an a-c voltage proportional to the indicated load. The transmitters of the 3 indicators for the 25-cycle stations are connected in series with an indicator showing the total load of these stations. The transmitters of the 2 indicators for the 60-cycle stations are also connected in series with an indicator totalizing their loads. Similarly the transmitters of these 2 totalizing indicators are connected in series with an indicator showing the total system generated load. A transmitter associated with this indicator operates a recorder in the rear of the office.

Thermal converters at Millwood transmit directly to the recorder at system operator's office. A re-

Fig. 2. System operator's board; note the 10 load indicators arranged across top

Fig. 3. Load totalizing recorders in system operator's office

transmitter operates the indicator on the board. This is also equipped with a retransmitter which acts in conjunction with that of the system generated load recorder to actuate a system total indicator and recorder. The tie line load is added or subtracted in the system total according to the direction of power flow to or from the system generated load; thus the total loads both generated and purchased or sold are recorded and indicated.

The receiving indicators developed for this installation are shown in Fig. 4. These indicators are of the potentiometer type and convert directly the totalized d-c voltage from the thermal converters into terms of megawatts load.

The potentiometer principle of balancing a known standardized emf against the emf of the converters is used and this permits a high degree of accuracy. Due to the fact that this principle involves balancing voltage and not measuring current, the IR drop in the line does not affect the accuracy. The current flowing is only that which causes the galvanometer to deflect when the voltages are not equal; hence, line resistance or changes in line resistance can affect only the sensitivity. The emf produced by the thermal converter provides ample sensitivity for any of the telephone channels used.

The load indicator is also arranged to transmit a low potential a-c proportional to the load which it indicates. The combining of the various loads as shown on Fig. 5 is, therefore, readily accomplished. The retransmitting and totalizing of the incoming load indications has been simplified in this installation by the use of alternating current. The only additional equipment necessary to accomplish this is an a-c potentiometer attached to the shaft of the individual indicators. The elimination of the standard cell, which would be necessary if totalizing were done by direct current, is of importance. Most of the possibilities of totalizing have been used in this installation, such as totalizing of individual station generator loads, totalizing of loads of different frequencies, and the combining of system generation with loads carried on interconnections to show net power consumed on the system. Only the retransmitting of totalized indications back to generating stations was omitted. While this could readily be accomplished with the system adopted, it was not thought necessary.

Table I—Resistance of Telephone Channels

	Ohms
East River	463
Hell Gate	1025
Hudson Avenue	1023
Millwood	3233

Fig. 4. Load indicator

Accuracy Obtained

An idea of the accuracy of the indications at the system operator's office may be obtained when it is understood that the indicators and recorders individually have a guaranteed accuracy of 0.33 per cent. As finally adjusted in the company laboratories the accuracy of the thermal converters is the same. Assuming the most improbable case wherein the individual errors are all in the same direction, let us determine the accumulated errors. At Hell Gate generating station during the normal evening load, generating capacity totalizing 300 megawatts will be on the line. The 5 thermal converters metering this load will introduce an error of 1 megawatt. In addition, the indicator on the system operator's board has a possible error of 0.33 per cent full scale reading (500 megawatts) which amounts to 1.67 megawatts, making a total possible error of 2.67 megawatts or 0.53 per cent on the 60-cycle Hell Gate indicator. Since the smallest division on this indicator represents 10 megawatts, the error of slightly over $^1/_4$ division is less than the error of reading.

Passing on now to a consideration of the next indicator which totalizes the Hudson Avenue sta-

tion load, we find that with a generating capacity of 540 megawatts connected to the line, the cumulative error in the thermal converters will be 1.8 megawatts. The Hudson Avenue indicator on the system operator's board with a scale of 800 megawatts has a possible error of 2.67 megawatts which, added to the converter error, gives a total of 4.47 megawatts or 0.56 per cent. The 60-cycle generation total indicator has a possible error of 3.33 megawatts based on the 1,000 megawatt scale. Adding all the above errors, a total possible error of 10.47 megawatts is obtained, which is slightly over 1 per cent of the full scale reading of the total 60-cycle generation indicator. Since the smallest division of this indicator represents 25 megawatts, the error of 10.47 megawatts is less than $^1/_2$ division, and is still within the error of reading.

In order to arrive at the possible error in the system total generated indicator, the same method of computing errors was applied to the 25-cycle load. This will give an accumulated error on the 25-cycle total indicator of 6.72 megawatts or 0.83 per cent. Adding this to the 60-cycle total error of 10.47 megawatts gives an accumulated error of 17.19 megawatts which is passed on to the system total indicator. This indicator with a scale of 1,600 megawatts will have an error of 5.33 megawatts. Therefore, the total possible error in the system total generated indicator is 22.5 megawatts, or less than $^1/_2$ division on this indicator. In terms of full scale reading, this error amounts to 1.4 per cent. It is evident, therefore, that at any point on the totalizing system, the accumulated errors are usually within the error of reading.

Standard telephone communication channels are used in every case to transmit the output of the thermal converters. Referring to Fig. 5, it will be seen that these channels vary in length from a few miles to 32 miles. The resistance of these channels is given in Table I.

Varying sizes of wire (No. 19 and No. 22) in the telephone channels and the fact that profile distances are given account for the lack of agreement between mileage and resistance.

Performance

Although no conclusion regarding the reliability of this equipment could be drawn from the satisfactory performance during the short period of its operation, it seems reasonable to expect little difficulty. The thermal converters have no moving parts, are mechanically strong and electrically well designed and should function correctly under all conditions which can reasonably be assumed. The potentiometer mechanism is essentially the same as that used in the temperature recorders, which have proved reliability by many years of satisfactory service. The telephone circuits have an excellent record of continuity.

Although the installation is too recent to enable its effect on operating economy to be measured, it is no exaggeration to say that it will contribute to economy. Before the installation of these meters, when the load on the regulating station varied, the operator at this station would report conditions to the system operator by telephone. The system operator would then by telephone issue instructions to operators in the base load stations to adjust load. Before these adjustments had been completed in the base load stations conditions in the regulating station might have changed so that the system operator's efforts to aid the regulating station were nullified. Moreover, the system operator was obliged to estimate the speed of the changes and to anticipate them if possible. Since the totalizing meters have been in service, the system operator has been able to distribute load changes so much more effectively that the number of telephone calls has been reduced by more than 75 per cent.

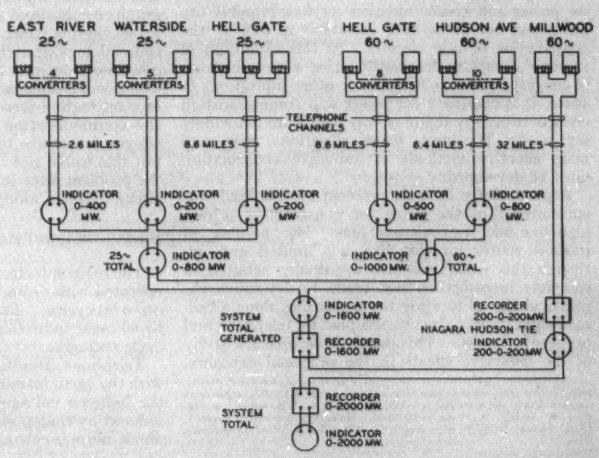


Fig. 5. Diagram of connections of the New York load totalizing system showing the method of combining the various load indications

MW—Megawatts

Iron Armored Aerial Communication Cable

This paper describes a study of the application of an iron armored aerial communication cable as an inductive coördination measure permitting a high voltage transmission line to occupy jointly for a distance of about 20 miles the same railroad right-of-way with telegraph and telephone circuits. Calculations are given indicating the induction to be expected on open wire communication circuits, and the degree of reduction afforded by several different designs of cables, both armored and non-armored. The effect of cable on the normal operation of the telegraph and telephone circuits carried through it also is considered.

By
C. L. GILKESON
MEMBER A.I.E.E.
Edison Elec. Institute, New York, N. Y.

A. J. HANKS
MEMBER A.I.E.E.
Western Union Telegraph Co., New York, N. Y.

INCREASING PUBLIC DEMAND for power and communication services requires the maximum use of existing facilities, as well as the construction of new circuits. In this expansion of service, situations frequently arise where, because of congestion of wire facilities or other limitations of space, it is necessary for power and communication circuits to occupy rights-of-way which are not widely separated. To meet these situations new and more effective methods of inductive coördination must be developed.

A particularly difficult problem of this kind was encountered in the plans for constructing a new high tension transmission line. The number of possible routes for this line was limited and, although this route was not eventually selected, a complete investigation was made to determine the practicability of locating the power line along a railroad right-of-way already occupied by telephone and telegraph circuits. This paper deals with the study of the inductive effects in the proposed exposure, the application of suitable coördinative measures to the power line, the design of a communication cable which meets the unusual conditions imposed, and the results which may be expected from the use of such a cable.

These studies of the application of iron armored cable as a remedial measure, where communication circuits are subject to large induced voltages, indicate the following conclusions:

1. An iron armored cable of practical design can be made which will give a large reduction in induced voltage.

2. The efficiency of the cable as a shielding medium can be greatly increased by increasing the conductivity of the sheath, but to take full advantage of this shielding, the sheath must be terminated at the ends of the exposure through the equivalent of a very small impedance to ground.

3. An iron armored cable is applicable to both ground return telegraph circuits and to telephone circuits, and its effect on the normal operation of both classes of circuits is in general but little different from that of an equal length of non-armored cable.

4. An iron armored cable, although expensive, is a practical means of coördination in certain situations where other methods will not give a sufficient reduction in voltage. It is effective under both normal and abnormal operating conditions on the power system.

Description of Exposure

The proposal contemplated the construction of a twin circuit line supported on a bridge type structure overbuilding the railroad for a distance of about 20 miles. The line was designed for vertical arrangement of the phase conductors with 2 overhead ground wires.

The width of the right-of-way would not permit the use of open wire construction for the communication lead, so no study of possible coördination of open wire was made. Aerial construction supported on the same structures as the transmission line was preferred to underground to reduce the cost and to avoid electrolysis from d-c traction current.

There is at present on this railroad right-of-way a pole line carrying high speed multiplex printing telegraph circuits, land wire connections for transatlantic cable circuits, and telephone circuits used by the railroad for dispatching. Obviously, these facilities could not continue to operate under such severe exposure conditions unless unusually effective methods of coördination were applied to both the power and the communication circuits. The removal of the telegraph circuits to another route was considered, but this would not have been a complete solution of the problem since it was essential that the telephone circuits remain along the railroad.

Effect of Induction on Communication Circuits

The telegraph circuits in this exposure are normally operated with ground return and employ frequencies up to 60 cycles. Thus they are especially susceptive to 60-cycle induction and are also affected by 180-cycle voltages.

Telephone circuits are operated on metallic pairs with the earth forming no part of the circuit. Hence the induced voltages between wires can be largely reduced by transposing both sides of the pair. Telephone noise is caused by voice-frequency harmonics,

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25-29, 1934. Manuscript submitted March 1, 1934; released for publication March 25, 1934. *Not published in pamphlet form.*

the fundamental 60-cycle induction being relatively unimportant unless it is of sufficient magnitude to operate protective devices or become hazardous to equipment or personnel.

In this particular situation, there are 3 sources of induction arising from the normal operation of the power system, and since the measures which may be applied to reduce their effects are different, they are treated separately. The sources are as follows:

1. Direct induction from the balanced 3-phase currents due to unequal distances of the several phase conductors from the communication circuit. Transposition and proper arrangement of phases of multiple circuit lines carrying equal current per conductor are effective in reducing this type of induction. The latter measure is, of course, not effective when only one circuit is in service.

2. Secondary induction from currents flowing in the ground wire circuit. These currents are caused by direct induction from the balanced phase currents, and may be reduced by transposition and proper phase arrangement.

3. Induction from residual currents. These currents flow in a circuit consisting of the phase conductors in parallel, with return through the earth or other metallic paths. Residual currents are caused by unbalances in the system or triple harmonic voltages. Transpositions and phase arrangements have no influence on these inductive effects, except in so far as they may reduce unbalances in the line. Overhead ground wires and other shielding structures are effective in reducing induction from this source.

The magnitude of the induction from these different sources is indicated in Table I, together with the degree of reduction that can be secured by the various methods of coördination mentioned. The direct induction from balanced currents and that from the currents in the ground wires are both related to the phase wire current, and therefore the inductions from these 2 sources must be added vectorially. The twin circuit transmission line was designed for a full load current of 625 amp, hence this figure is taken as the basis for the calculations.

For the purpose of this study, a residual current of 6 amp is assumed; and, since its relationship to the load current is not known, the induction from this source has been added arithmetically to that resulting from the load current in order to get the total maximum induced voltage under normal operating conditions.

Calculations indicated that, in the event of a ground fault on one phase, a maximum current of 2,600 amp might be drawn through the exposure;

Curve A—original line
Curve B—open wire in exposure replaced by cable
Curve C—transmission to intermediate repeater, with cable through exposure

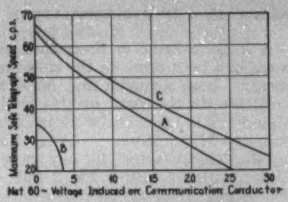


Fig. 1. Relation between telegraph transmitting frequency and induced voltage

therefore the calculated abnormal voltage is based upon this value. This fault current is a residual current and therefore its effect is reduced by the shielding effect of the ground wires, but it is not affected by transpositions. The calculated shield factor for the ground wires (0.67) is not so good as is usually secured with ground wires of this conductivity, because the phase conductors are about midway between the ground wires and the communication conductors.

In Fig. 1 are given the results of a study made to determine the effect of various amounts of induced voltage on the transmission speed of the multiplex telegraph circuits. It is apparent that measures in addition to those indicated in Table I must be provided if satisfactory coördination of these circuits is to be secured. A method suggested was the use of an iron armored cable for the communication conductors. To satisfy all the desired conditions of this particular case, it should accomplish the following:

1. Reduce the normal induced voltage as much as is economically justified. In the present case, it was recommended that the induced voltage with only a single power circuit in service, which is the more severe condition of operation, should be reduced from 170 volts to about 5.

2. Reduce the induced voltage under abnormal conditions from 18,600 volts to less than 900, which is the breakdown potential of the standard cable protectors.

3. Provide a sufficiently low impedance path from cable sheath to ground so that in case of contact with a phase conductor the communication cable would not be raised to such a voltage that its insulation would be broken down.

Table I—Calculated Open Circuit 60-Cycle Voltage Induced Along Communication Circuit Without Cable Shielding

Length of Exposure 20 miles; Earth Resistivity 100 meter-ohms; Efficiency of Transpositions 90%

	Normal Induction						Total Induction	
	From Balanced Current			From Residual Current*			Max.	Max.**
	Direct	Ground Wire	Total	Direct	Ground Wire	Total	Normal	Abnormal
Twin Circuit Operation; 312.5 amp per phase								
No transpositions; horizontal arrangement	940	315	1,250	64	23	42	1,290	18,600
No transpositions; diagonal arrangement	101	37	64	64	23	42	106	18,600
Line transposed; diagonal arrangement	10	4	6	64	23	42	48	18,600
Single Circuit Operation; 625 amp per phase								
No transpositions; horizontal arrangement	990	290	1,270	64	23	42	1,310	
No transpositions; diagonal arrangement	990	290	1,270	64	23	42	1,310	
Line transposed; diagonal arrangement	99	29	127	64	23	42	169	

Horizontal Arrangement		Vertical Arrangement	
Circuit 1	Circuit 2	Circuit 1	Circuit 2
Phase ....A	A	Phase ....A	C
Phase ....B	B	Phase ....B	B
Phase C	C	Phase C	A
Horizontal arrangement		Diagonal arrangement	

* Assuming 6-amp residual current.
** Including shield factor of ground wires (0.67).

Application of Cable Shielding

A large amount of theoretical and experimental work had been done on the shielding effect of cable sheaths, both armored and non-armored, and was available at the time of this study. The theory underlying much of this work has been described in a paper by H. R. Moore.[1] An equation is there given for the "shield factor" for any aerial communication cable grounded only at the 2 ends of the exposure. The shield factor (η) may be defined as the ratio of the resultant or shielded voltage to the initial or non-shielded voltage. Lower values of the shield factor thus indicate greater shielding. The equation is as follows:

$$\eta = \frac{r_{22} + R/l}{z_{22} + Z_{22}^{\circ} + R/l} \tag{1}$$

Where

r_{22} = d-c resistance of cable sheath per unit length
z_{22} = internal impedance of cable sheath per unit length
Z_{22}° = external impedance of cable sheath per unit length
R = total resistance of grounding connections
l = length of exposure

The external self impedance Z_{22}° is the same as the impedance with ground return of a thin walled, perfectly conducting tube, closely fitted about the cable sheath and grounded at the ends through a resistanceless connection. It is dependent upon the radius of the sheath, its position with respect to the earth, and the earth resistivity. The magnitude of the external self-impedance may be determined from Carson's equation.[2]

The internal self impedance z_{22} depends solely upon the composition of the cable sheath, and consists of the sheath d-c resistance r_{22} plus contributions due to the flux within the iron armor. The latter comprise a resistance increment Δr_{22} due to hysteresis, eddy currents, and skin effect, and a reactance increment X_{22} due to the linkages of the flux within the boundaries of the iron. Thus

$$z_{22} = r_{22} + \Delta r_{22} + jX_{22} \tag{2}$$

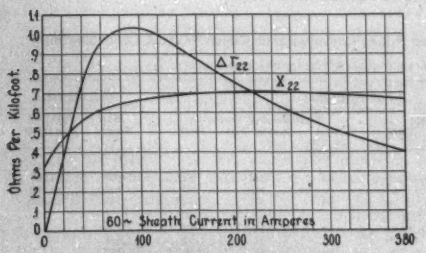


Fig. 2. Internal impedance components of an armored communication cable

Armor comprising 2 steel tapes each 2x0.04 in.; main radius of armor, 1.3 in.; Δr_{22} does not include d-c resistance

The values of Δr_{22} and X_{22} depend upon the current in the cable sheath and its frequency, as well as on the characteristics of the iron armor, its dimensions and position. These values can best be determined experimentally, and curves for a representative armored cable are given in Fig. 2.

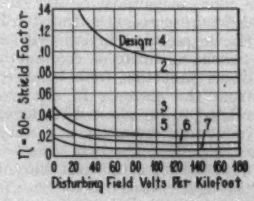
Combining equations (1) and (2), the shield factor may be expressed as

$$\eta = \frac{r_{22} + R/l}{r_{22} + \Delta r_{22} + jX_{22} + Z_{22}^{\circ} + R/l} \tag{3}$$

It is evident that the shield factor may be reduced either by decreasing the ground resistance R or by reducing the sheath resistance r_{22}. The same result can be obtained by increasing the internal impedance components Δr_{22} and X_{22}, but the external impedance Z_{22} is usually fixed rather definitely by the conditions of the problem. The d-c resistance of the sheath may be reduced by introducing copper conductors in parallel with the lead sheath, and the quantities Δr_{22} and X_{22} may be controlled by the type of armor employed. The problem is to determine the most economical combination of iron armoring and copper shielding capable of providing the desired degree of reduction.

Fig. 3. Relation between shield factor and disturbing field

Cable comprising 38 pairs of No. 13 A.W.G.; earth resistance 100 meter-ohms; sheath perfectly grounded
Armoring comprises 2 iron tapes each 2x0.04 in.



Design No. 1 (not shown) non-armored cable; shielding copper, none; sheath d-c resistance (r_{22}), 0.135 ohm per 1,000 ft
Design No. 2—non-armored cable; shielding copper, 500,000 cir mils; sheath resistance (r_{22}), 0.018 ohm per 1,000 ft
Design No. 3—non-armored cable; shielding copper, 1,000,000 cir mils; sheath resistance (r_{22}), 0.0097 ohm per 1,000 ft
Design No. 4—armored cable; shielding copper, none; sheath resistance (r_{22}), 0.135 ohm per 1,000 ft
Design No. 5—armored cable shielding copper, 300,000 cir mils; sheath resistance (r_{22}), 0.028 ohm per 1,000 ft
Design No. 6—armored cable; shielding copper, 500,000 cir mils; sheath d-c resistance (r_{22}), 0.018 ohm per 1,000 ft
Design No. 7—armored cable; shielding copper, 1,000,000 cir mils; sheath d-c resistance (r_{22}), 0.0097 ohm per 1,000 ft

Fig. 3 shows the shield factor, calculated from eq 3, for several non-armored and armored cables containing various amounts of shielding copper. The shield factors are plotted against the disturbing field intensity, i. e., the voltage which would be induced along the conductor in the absence of any cable shielding. It is seen that non-armored cables provide uniform shielding regardless of the value of the disturbing field. The armored cables give better shielding as the disturbing field is increased, up to about 150 volts per 1,000 ft.

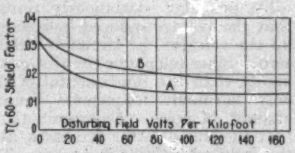
This variation in the shield factor is caused by the non-linear relation between the sheath internal impedance and the sheath current. The induced sheath current depends upon the magnitude of the disturbing field and the self impedance of the sheath

circuit; and the internal component of this self impedance depends, in turn, upon the value of the current. As a result of this mutual interdependence, the shield factor corresponding to a given disturbing field intensity can be determined only by a laborious cut and try solution. The curves in Fig. 3 were prepared in order to avoid this method. First several arbitrary values of sheath current I_2 were chosen and the corresponding values of Δr_{22} and X_{22} were obtained from Fig. 2. Then assuming a zero grounding resistance R, the disturbing fields

$$E_2 = I_2\,(r_{22} + \Delta r_{22} + jX_{22} + Z_{22}^{*})$$

which would produce these sheath currents were computed. Using the same values of Δr_{22} and X_{22}, the shield factors were calculated and plotted (η vs. E_2) for each cable.

Fig. 4. Effect of cable termination



Curve A—cable grounded at ends of exposure through zero ohms
Curve B—cable extended 1 mile beyond each end of exposure and grounded at ends and at each tower
Cable Design No. 6; 20-mile exposure; 15 towers per mile; tower footing resistance 10 ohms each; earth resistivity 100 meter-ohms

Due to the small separations existing in this exposure, it was considered desirable to investigate the effect of the cable sheath current in inducing additional currents in the ground wires on the power line. A calculation was made by the method of successive approximations to determine this effect. The results indicated that the mutual interaction between the circuits introduces a modification of only 5 per cent in the induced voltages. Accordingly, this refinement was neglected.

Table II was prepared to show the shielding to be expected from each of the cable designs in Fig. 3 under 2 important conditions. In this particular exposure, the maximum disturbing field, as given in Table I, is about 175 volts per 1,000 ft for abnormals and 1.6 volts per 1,000 ft for normal single circuit operation. Cable designs Nos. 3 and 6 both provide sufficient shielding to reduce this induction to the approximate condition desired, but design No. 6 was accepted as the better solution because of lower cost, and because it provides greater shielding at the higher intensities of disturbing field. Design No. 6 will also be less influenced by the resistance of the grounding connections than No. 3, since the d-c resistance of a 20-mile length of cable No. 6 is 1.9 ohms while the resistance of cable No. 3 is only about 1.0 ohm.

Effect of Sheath Grounding Connections

The shield factors presented in Fig. 3 are based on the assumption that the cable sheath will be provided with perfect ground connections at the ends of the exposure. Actually the character of the terrain in the vicinity of this exposure is such that it would be impracticable to secure and maintain ground connections with the extremely low resistance required. In practice, the sheath would be grounded at each tower through the tower footing resistance, and the cable would be extended some distance beyond the ends of the exposure. The theoretical considerations applying to this problem are the same as those for an underground cable with distributed leakance to ground, the assumption being that the tower footings are of uniform resistance.

Table II—Effect of Type and Conductivity of Cable Sheaths on 60-Cycle Induced Voltages Given in Table I

Design No.	Shielding Copper (cir mils)	Cost Factor	Shield Factor* Max. Normal	Shield Factor* Max. Abnormal	Remaining Voltage Max.** Normal	Remaining Voltage Max. Abnormal
Non-Armored Cable						
1	None	0.49	0.480	0.480	81.1	8,930
2	500,000	0.86	0.075	0.075	12.7	1,390
3	1,000,000	1.20	0.040	0.040	6.8	740
Armored Cable						
4	None	0.64	0.213	0.091	36.0	1,690
5	300,000	0.89	0.048	0.020	8.1	370
6	500,000	1.00	0.031	0.013	5.2	240
7	1,000,000	1.34	0.017	0.007	2.9	130

* Assuming no resistance from sheath to ground.
** Single circuit operation, with power line transposed.

Calculations were made to determine the degree to which the shielding from such a cable can be made to approach that obtainable when the sheath is perfectly grounded. In Fig. 4 is shown a comparison between the shield factor for cable No. 6 when solidly grounded, and when grounded through 15 towers per mile and extended one mile beyond each end of the exposure. The towers were assumed to have a footing resistance of 10 ohms each. It is seen that, for the normal induction of 1.6 volts per 1,000 ft, the shield factor is within 10 per cent of that obtainable under ideal conditions. For the abnormal induction of 175 volts per 1,000 ft, the shield factor is 30 per cent greater than that provided by a perfectly grounded sheath. Reference to Table II indicates that neither of these increases is sufficient to make the resultant voltages exceed the design requirements.

Recommended Cable Design

The recommended cable, which is shown in Fig. 5, contains 19 quads of 13-gauge conductors. It is provided with paper insulation to withstand 1,200 volts rms between conductors and 3,500 volts rms between the conductors and sheath. Over this insulation, and in contact with the lead sheath, is spiraled 500,000 cir mils of bare copper wire to provide the necessary additional sheath conductivity. Contact between the spiraled layer and the sheath is afforded by a helical winding of thin copper strip, partly overlaid with paper. This construction prevents the bare copper winding from adhering to the

lead sheath, which might cause the latter to tear when it is bent. External protection of the lead sheath is secured by means of a paper wrapping and a covering of jute over which are spiraled 2 galvanized iron tapes each 40 mils in thickness and 2 in. in width. They are put on in 2 layers with a $^1/_2$-in. gap between turns and with gaps overlapped, giving an over-all diameter to the cable of $2^3/_4$ in. The weight of the cable, 10.66 lb per ft, necessitates the use of 2 cable messengers and catenary construction.

Voltage Between Cable Sheath and Conductors in Case of Contact With a Phase Wire

Operating experience with transmission lines, of the same grade of construction as this line, has indicated that the possibility of a conductor falling is remote, but because of the location of the cable, consideration must be given to the effects which might result from a direct contact between the sheath and a fallen phase conductor. In the event of such a contact, the cable sheath will be raised to a potential above earth equal to the product of the fault current and the impedance of the sheath to ground. This potential will exist between the sheath and the internal conductors at the point of contact, but will not appear along the conductors or at the terminals as will the induced voltage. The voltage of the sheath above ground in case of direct contact was calculated for two locations of the fault. In both cases the fault currents were calculated for the arrangement of lines, station capacity, etc., giving the largest fault current. The impedance of the cable sheath to ground was obtained by assuming 15 towers per mile, each with a tower footing resistance of 10 ohms. The computed voltage of the sheath above ground and internal conductors for contact either in the middle of a span or at a tower is given below.

Location of Fault at End of Line to Give	Fault Current (Amp)	Voltage of Sheath to Ground: Contact in Middle of Span	Voltage of Sheath to Ground: Contact at Tower
Max Current	6,400	3,650	2,400
Min Current	2,800	1,480	980

Effect of Cable on Normal Circuit Operation

Telegraph Circuits. For telegraph transmission open wire construction is preferred to cable, partly for financial reasons and partly because any kind of cable has higher transmission losses than an open wire circuit. For multiplex circuits, a mile of 13-gauge cable is equivalent to about 5 miles of open wire; and for carrier circuits, the cable loss is from 6 to 10 times that of open wire. The additional losses caused by the insertion of over 20 miles of 13-gauge cable in this case will require the establishment of an additional repeater point for the telegraph circuits. Figure 1, previously discussed, shows a comparison of the estimated speeds of transmission, with various magnitudes of induced voltage, for the present open wire circuit, and for the modified circuit with and without an added repeater.

This investigation indicates that the effect of the iron armored cable on normal telegraph operation is practically the same as that of an equal length of non-armored cable. The only change in the constants of the circuits is a slight difference in the ground-return self impedance of the telegraph circuits due to the iron armor, a modification which is not important.

Some generation of harmonics is to be expected from the current in the non-linear impedance of the cable sheath circuit, but theoretical and laboratory studies indicate that the magnitude of these harmonics is so small that they will have no appreciable effect on the operation of the telegraph circuits.

Telephone Circuits. Earlier in the paper attention was called to the fact that the voltage induced between the sides of the telephone circuits can be reduced to small values by transposition. The use of cable provides continuously transposed circuits so that the voltage induced between the wires making up the sides of the circuit is reduced practically to zero. Since telephone circuits operate at frequencies higher than the fundamental of the power system, only harmonic frequencies cause an appreciable amount of noise. An examination of eq 3 indicates that the shield factor decreases, as the frequency of the induced voltage increases. Thus an increased efficiency of shielding exists at the higher frequencies, compensating in part for the greater coupling at these frequencies.

There will be some high frequency voltages appearing along the telephone conductors due to harmonic generation in the cable sheath, but a low impedance path is provided for the harmonic currents in the sheath ground-return circuit; thus the voltages along the internal conductors will be small. Furthermore, such induced voltages are along the conductors in parallel and not between the sides of the circuit, so any current producing noise will be

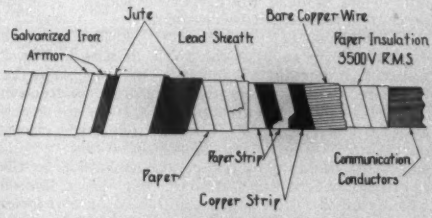


Fig. 5. Recommended design for armored aerial cable

due to this voltage acting on unbalances in the telephone circuit. With the type of telephone terminal equipment normally used with this type of circuit and the high degree of balance in communication cable, the noise from this source will be so small that it cannot be easily measured.

As in the case of the telegraph circuits, the use of

cable introduces additional losses in the telephone circuits. Since some of the open wire telephone circuits are already long and are working near their limits of satisfactory operation, the addition of cable will require the insertion of loading coils and repeaters to compensate for losses and distortion.

References

1. Iron Shielding for Telephone Cables, H. R. Moore. Elec. Engg., Feb. 1934, p. 274–80.
2. Wave Propagation in Overhead Wires With Ground Return. *Bell Syst. Tech. Jl.*, Oct. 1926.

The Suspension Insulator

Improvements and strengths of suspension insulators which have been attained since the publication in 1931 of a paper by the present author are outlined in this paper. Details of the improvements which have been made since that time are discussed herein, and considerable data on the strength of suspension insulators of different types are given.

By
K. A. HAWLEY
MEMBER A.I.E.E.

Locke Insulator Corporation, Baltimore, Md.

A PREVIOUS paper on the development of the porcelain insulator, as of September 1930, told of the step-by-step process of suspension insulator improvement. (See "Development of the Porcelain Insulator," by K. A. Hawley, A.I.E.E. Trans., v. 50, 1931, page 47–51.) Progress has been made in the meantime calling for a further report on this subject.

Strength Rating and Safety Factors

Insulators are given strength ratings based upon quick laboratory tests according to the A.I.E.E. Standards 41–154. The question is frequently asked as to how these are to be interpreted in terms of time loadings, what the elastic limits will be, and what safety factors are to be used. The purpose of this paper is to discuss these further developments and to establish insulator strengths in terms of their ratings.

Need for Higher Strength

The earlier insulators, as reported, had a strength under sustained load of barely 7,000 lb before fracture and electrical failure would occur. Many thousands of these insulators are in service giving an excellent account of themselves. Yet occasionally through overloads breakages have occurred. We know of at least 4 separate cases, well scattered from coast to coast, where insulators of these strengths and of various origin have been literally pulled apart by excessive ice loadings.

It was shown in the previous paper how, by a slight change in the hardware structure, this strength was increased first to 10,000 lb and then by further checking and balancing to 17,000 lb before failure on time loading tests.

Ratings of Insulators Investigated

The insulators covered are those which would be given A.I.E.E. strength ratings of 15,000, 18,000, 25,000, and 30,000 lb, respectively. While more complete tests have been made upon the 18,000 and 30,000 lb types than upon the others, efforts at strength standardization among the manufacturers are bringing the other 2 to the fore.

Improvement Details

After the initial work of providing resilience between the inner surface of the cap and the cement, as described in the previous paper, the increase in strengths of suspension insulators had been largely a matter of increasing head heights. An extensive series of tests and research culminating around 1931 showed the value of slight modifications of design. Notable among these were improved methods of manufacture allowing the insulator head to be made with a more nearly vertical side wall on the outside and in the pinhole, greater accuracy in glaze fit, the adoption of definitely graded "sand" for the cement grips, and the reglazing of these cement grips. This work has been fully covered in the previous A.I.E.E. paper by the author and in articles by D. H. Rowland (see "The Influence of Glaze on Insulator Strength," *G. E. Rev.*, v. 32, 1929, p. 136–8; and "Recent Improvements in High-Voltage Insulator Design," v. 33, 1930, p. 384–7). This allowed the height of the head to be decreased without sacrifice of strength and added considerably to the uniformity of the insulator strengths.

The cost of firing and consequently the cost of the completed insulator are to a certain large extent dependent upon over-all height. The reduction in the head height allows fuller porcelain hood depth, more rugged exposed parts, greater leakage surface, and a measurable if not marked increase in impulse

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 13, 1934; released for publication April 30, 1934. *Not published in pamphlet form.*

arc-over value, features which have all been incorporated in the present standard suspension insulator.

It has been recognized for years that the centering of the bolt within the pinhole had a direct influence on the strength of the insulator. If the edge of the

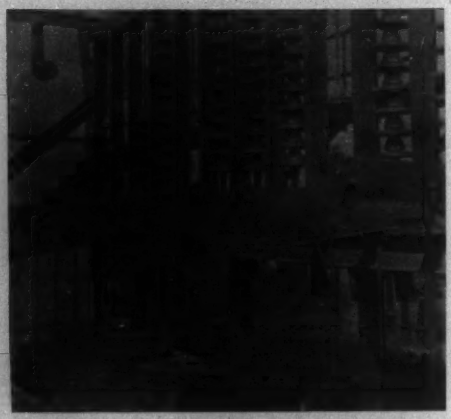


Fig. 1. Outdoor test frame at Baltimore, Md., for making duration strength tests on suspension insulators

bolt bore upon the porcelain, concentrated loads upon the porcelain were likely to cause cracking and failure at a low value. This difficulty has been overcome by the use of a star shaped pad or washer of impregnated paper glued to the top of the bolt. This washer is so designed to allow free flowing of the cement past it as the bolt is introduced into the cement filled pinhole. Its star shaped prongs are adequately flexible to enter the hole and yet quite accurately center the bolt. The adoption of this type of washer in preference to the old round washer

Table I—Tests on Insulators, 18,000-lb Rating, Single-Stepped Bolt

Test	Cement 24 Days Old M. & E.	Ultimate
1	23,800 lb	23,800 lb
2	24,700 lb	24,700 lb
3	23,000 lb	25,000 lb
4	24,400 lb	24,400 lb

which merely covered the bolt head has greatly contributed to the present marked uniformity found on routine test.

Another feature that has always introduced a variable had been the need for exact placement of the edge of the sand belt. If the edge of the sand belt falls within the area of load application, slippage of the cement upon the smooth glazed unsanded surface may throw an excess load directly upon this point. The flexibility of the cap lip adequately cares for the loading upon the outside of the head at the lower edge of the sand belt.

However, locating the inner edge of the sand belt within the pinhole at a definite point is difficult for even the most skilled operators. This difficulty has been overcome by extending the sand belt completely down the walls and over the bottom of the pinhole.

The Multiple-Stepped Bolt

The construction of an insulator can be likened to an arch in which the lower part of the cap forms the abutments with the bolt for a keystone. The conception indicates the requirements in bolt design. A reduction in the height of the dome necessitates a reduction in the height of the keystone as represented by the stepped top end of the bolt. If the bottom step of the bolt comes below the level of the abutment of the arch we have a condition in which the tendency is for the arch to turn inside out much as the bottom of an oil can turns when pressed. The insulator, however, not being of flexible material like the oil can, cannot bend and consequently breaks. This is obviated by the number of steps used on the bolt.

The shape of the stepped bearing surfaces of the bolts has been the subject of many studies. The cement and porcelain, having almost identical moduli of elasticity, structurally work together as a

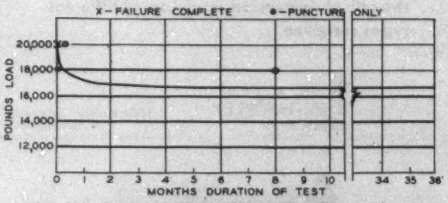


Fig. 2. Probable life of 18,000-lb class insulators under stress

single piece. Small but positive cement thickness is needed to distribute the load through the porcelain. Tests with the single-stepped bolts with curved or straight surfaces have shown no advantages in their favor. Tests results listed in Table I give actual values for insulators with single curved stepped bolts and may be compared with those given in Table II for insulators with 2-stepped bolts.

Insulators of 18,000-lb rating and with 2-stepped bolts were also tested to demonstrate:

a. The effectiveness of the 2-stepped bolt.
b. The uniformity of strength with well set cement.

Those who work with cement know the varying

rate of cement setting prevents uniform strengths with relatively green cement. Many variables affect the rate of setting, such as size of cement grains, time between mixing and using of cement, and the temperature of the insulator during the entire cementing period. Table II, an excerpt from a typical test report, will make this point clear. The insulators in each batch were identical except in the length of time elapsed between assembly and testing.

Table II—Tests on Insulators, 18,000-lb Rating, 2-Stepped Bolts

Test	18 Day Cement		28 Day Cement	
	M. & E.	Ultimate	M. & E.	Ultimate
1	22,000 lb	25,900 lb	27,150 lb	27,150 lb
2	19,900 lb	29,000 lb	27,100 lb	27,100 lb
3	23,450 lb	28,300 lb	27,750 lb	27,750 lb
4	22,300 lb	27,700 lb	26,100 lb	26,100 lb
5	24,350 lb	26,200 lb	25,000 lb	26,850 lb
6	27,900 lb	28,400 lb	26,800 lb	26,800 lb
High	27,900 lb	29,000 lb	27,750 lb	27,750 lb
Low	19,900 lb	25,900 lb	25,000 lb	26,100 lb
Avg.	23,308 lb	27,583 lb	26,650 lb	26,958 lb

Repeated tests along these same lines have given parallel results.

A period of tests extending back for over a decade has invariably shown more uniform results with the multiple step bolt, 2, 3, or 4 steps according to the depth of the pinhole. In addition to this, failures in service of insulators assembled with the one step

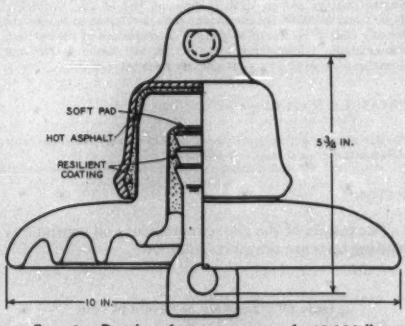


Fig. 3. Details of construction of 18,000-lb suspension insulator

bolt have definitely indicated the inadvisability of large masses of cement in the pinhole. These masses are reduced to a minimum by means of a correctly designed multiple-step bolt.

Safety Feature of Cap and Pin Insulators

One thing that has been very noticeable on all these tests and which has borne out field experience is that with the cemented cap and pin insulator the overlap of the 2 is such that the line will be held in the air even should porcelain breakage occur. This is most important where the dropping of a conductor can in any way be a hazard. This is serious enough with the ordinary transmission line but becomes of prime importance with trolleys over electrified railways where moving equipment is likely to encounter such dropped conductors.

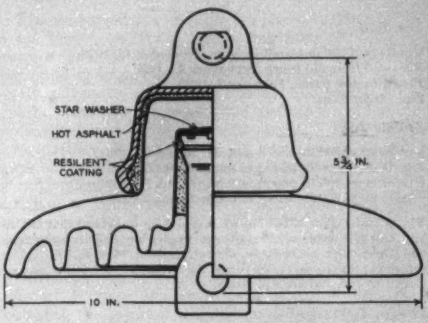


Fig. 4. Details of construction of 15,000-lb insulator

Check tests to show that standard suspension insulators maintain their full strength even when damaged by external violence have been conducted. The hoods were completely broken from 6 15,000-lb insulators and mechanical tests were then made with results as shown in Table III.

Table III—Mechanical Tests on 15,000-lb Insulators

Unit No. 1 ..... 16,550 lb	Unit No. 4 ..... 18,350 lb
Unit No. 2 ..... 15,750 lb	Unit No. 5 ..... 16,500 lb
Unit No. 3 ..... 18,400 lb	Unit No. 6 ..... 17,200 lb

Duration Tests

The previous paper showed a strength of 17,000 lb per unit with load increments of 1,000 lb per day for the 18,000-lb rated insulator. Subsequent tests upon improved units have shown strengths on similar tests varying from 23,000 to 27,000 lb.

An effort to establish through a long time life test the maximum load that the insulator will carry through all weather conditions has been made by exposing several strings of insulators at different loads in the out-of-door testing frames at Baltimore, Md.

While no record has been kept of freezing cycles passed through at the point of exposure, experience has shown that for this territory there will be a great number of alternate freezings and thawings each year. The past 2 years have been above the average in rain fall, each of about 50 in., quite uniformly distributed

through the year. The cement within the insulators would not at any time be thoroughly dried, but instead would be moist and active chemically if at all. Considerable hot weather, up to 100 deg F also was experienced.

Duration tests in the outdoor frame, Fig. 1, on similar insulators are given below. Individual units under the duration test are given frequent tests at flashover while under load.

18,000-Lb Rating

Test No. 1

6 units at 5,000 lb placed in frame September 13, 1928.
Removed from old frame, September 23, 1929.
Placed in new frame, February 4, 1930.
Still without loss.

Test No. 2

3 units at 10,000 lb placed in frame March 20, 1931.
3 units at 12,000 lb placed in frame March 20, 1931.
6 units at 14,000 lb placed in frame March 20, 1931.
6 units at 16,000 lb placed in frame March 20, 1931.

The consideration of laboratory tests led us to believe that the 10 and 12,000-lb loads were insufficient to give any definite indications and these were accordingly discontinued on May 4, 1931. The remaining 6 units at 14,000 lb and the 6 units at 16,000 lb were continued on test and are still intact.

Test No. 3

3 units at 18,000 lb placed in frame March 20, 1931.
No. 1 punctured March 21, 1931. Broke March 23.
No. 2 punctured November 9, 1931.
No. 3 O. K. electrically and mechanically September 14, 1932, when test was stopped.

Test No. 4

3 units at 20,000 lb placed in frame March 20, 1931.
No. 3 broke promptly.
No. 1 punctured.
No. 2 O. K. July 11, 1931, test stopped.

Insulators Having 2-Step Bolts

The insulators shown in the preceding tabulation of duration tests were slightly higher in the head than the present standard and accordingly employed a 3-step bolt. (See Fig. 3.) Similar tests on the revised insulators (See Fig. 4) which employ 2-step bolts follow:

Test No. 5

12 units at 14,000 lb placed in frame September 21, 1932.
12 units at 16,000 lb placed in frame September 21, 1932.

All units have been regularly flashed over individually while under load and are still mechanically and electrically perfect.

The above test results are shown graphically in Fig. 2, indicating clearly a probable continuous life at more than 16,000 lb loading for the 18,000-lb rated unit.

30,000-Lb Rating

Insulators of the higher strength rating, cataloged at 25,000 but more properly of 30,000-lb A.I.E.E. rating have also been tested in the out-of-door test frame with the following results.

Increment Tests

A typical test using the 1,000 lb per day increment method, beginning at 20,000 lb shows first electrical failure at 33,000 lb. (Test report, June 10, 1930.)

Continuous Tests

Test No. 6

12 units at 19,000 lb placed in frame June 12, 1931.
1 unit punctured September 24, 1931. (Without centering washer.)
Test is continuing and remaining units are still good.
12 units at 19,000 lb placed in frame June 12, 1931.
1 unit punctured January 2, 1934. (Without centering washer.)
Test is continuing and remaining units are still good.
12 units at 20,000 lb placed in frame June 12, 1931 without failure to date. (Without centering washer.)

Test No. 7

12 units at 23,000 lb placed in frame June 18, 1932.
12 units at 23,000 lb placed in frame June 18, 1932.
12 units at 25,000 lb placed in frame June 18, 1932.
12 units at 25,000 lb placed in frame June 25, 1932.
These insulators assembled with the star centering washer are still intact.

It is evident from these tests that the 30,000-lb insulator has a continuous strength of at least 25,000 lb when assembled with the centering washer as previously described.

15,000-Lb Rating

Two strings of 6 units at 15,000 lb rated strength placed in frame at 6,000 lb increasing loads each working day 1,000 lb. First failure in string No. 1, one unit punctured, load 15,000 lb, total time elapsed 18 days. Second string, one unit punctured. Load 16,000 lb. Time elapsed 20 days.
Further strings are on straight duration test at 12,000, 13,000, 14,000, and 16,000 lb but insufficient time has elapsed to the present for any definite results to be given. A comparison of the strength values obtained from quick pull tests on well seasoned units and duration tests show a very satisfactory ratio between the 2.

25,000-Lb Rating

Similar increment tests upon the 25,000-lb average rated insulator shows first electrical failure at 25,000 lb.

Résumé

The results of the above increment and continuous loading tests are shown in Table IV.

Table IV—Summary of Results of Tests

Rating Pounds	1,000 Lb per Day Increment Tests, First Elec. Failure	Continuous Load Test Without Failure
15,000	15,000 lb	
18,000	33,000 lb	16,000 lb
25,000	25,000 lb	
30,000	33,000 lb	above 25,000 lb

Suspension insulators of the cemented cap and pin types may be used with safety factors based upon their rating that would be considered reasonable with any structural material.

Radio Influence Insulator Characteristics

Insulators on high voltage lines may cause radio interference by the arcing of the insulator charging current. A copper oxide glaze for new insulators has been developed to prevent this arcing; treatment of old insulators with special compounds to exclude air is reported as helpful. Suspension insulators are found to require no treatment.

By
G. I. GILCHREST
ASSOCIATE A.I.E.E.

Westinghouse Elec. & Mfg. Co., Derry, Pa.

TRANSMISSION and distribution lines with their auxiliary apparatus may be and sometimes are the source of disturbing radio frequency voltage with broadcast programs. Pin type insulators, for transmission and the higher distribution voltages, in good serviceable condition, are generally considered free from such disturbance but there may be cases where they are the source of trouble. Field investigations[1] show that insulators on lower voltage distribution are a minor contributing factor.

The radio influence characteristics of insulators have been investigated during recent years by the insulator manufacturers and some of the college laboratories[2] and treatments have been developed for improving their performance. (The term "radio influence" is used to describe that characteristic of apparatus or circuit which produces radio frequency voltages and that may, under certain conditions, cause interference with radio reception.) In general, the principal facts determined to date are as follows:

1. Pin type, apparatus type, and suspension type insulators, at various voltages, generate energy at broadcast frequencies.

2. In normal application and operation the energy output from insulators may produce voltages which may cause interference with broadcast reception, depending upon the coupling and sensitivity of the receiver.

3. The output of insulators or any device of this nature depends upon the impedance at broadcast frequency of the circuit to which they are connected; a grounded or ungrounded supporting pin.

4. Through several years' development of metallic glaze, a copper oxide glaze has been produced that fits into the regular manufacturing process of insulators; provides a treatment that improves the output characteristics of pin type and apparatus type insulators; and has been demonstrated by accelerated life tests to be permanent and effective.

5. The performance of suspension insulators is such that treatment does not appear to be required.

6. Filling the wire grooves and corona spaces on pin type and apparatus type insulators with asphalt emulsion or similar materials gives a temporary treatment, depending upon the life of the materials, that improves the radio influence characteristics of such insulators now in service.

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 26, 1934; released for publication April 13, 1934. *Not published in pamphlet form.*

Causes and Detection of Interference

The primary cause of radio frequency voltage from a pin type insulator is the arcing flow of charging current from the conductor and tie wire to the insulator and in some cases from the insulator to the pin in the pin hole. A very high resistance exists in the contact between the conductor and tie wire and the ordinary glazed surface of an insulator. The minute irregularities of the surface in contact form small gaps across which the current discharges, generating a radio signal in a manner similar to the old type spark gap radio transmitters. The output is low, largely because of the high internal impedance of the insulator. There may be other causes, such as corona between parts of the insulator or bad service conditions of dirt and moisture permitting the formation of leakage streamers. In normal operation, however, the primary cause as reviewed accounts for most of the disturbance.

The absence of standards for tests and evaluation of results in the early work did not permit an exact nor satisfactory comparison of the data obtained by the various investigators. Within recent months such standards[3] have been determined and tests made in accordance with these standards should permit such correlation.

The circuit used for determining the radio influence characteristics of insulators is shown in Fig. 1. All of the tests were made at a frequency of 1,000 kc. The device under test, in this case the insulator, generates energy at broadcast frequency

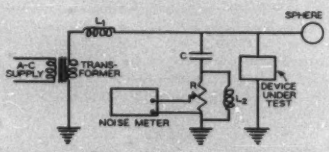


Fig. 1. Circuit for determining radio frequency influence of a device

when potential is applied. This is readily passed by condenser C, producing a drop across the resistance, R. This potential is measured by the noise meter in which it is balanced to the output of a calibrated signal generator. In this circuit, the high impedance of radio frequency choke coil $L1$ practically gives the effect of an open end line and resistance R determines the impedance to ground. With a value of R of 250 ohms the measured impedance of the circuit at 1,000 kc was 250 ohms. Radio frequency choke coil $L2$ by-passes the 60-cycle charging current of the condenser and acts as a safeguard to the operator and noise meter in case an

open circuit occurs through the resistance R.

Attention is called to the importance of circuit impedance at the broadcast frequencies upon the radio frequency output. Thus for an impedance of 100 ohms the output is approximately 15 per cent of that for an impedance of 500 ohms.

Another factor affecting the output is a grounded or ungrounded supporting or insulator pin. The curves, Fig. 2, illustrate the effect of circuit impedance on the output of a 66-kv pin type insulator with a grounded pin. Fig. 3 illustrates the same characteristics for the same insulator with an ungrounded pin. Table I shows the output values for grounded and ungrounded pins at normal operating voltage to ground. It also shows the values for the same insulators with a treatment for improving the performance.

Table I—Radio Frequency Output of 66-kv and 33-kv Pin Type Insulators With Regular Glaze and Treated Glaze at Normal Operating Voltage to Ground With Grounded and Ungrounded Pins

Insulator	Pin	Microvolt Output for Circuit Impedance of 100	250	500 ohms
66 kv with regular glaze	Grounded	4,200	12,600	27,400
38 kv to ground	Ungrounded	450	1,290	2,500
66 kv with treated glaze	Grounded	*	*	*
38 kv to ground	Ungrounded	*	*	*
33 kv with regular glaze	Grounded	2,880	8,500	17,000
19 kv to ground	Ungrounded	115	310	600
33 kv with treated glaze	Grounded	*	*	*
19 kv to ground	Ungrounded	*	*	*

* Less than 5.

The effect of the performance upon broadcast reception depends upon the propagation of the signal, its modulation and coupling and the sensitivity of the receiver. So many variables are encountered in these factors that a measure of the uniform effect on reception seems remote. To obtain an indication of the audible effect of such characteristics with very close coupling and high sensitivity of receiver, a tuned loop was located symmetrically between the conductor and ground within 8 ft of the insulator and connected to a receiver with a sensitivity of 2 microvolts per meter. Voltage was applied to the insulator and increased until the interference was just audible with full amplification in an earphone set. The sensitivity of this same receiver is 5 microvolts per meter when connected as in Fig. 1. To obtain similar audible effect using the circuit as in Fig. 1 on the same insulator with the same value of voltage applied, it was necessary to make a 10 per cent potentiometer connection for the noise meter on resistance R. The output for the insulator at that voltage was, therefore, 50 microvolts at radio frequency and represents the starting value of interference for the particular arrangement described. In Fig. 4 is illustrated the output for insulators with and without treatments. This is on a larger scale that permits more accurate selection of output values for respective voltages.

Curve 1—microvolts - impedance; 38 kv to ground
Curve 2—microvolts - voltage; 500 ohms impedance
Curve 3—microvolts - voltage; 250 ohms impedance
Curve 4—microvolts - voltage; 150 ohms impedance

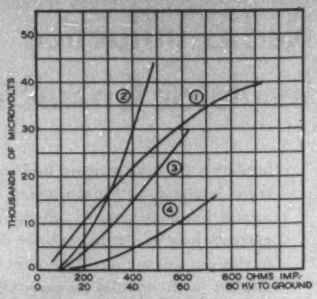


Fig. 2. Radio frequency output for a 66-kv pin type insulator with grounded pin

Metallic Glaze Treatment

Reference was made to the development of treatments for improving the radio influence characteristics of insulators. Table I and Fig. 4 give data showing such improvement for a treated pin type insulator. The improvement is obtained by eliminating the ionization surrounding the conductor and tie wire areas and any discharge in the pin hole. This is accomplished by the use of a metallic glaze over the crown area that provides a low resistance metal to metal contact between the conductor and tie wire and the insulator, with a metal thimble cemented into the pin hole.

A number of methods for eliminating or reducing the ionization and other distress over the crown area were proposed and tried by the various investigators in their early work. In addition to several types of metallic glazes, other promising features were modifications in shape to control the discharge, a metal cap cemented to the crown for the attachment of the conductor and tie wire, and the filling of the wire grooves with compounds to exclude the air. All of these gave varying degrees of improvement; all possess some disadvantages.

Curve 1—microvolts - impedance; 38 kv to ground
Curve 2—microvolts - voltage; 500 ohms impedance
Curve 3—microvolts - voltage; 250 ohms impedance
Curve 4—microvolts - voltage; 100 ohms impedance

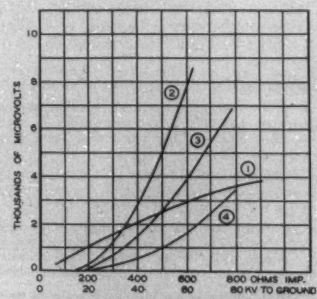


Fig. 3. Radio frequency output for a 66-kv pin type insulator with ungrounded pin

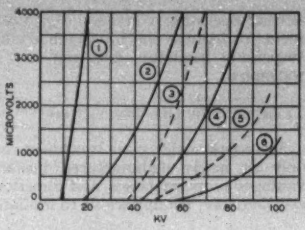


Fig. 4. Radio frequency output, regular and treated 66-kv pin type insulators

Curve 1—regular insulator, grounded pin
Curve 2—regular insulator, ungrounded pin
Curve 3—asphalt treated insulator, grounded pin
Curve 4—copper oxide glaze treated insulator, ungrounded pin
Curve 5—asphalt treated insulator, grounded pin
Curve 6—copper oxide glaze treated insulator, ungrounded pin

The first metallic glazes transferred the potential and the corona discharge from the wire grooves to the periphery of the conducting coating. This difficulty has been overcome with a later development in the art and science of a metallic glaze. The first metallic glazes were applied to the regular insulator glaze after the firing of the porcelain was completed. The later development uses a copper oxide glaze to replace the regular silicate glaze on the insulator. The copper oxide glaze comprises a large percentage of copper oxide in a composition that is applied and matured in the regular manufacturing processes. This special glaze is applied in commercial production to the upper side of the top part of the insulator, the other surfaces having the regular silicate glaze coating. After the porcelain is fired the copper oxide glaze is reduced to metallic copper over the area surrounding the wire grooves. This metallic copper coating which is molecularly attached to the porcelain is developed by a chemical reaction between zinc and a solvent in contact with the oxide glaze. This developing agent can be confined to any local area so that only the desired surface is changed to the metallic state.

The edge of the developed metallic coating has an inherent graded conductivity from the fully conducting area to the undeveloped high resistance area. This is effective in damping out the edge discharge difficulty of the early metallic glazes. The developed copper area is given a tinned coating to protect it against oxidation and mechanical abrasion. Fig. 5 is a photograph of the copper oxide treated insulator with the tinned coating.

Fig. 5. Insulator with copper oxide glaze treatment

The data given in the tables for the treated insulators were obtained on insulators with the copper oxide glaze treatment on the top of the head and a thimble cemented into the pin hole. Successive tests show no change in this performance over a period of 2 years of accelerated life test, with 170 per cent of normal potential applied.

Curves 4 and 6, Fig. 4, show the improvement obtained with the copper oxide glaze treatment on a 66-kv insulator. Comparative results are obtained with the treatment on insulators of other ratings.

The values of voltage at which the 50 microvolt signal is produced for pin type insulators of standard size and rating, with and without treatment, are given in Table II.

Table II—Kilovolt to Ground to Produce 50 Microvolts at Radio Frequency in a Circuit of 250 Ohms Impedance

Size of Insulator				
Kv	Diam. In.	Condition	Grounded Pin (Kv)	Ungrounded Pin (Kv)
15	7 1/2	Regular	9	18
		Treated	22	50
23 1/2	9	Regular	9	19
		Treated	22	54
34 1/2	10	Regular	10	21
		Treated	28	56
46	12	Regular	10	21
		Treated	40	56
66	13 1/2	Regular	9	18
		Treated	41	58

Apparatus and Suspension Type Insulators

The characteristics of apparatus insulators, such as are used in switches and bus structure, and of suspension insulators also are of interest.

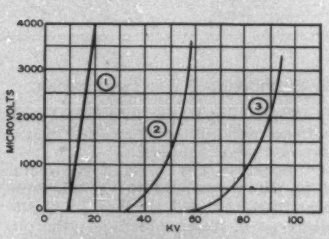
The apparatus insulator, Fig. 6, with the metal parts cemented to the crown and in the pin hole presents a combination that led to the use of the metal cap as one type of improvement for the pin type insulator. The cap furnishes a low resistance metal to metal contact with energized parts connected to it. The cement between the cap and the porcelain excludes the air between them, thus reducing or eliminating any ionization over that area. This results in substantial improvement in the signal level as indicated in Fig. 7, which shows that the characteristics for a 66-kv pin type insulator and for the same insulator in the apparatus type assembly. The improvement is limited by the ionization in the gap between the edge of the cap and the porcelain that is provided in the usual assembly to permit differential expansion without damage to the porcelain. The copper oxide glaze treatment over the crown area eliminates the potential and corona across this gap and gives further improvement.

Suspension insulators have similar characteristics but much lower output over the normal voltage range. In Fig. 8 is illustrated their performance in

string lengths of 4, 8, 12, and 18 units. These were the so-called 10 x $5^3/_4$ standard rating. At critical voltages the output for the longer string lengths rises abruptly as indicated by the curves. A circuit

Fig. 6 Apparatus type insulator

similar to Fig. 1, but with a high voltage transformer set-up was used for the tests on suspension insulators. An indication of the audible effect of such performance was obtained with the receiving instrument[3]



Curve 1—regular pin type design, grounded pin
Curve 2—regular apparatus design, grounded pin
Curve 3—copper oxide glaze treated apparatus design, grounded pin

Fig. 7. Radio frequency output for apparatus type insulator, 250 ohms circuit impedance

on the ground 23 ft below and 15 ft to the side of the test bus. The voltages at which interference was first detected with an earphone set are as follows:

Units in String	Kv	Equivalent 3-phase Voltage, Kv
4	85	145
8	140	240
12	180	310
18	195	335

These voltages correspond to the critical values on the output curves. They show a wide margin, especially at the shorter string lengths, over present normal operating voltages. For this reason treatment to improve the interference characteristics of suspension insulators does not now appear to be warranted.

Treatment of Old Insulators

The copper oxide glaze treatment can be furnished only on newly manufactured insulators. Its advantages of permanence and superior performance are, therefore, not applicable to insulators now in service. A treatment that can be applied to insulators now in service is the filling of the wire grooves with a compound to exclude the air. At best, this treatment can be considered as a temporary expedient because of the limited life of the filling materials that will serve for this purpose. Asphalt compounds offer the best known weathering properties of such a material. A compound in semi-paste form, as asphalt emulsion, can be applied more easily than a paint or melted type of material. In Fig. 9 is shown an insulator with the asphalt emulsion treatment. Curves 3 and 5, Fig. 4, show the radio influence characteristics of a 66-kv insulator with this treatment over the crown and a thimble in the pin hole, with grounded and ungrounded pin.

The asphalt emulsion treatment can be applied to

Fig. 8. Radio frequency output for suspension type insulators, 600 ohms circuit impedance

Curves show respectively result for 4, 8, 12, and 18 units

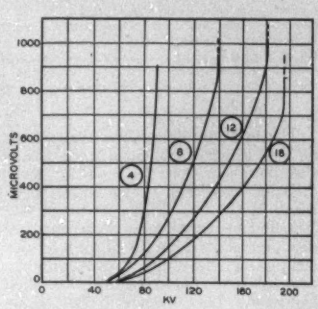


Fig. 9. Standard pin type insulator with asphalt emulsion treatment

the gap between the cap and the porcelain on apparatus type insulators with improved results.

REFERENCES

1. SOURCES AND METHODS OF SUPPRESSION OF RADIO INTERFERENCE, H. O. Merriman. *Elec. News and Engg.*, April 15, 1931.

2. Reports of the eighth and ninth meetings, Prof. F. O. McMillan, Oregon State College. Northwest Elec. Lt. & Pwr. Assoc., 1931, 1932.

3. RADIO NOISE MEASURING SET, report of the joint coördination committee on radio reception. N.E.L.A. Pub. Nos. 32 and 33.

Voltage Regulation and Load Control

Some of the problems involved in supplying electric power to the business sections of large metropolitan areas are dealt with in this article which describes the development and operation of new methods of voltage regulation and load control by means of which improved conditions are being obtained on the distribution system in New York City.

By
H. C. FORBES
MEMBER A.I.E.E.

H. R. SEARING
FELLOW A.I.E.E.

The New York Edison-United Cos., New York, N. Y.

THE A-C distribution system in New York City is mainly supplied by feeders direct from the generating station buses, the necessary transformation to reduce the voltage to the network potential being made by network transformer installations located in street manholes and in vaults in buildings. This major supply is supplemented in certain areas by substation feeders of lower voltage which were formerly used for radial service.

In the early stages of the development of the network it was considered advisable to have feeders in each network area from as many sources of supply as practicable. As a result, many network areas exist where feeders from two generating stations are paralleled, or "intermeshed" on the secondary side of their respective network transformers. In the case of individual generating stations it has also been found desirable in the interest of improved reliability and reduced circuit breaker duty to operate the station buses in two or more distinct sections. Feeders emanating from these bus sections likewise are intermeshed mutually on the secondary network as described above. The present major connections of the 60-cycle system are illustrated in Fig. 1.

VOLTAGE CONTROL

As the network system progressed the high cost of using feeder regulators for controlling the network voltage led to the idea of obtaining the necessary regulation by varying the voltage on the generating station buses and thus a closer relationship between the generating stations and the distribution system was first established. As a result of calculations and various experiments there was finally established the practice of varying the bus voltage in accordance with a schedule which was determined as a function of the total system load. This plan largely eliminated the difficulties inherent in any scheme based on varying the voltage according to a definite time schedule, this method being subject to criticism on account of the unpredictable variations in the daily load curve. It will be obvious that controlling the voltage in this manner requires very accurate voltmeters at the generating stations if good results are to be obtained. The present voltmeters at Hell Gate station are considered to be somewhat deficient in this respect since their accuracy is only plus or minus 1 per cent so that even if the voltage schedule is strictly adhered to, the network voltage may vary as much as plus or minus 1.2 volts in addition to the normal variation associated with the distribution system potential drop. While this may seem slight nevertheless when it is the aim to maintain the voltage delivered at the consumers services within a band of 8 volts it is a serious handicap to lose at the outset, due to inaccuracy of voltmeters, about 2.5 volts. It is now proposed to install at Hell Gate combined indicating and recording voltmeters of the type shown in Fig. 2. These equipments which are manufactured by the Leeds and Northrup Company are accurate to plus or minus 50 volts based on a 2,000-volt range of scale, so that in controlling a nominal voltage of 13,800 volts the accuracy is better than plus or minus 0.5 per cent. In providing voltmeters for use in supervising such an important function, of course, it is equally necessary that the instruments be of a type which have a large scale so that they can be read closely.

With the careful coöperation of the generating station operators the method of regulation by control of bus voltage has given excellent results on the whole. There are, however, certain areas having load characteristics differing substantially from the major part of the system where the scheme of bus regulation leaves something to be desired. In the southern part of Manhattan Island for example, the load is largely for office buildings and after 5 p.m. it drops to a low amount, whereas the load on the major part of the system continues near its peak for some time. Under these conditions it is obvious that

Full text of a paper recommended for publication by the A.I.E.E. committee on power generation, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 6, 1934; released for publication April 26, 1934. *Not published in pamphlet form.*

ideal results cannot be obtained by bus regulation as the voltage will necessarily be higher in the lightly loaded area than elsewhere on the system. It may be necessary to supply areas of this type with feeders having individual regulators or possibly from a bus which does not supply any other load and so can be regulated independently of the rest of the system.

Coöperation in the design and operation of the generating systems has been of definite value also in the problem of controlling the division of load on transformers connecting to feeders which are derived from different stations or from independent bus sections in the same station and intermeshed at the network. Under these conditions if one supply bus happens to be appreciably leading or lagging in phase position with respect to the other sources of supply a corresponding increase or decrease in the loading of the transformer banks connecting to the feeders will occur. As an example, consider the network in lower Manhattan which is fed jointly by Hell Gate and Hudson Avenue generating stations. At the time of peak load and with zero phase displacement between

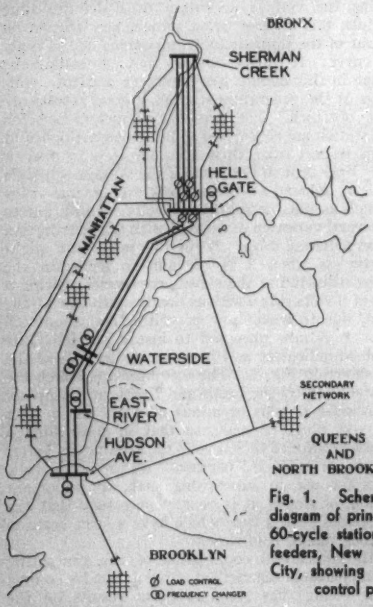


Fig. 1. Schematic diagram of principal 60-cycle station tie feeders, New York City, showing load control points

the station buses, the average transformer on a Hell Gate feeder is loaded to 47 per cent of its kva rating and at 92 per cent power factor, but some transformers are 80 per cent and others only 20 per cent loaded. Likewise the average transformer on a Hudson Avenue feeder is loaded to 50 per cent of its kva rating and at 89 per cent power factor, but some transformers on this feeder are loaded also 80 and 20 per cent, respectively. With Hell Gate leading Hudson Avenue by 3 deg the 80 per cent loaded transformer on the Hell Gate feeder would be 100 per cent loaded and the 20 per cent loaded transformer on the Hudson Avenue feeder would be carrying a load equal to 6 per cent of its kva rating. On the

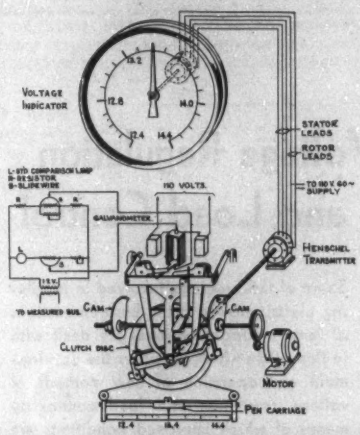


Fig. 2. Bus voltage recorder and remote indicator proposed for installation at Hell Gate Station

other hand, if Hudson Avenue leads Hell Gate by 3 deg, the 80 per cent loaded transformer on the Hudson Avenue feeder would be 90 per cent loaded, but the 20 per cent loaded transformer on the Hell Gate feeder would be feeding back toward Hell Gate a kw load equal to 2 per cent of the transformer rating. The network protector associated with this transformer would automatically open if the relays were given a sensitive reverse energy setting.

If angular displacements of the order of 3 degrees were introduced during off-peak periods, inevitably a large number of sensitive protectors would open and remain open well into the peak load period, in some cases even remaining open regardless of load period until the phase-angle condition was corrected or until the protector was closed by hand. This operating difficulty obviously could not be attributed to any deficiency on the part of the operators who had no means of knowing the relative phase position of the several bus sections. Evidently an instrument which would give this information, was needed both for the guidance of the station operators and for the benefit of the engineers concerned with the layout of the distribution system.

Phase Measuring Equipment

In discussing the development of phase-measuring equipment we shall first consider its application to

the measurement of phase displacement between bus sections located in the same station. Fig. 3 showing the present normal operating connections at Hell Gate is illustrative of this case. In casting about for a suitable measuring equipment the first thought was to use an instrument of the electrodynamometer type. It was found soon, however, that ordinary instruments of this type were not sufficiently sensitive to small angular differences and even with improved instruments an accuracy of not better than plus or minus 30 min was the best that could be expected. Moreover, all of the available instruments were of the indicating type whereas it was felt that a recording equipment was much more suitable since it permits a day-to-day study of changing conditions which periodic and nonsimultaneous readings do not afford. Eventually as the result of development work which was carried out in the laboratories of the New York Edison Company in

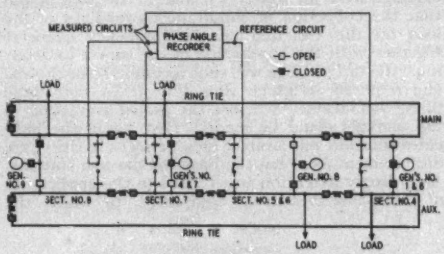


Fig. 3. Present normal operating connections at Hell Gate

coöperation with the Leeds and Northrup Company, who were interested in the problem from the manufacturing standpoint, a suitable recorder was constructed. The instrument is basically a form of a-c potentiometer and employs a null method of measuring the angle between two sources. It is a modification of the potential transformer testing set manufactured by Leeds and Northrup of which the fundamental principles were described by Dr. F. B. Silsbee in his paper entitled "A Method for Testing Current Transformers" (U. S. Bureau of Standards Scientific Paper 309, 1917).

The features of the potential transformer testing set necessary for measurement of phase difference were combined with the Leeds and Northrup Micromax recorder forming an instrument of which the electrical and physical features are illustrated by Fig. 4. The slide wires S_1, S_2, and S_3 were mounted on the same shaft and by their movement cause the relative values of capacity and resistance to change until zero deflection of the galvanometer is obtained. The recording pen is belted to the slide wire and records the position of the slide wires when the galvanometer reaches a balance. The range was extended by using suitable resistors and condensers to give a record of phase difference of from plus 5 to minus 5 deg. The resistor R_6 and condenser C are used to provide damping and stability of the galvanometer.

The instrument will measure the phase displacement between constant potentials to an accuracy of plus or minus 3 min and variations in the potential of 10 per cent only decrease the accuracy to plus or minus 9 min. The over-all accuracy of the record, however, also depends upon the care which is taken to compensate for the phase-angle error of the potential transformers to which the instrument is connected. Ordinarily where the burdens are small it should be possible to connect the instrument to existing transformers without appreciable error. However, the burdens should not be subject to alternate connection and disconnection. Potential transformers connected Y–Y may be used if all the burden is connected phase to neutral on the transformer used for phase-angle measurements. Care must be taken however, to prevent stray secondary currents from entering the circuit. The high lagging burden of the galvanometer field is compensated by a shunt condenser.

The protective relay shown in Fig. 4 is used to avoid the possibility of unintentionally keeping a bus section alive by reason of a back feed through the potential transformers which have their secondary circuits interconnected through the instrument. The isolating transformers are used to prevent circulating current due to differences in potential between the transformer secondary grounds. The selector switch of the multiple point unit is covered with a bakelite cap to prevent the accidental bridging of contacts.

The connections of the instrument as installed at Hell Gate station were shown in Fig. 3. It may be noted that the device measures the phase displace-

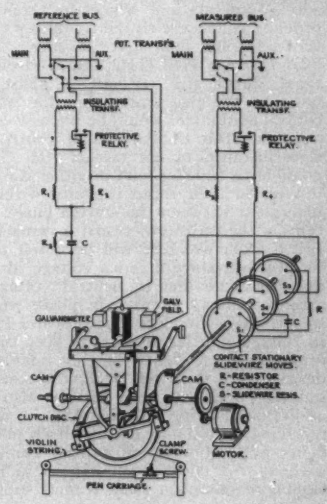


Fig. 4. Electrical and physical connections of a phase angle recorder, combining features of potential transformer testing set and "Micromax" recorder

ment between one bus section which is arbitrarily chosen as the master or reference bus and 3 other bus sections. By means of selector switches it is possible to obtain phase measurements of the remaining bus sections, if desired, although this is ordinarily unnecessary. Fig. 6 shows the phase conditions immediately after installing the instrument, before any corrective steps had been taken as compared to the conditions after loading and operating practice had

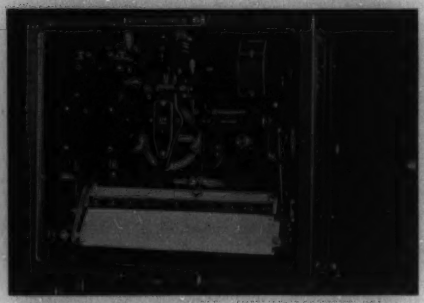


Fig. 5. Phase-angle recorder used at Hell Gate

been readjusted to minimize as far as practicable phase displacements.

We shall turn now to the case where feeders from separate generating stations are intermeshed at the network. Referring to the diagram of system connections (Fig. 1) attention is called to the arrangement of the direct ties between Hell Gate and Hudson Avenue stations which are tapped as shown in order to connect with the frequency changers at the Waterside and East River stations. The transfer of load between Hell Gate and Hudson Avenue over these direct ties without a phase displacement between the two stations in the absence of load control equipment would be impossible. In order to overcome this difficulty load control transformers were installed in the ties at Hell Gate making it possible to transfer load in either direction over the ties up to their rated capacity without phase displacement between the station buses. The connections of the transformers are shown schematically by Fig. 7 from which it will be noted that the transformers introduce a series voltage displaced by 120 deg from the line to neutral voltage. With this arrangement an advance in phase when introduced by the series windings is accompanied by an increase in voltage and this operates to keep the power factor on the ties at a slightly lagging value. This is to be desired since it is well to have the station which is sending energy out over the ties also take on some additional lagging reactive kva in order that the receiving station may not find itself in the position of being relieved of a substantial amount of energy without any corresponding relief in the amount of lagging reactive kva which it must supply.

Measurement of Phase Displacement Between Generating Stations

The mere installation of load control transformers at Hell Gate, however, was not a complete solution to the problem for although it made possible the transferring of power over the ties without requiring phase displacement between the buses of the two stations it still left the operators without any way of knowing whether they were obtaining the desired load transfer from a proper adjustment of the load control transformers or whether the load transfer was being obtained in part by an unwanted phase displacement between the stations. A first attempt to solve this difficulty consisted of providing the operators with a somewhat complicated set of curves from which the correct setting of the tap changers could be determined in terms of the load on the ties and the loading of the frequency changers which were connected to the ties. Since the various loadings were all widely variable it was soon found that the collection of simultaneous readings of the load on the ties and on the frequency changers together with the application of the curves to determine the tap settings was such a cumbersome process and required so much time that there were large phase displacements before the proper correction in tap settings could be made. Here again the indicated solution was a direct measurement of the phase displacement between the buses of the two stations. Accordingly attention was turned to the application of the phase-measuring equipment, of which the

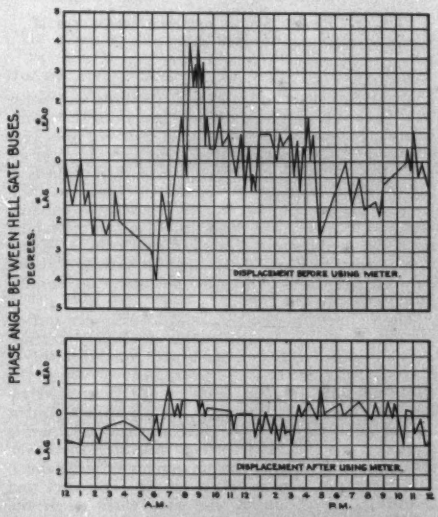


Fig. 6. Comparative phase angle displacement between Hell Gate buses before and after using phase angle meter

development has already been described, for use in connection with a pilot wire in order to determine the phase displacement between two comparatively remote potentials. It was known that the pilot wire impedance would necessarily be large and would be variable to a considerable extent due to temperature changes so that some form of compensation would be required. One solution to the compensation problem which was suggested was to use one instrument at each end of a symmetrical line as shown in Fig. 8. Under this set-up the effect of the pilot wire impedance is cancelled.

This may be shown by the following simple equations:

θ_x = true phase angle between stations.
ϕ = phase displacement caused by the pilot wire.
θ_1 = reading taken at station A.
θ_2 = reading taken at station B.

Then $\theta_1 = \phi + \theta_x$

$\theta_2 = \phi - \theta_x$

Subtracting, $\theta_x = \dfrac{\theta_1 - \theta_2}{2}$

The success of this method depends on the lines being symmetrical, that is, the lines may be made up of different wire sizes but the electrical constants looking into the line in either direction from its midpoint must be the same. If not, the angular displacement in one direction will be different from the displacement in the other direction because of the distribution of the capacity and resistance. Since commercially available telephone circuits are rarely symmetrical as herein defined and because of the expense of the additional instrument, further tests were made to determine the limits of accuracy and

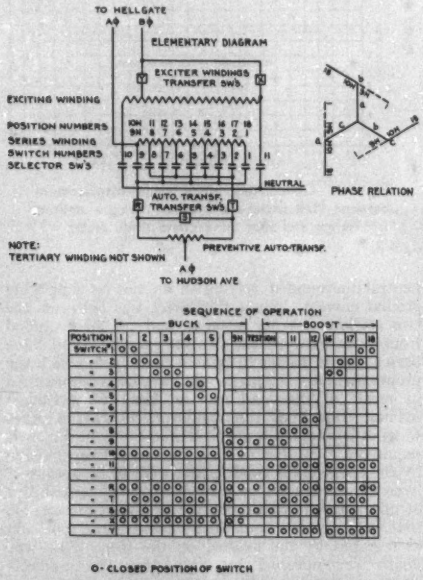


Fig. 7. Load ratio control transformer and sequence chart, Hell Gate station

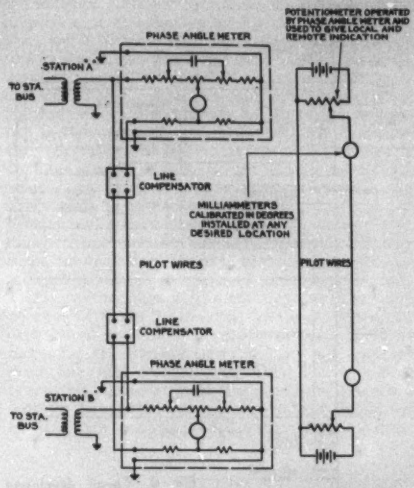


Fig. 8. Null method of remote measurement of phase angle

the practicability of using a single instrument and a compensator for the angle introduced by the pilot wire. Tests conducted in coöperation with the New York Telephone Company and the American Telephone and Telegraph Company, determined that, with the exception of special routing through the control office and the addition of compensating equipment at the terminus, commercial telephone circuits could be used as pilot wires. Fig. 9 shows the circuit used for a single-phase measuring instrument, including compensation for angular displacement in the pilot wire between zero and 45 deg leading. Using such a circuit and a pilot wire looped back to the same point it was found that an error of less than 1 deg was introduced. The compensator is designed so that a constant potential may be obtained from the output terminals of the instrument over a wide range of angular compensation.

Temperature changes affect the impedance and hence the phase angle of the pilot wire, but these changes are gradual. To detect these changes and obtain constant supervision of the pilot wire (detect open circuits, etc.), the voltmeter shown in the diagram of connections, Fig. 9, is used. This voltmeter is a d-c milliammeter used with a copper oxide rectifier and a resistance of 2,000 ohms per volt and hence does not require enough current to affect the accuracy of the indication. The instrument is

first calibrated by checking against two voltages of known displacement and then the circuit is calibrated at zero by adjusting the generators in each station until minimum current passes through a direct circuit between the remote buses.

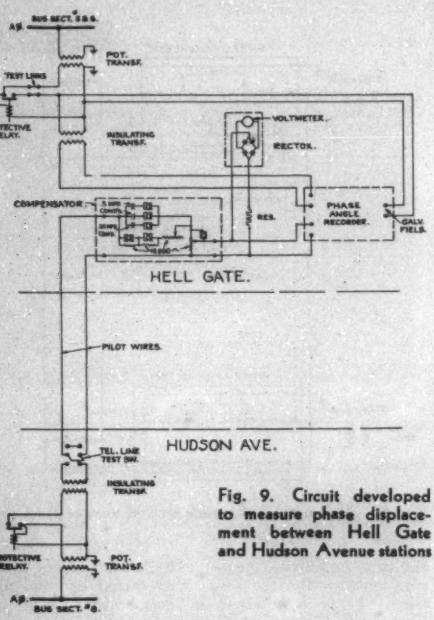


Fig. 9. Circuit developed to measure phase displacement between Hell Gate and Hudson Avenue stations

The comparative conditions as to phase displacement when operating the load control transformers in accordance with the method previously described and when controlling the tap changers by direct observation of the phase meter are illustrated by Fig. 10. Under normal operating conditions it is now practical to keep the angular displacement within plus or minus 30 minutes. It is to be noted that at Hell Gate the phase meter is connected to the bus section which is used as a reference bus for the local phase meter.

Referring again to the diagram of system connections (Fig. 1) it will be seen that the same operating problem exists in the case of the Hell Gate and Sherman Creek stations as in that of Hell Gate and Hudson Avenue. However, the problem of keeping the buses of the two stations in phase in this instance was solved in a different manner.

Using Regulators for Phase Control

The availability of several sets of induction regulators at Hell Gate led to the thought of using them to provide the desired load control in the direct ties between Hell Gate and Sherman Creek. These regulators were single phase and had formerly been used in pairs with the open delta connection as feeder voltage regulators. Reconnecting the regulators as shown by Fig 11, it was possible to obtain an advance or retardation in phase by changing the position of the regulators without any distortion in the 3-phase voltage although a change in the position of the neutral was involved. The neutral shift, however, occasioned no difficulty since it was possible to operate the Sherman Creek station with the

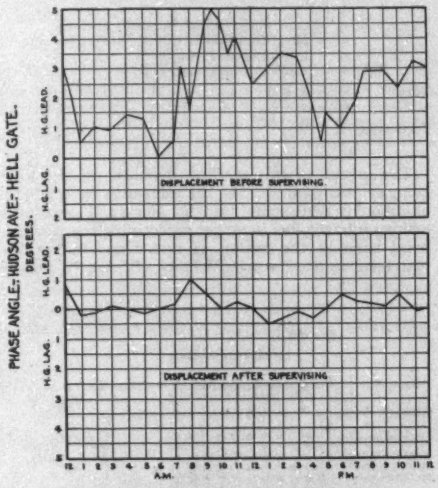


Fig. 10. Comparative phase angle displacement between Hell Gate and Hudson Avenue stations before and after using phase angle meter

neutral ungrounded, relying on the ties for supplying ground current. Since the direct ties between the two stations in this instance had no load tapped from them between the two stations it would have been a simple matter to make a chart from which the proper regulator settings could have been determined in terms of the load on the ties. Nevertheless manual control of the regulators in this manner was not considered a very satisfactory solution as it required a great deal of time and careful supervision by the operators if good results were to be obtained. Accordingly, studies were made of the practicability of applying automatic control to the regulators so that they would automatically change their position as required by the loading on the ties. This was finally accomplished by connecting the contact-making voltmeter and line drop compensator mechanisms, with which the regulators were already provided, in the manner shown by Fig. 11. It is

believed that this diagram of operating connections is largely self-explanatory except that the purpose of the transformer which steps down the base potential applied to the contact-making voltmeters may not be clear. It was the purpose of this transformer to reduce the basic potential to a value low enough so that the variations in it due to the daily variation of bus potential, for the purpose of controlling the network voltage, would be insignificant by comparison with the voltage variations set up in the line drop compensator as a function of the load on the ties. The position of the regulators, therefore, could be regarded as being substantially proportional to the load on the ties.

It can easily be shown that the phase control provided by the regulators is such that energy is transferred over the ties at substantially unity power factor. With energy normally being fed toward Sherman Creek and operation at that station

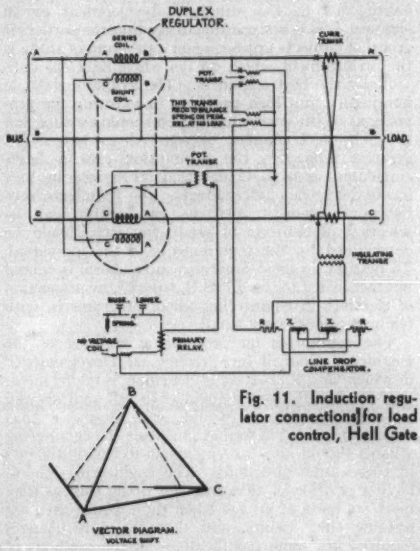


Fig. 11. Induction regulator connections for load control, Hell Gate

at a reduced basis, except under emergency conditions, it became a problem as to how the necessary reactive kva was to be supplied, the situation having reached a point such that generators required on the bus to carry the energy load were not of sufficient capacity to handle the reactive load. This was satisfactorily taken care of by uncoupling two of the generators from their turbines and operating them as synchronous condensers. A separate turbo-generator unit which applied gradually increasing voltage and speed was used to start these uncoupled generators and bring them up to synchronous speed. Although this method of starting is cumbersome it is satisfactory enough where as in this case, it is not necessary to do it often.

Better Network Protector Operations

After the installation of phase-angle indication, the network protector operations showed a marked improvement as indicated by Fig. 12. This record gives the experience with sensitive network protectors in Manhattan which represent 75 per cent of all network protectors installed in the Manhattan district. These protectors and their associated distribution transformers are fed from the various bus sections of three generating stations, therefore their operation is representative and provides a definite means of comparing system operations before and after the installation of phase-angle indications. The average operations per protector per day were reduced from 0.89 to 0.57, a 36 per cent improvement over the earlier condition. Furthermore, the operations in excess of the average per day are confined to 25 per cent of all sensitive protectors.

It is expected that many protectors now insensitive because of feeder phase-angle relations previously experienced may now be made sensitive without increasing the average operations for all sensitive protectors, and changes along these lines are now proceeding. The work of the engineers concerned with the distribution system has also been facilitated for it is now possible to tell with a much greater

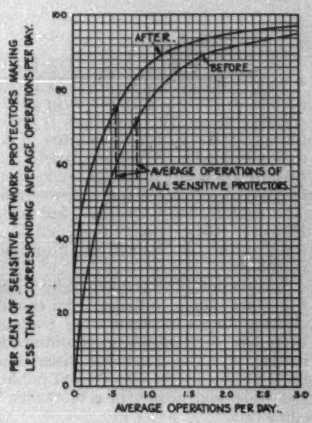


Fig. 12. Network protector operations before and after installation of phase angle recorders at generating stations

degree of accuracy the true distribution load carried by the network transformer installation, since measurements of transformer loading are largely uncomplicated by artificial circulating load due to improper phase conditions within the stations. Therefore additional network transformer installations can be placed on a more rational and economical basis.

Encouraging Initiative in the Engineering Student

Engineering education today is being examined from within as well as from without, with the object of adapting it to meet more adequately the changing demands of a profession broad and diverse although relatively young. With no precedent or past experience to serve as a guide, engineering education necessarily has developed by its own efforts through trial and experiment. This paper describes the educational methods adopted at Harvard Engineering School in an effort to solve the problem of training engineering graduates for the varied responsibilities that they may be called upon to assume.

By
CHESTER L. DAWES
MEMBER A.I.E.E.

Harvard Univ.,
Cambridge, Mass.

WE ALL ARE familiar with many specific criticisms of engineering graduates; they are unable to express themselves in good English; their training in the fundamentals is deficient; they are failing in the broad knowledge of human qualities and in economics; they are narrow technicians; their technical training is shallow and superficial; they are lacking in initiative and resourcefulness, and so on. The commendable qualities are seldom mentioned. However, these criticisms should be examined carefully with the object of improving educational methods.

Although it has been generally recognized for some time that lack of initiative and resourcefulness is an existing defect in engineering graduates, there have been few suggestions or recommendations for correcting it. The numerous discussions appearing in both technical and educational publications indicate the wide and active interest taken in engineering education.[1]

In a recent paper, Dean Dyche of the University of Pittsburgh and R. E. Hellmund of the Westinghouse company[2] discussed in some detail the lack of initiative and resourcefulness in engineering graduates and offer as a remedy the Pitt-Westinghouse graduate program. But this program is adapted to graduates only and is limited to very few schools which are located near a large electrical industry.

In its extensive report on engineering education, the Society for the Promotion of Engineering Education board of investigation and coördination[3] devotes almost no space at all to this question. One short paragraph on p. 130 is as follows:

> Motivation.—One of the marked values of the unified program entered directly from the secondary schools is that it capitalizes the student's natural motivation. To keep the student longer away from studies which bear on his life purposes tends to prolong a juvenile attitude toward education at a time when he needs to learn the method of intensive directed effort.

A large part of the report[3] is devoted to studies of the curriculum, with special reference to the percentages for each subject. The amount of thought and discussion given to balancing the curriculum seems to imply that improvement in engineering education lies almost entirely in that direction. Standardization of the curriculum is disadvantageous to the student's development as an engineer. It is not possible to say that the particular group of subjects appearing on a program of study is the arrangement which on the whole develops individually the best engineers. The available data do not justify any high precision in selecting the proportions of the curriculum which should be allocated to each of a number of selected subjects. The greatest fallacy is the assumption that a single curriculum in a particular field of engineering best meets the needs of all students. No 2 students have the same interests, aptitudes, or abilities, and the selection of subjects of study for each should be determined by the requirements of the individual. To be sure, in most programs some choice is offered but, according to the S.P.E.E. report,[3] the proportion of electives in engineering-school programs is, with few exceptions, very small.

The committee on professional training of the Engineers' Council for Professional Development,[4] of which Col. R. I. Rees is chairman, is taking measures to assist the young engineer in self-analysis and self-development. It would seem desirable that during the period of formal education the engineering schools should also take measures to assist students in these same directions. The engineering schools have a position of advantage for doing this, as they meet students at an age when these young men are forming their habits, and thus the only changes required are some modifications in the methods of instruction.

Faults of Prearranged Curricula

Setting up fixed educational requirements, rather than adapting these to the characteristics of the individual, has the effect of discouraging and suppressing initiative and resourcefulness in the student. This is true not only in the engineering school, but throughout the student's educational career. From elementary school days the engineering student is accustomed to having his educational career planned for him to the smallest detail. The program of study, allocation of time, and even the method of

Full text of a paper recommended for publication by the A.I.E.E. committee on education and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 10, 1934; released for publication March 14, 1934. *Not published in pamphlet form.*

1. Numbers refer to bibliographic references at end of paper.

holding a pencil and of writing have been carefully planned and standardized, irrespective of individual ability and talent. Although in the better secondary schools a diversity of subjects is offered, students preparing for college have little option. By their entrance requirements the colleges in large measure determine the program of study and the student, in soldierly fashion, follows the program, usually faithfully, but also blindly. He does not know why such a group of studies prepares him for college better than some other group that perhaps might arouse in him a much keener interest.

In the usual engineering school, after selecting his general field of study, the student finds the curriculum all arranged for him and, with minor options, is identical for all students in the same field. He does not know why this prescribed course of study best fits him and his fellow students for their chosen profession. He probably gives little thought to this particular question, but he may unconsciously assume the plan to be due to the wisdom of some one higher up who should know. He does know that if he completes with success the schedule of individual courses prescribed, he will be awarded the degree and that he should then be fitted to begin professional work. He also finds in the classroom and in the laboratory a definite schedule arranged for him. Formal lectures and definite problem assignments follow each other leading to the final examination of the term. In the laboratory he is assigned from week to week definite tests on certain pieces of apparatus. In many cases the laboratory procedure and the necessary instruments are prescribed for him and he finds the apparatus already set up. To be sure, the preliminary report method if used does require some planning on the part of the student, but the effect of this alone develops little if any initiative.

Educational Plan

Feeling that the rigid curriculum and the usual methods for teaching engineering students was confining them to an educational strait-jacket, the faculty of the Harvard Engineering School under the leadership of Dean H. E. Clifford studied the problem carefully and decided that placing a large measure of responsibility on the student would tend to develop self-reliance, the habit of planning his future, and initiative as well. Also, history has shown that, as a rule, men are developed in proportion to the responsibility placed upon them.

Therefore, the following policies were adopted and have been followed for 2 years.

1. The curriculum was to be elective, not fixed. The student, even as a freshman, was to plan his course of study and arrange his entire program.

2. The reading period was adopted in those courses in which the student has acquired sufficient background to continue the course without classroom supervision.

3. Emphasis was changed from the specifying of a definite number of individual courses as a requirement for the degree to the plan of awarding the degree for the satisfactory completion of a substantial coördinated program of study.

4. Opportunity for initiative was to be afforded by special work. In the laboratory work of the electrical engineering department, for example, the standard laboratory experiment has been replaced by original projects and students are encouraged to originate experiments for themselves.

Elective Curriculum

Under the elective curriculum plan the student arranges his program of study. The only restrictions are that the program shall be substantial and that it shall have a definite purpose. In order to obtain a degree with designation of field the student is required to complete satisfactorily 2 professional courses in that field. The program must be approved by the administrative board but, so far as I know, the board has required little if any change in the programs that have been submitted by the students. In fact, nearly all the changes are made by the students themselves as they learn from time to time of adjustments which they feel are better adapted to their requirements.

The student, particularly in his freshman year, obviously requires some assistance. This is given primarily by his faculty adviser, although the student is free to and does consult other members of the faculty. Students also obtain considerable information from their fellow students, particularly from the upper classmen. When he enters as a freshman, the student is assigned an adviser in the particular field in which he expresses the most interest, such as electrical engineering, for example. His adviser determines as far as possible the particular phase of the field in which the student seems most interested or to which he is best adapted, although in the freshman year it is not highly important that this be known. If, for example, the student chooses the field of electrical engineering or electric communication engineering in his freshman year, he must plan his sequence of studies so that he will be prepared for the professional courses in that field which usually are taken during the senior year. Assume that one student is interested in electric-power engineering and that he intends to elect power transmission and a-c machinery as the professional courses to be taken during his last year. He would elect substantially the following sequence of studies, which would form the backbone of his program. The subjects bracketed may be taken simultaneously. If it is required that the course be completed in 4 years, they must be taken the same year.

{Experimental physics
{Mathematics to introduction to the calculus

{Electrodynamics; or electricity, magnetism, and d-c electrical measurements
{Differential and integral calculus, analytic geometry

{A-c theory

{Power transmission
{A-c machinery

If, however, the student is interested in electric communication, a program of studies similar to the following would be arranged:

{Experimental physics
{Mathematics to introduction to the calculus

{Electricity, magnetism, and d-c electrical measurements
{Differential and integral calculus, analytic geometry

{Differential and integral calculus (advanced course)
Electric oscillations, radiotelephony, radiotelegraphy, electric waves
Electron Tubes

{Electric communication
Telephony

Of course some departures from these fundamental sequences are permitted and usually the student supplements these courses with others, usually in advanced mathematics and physics.

The remainder of the program is arranged by the student in accordance with his interests, and usually he will elect courses in related engineering fields. If he feels that he is best adapted to analytic and research work, he will add more courses in advanced physics, mathematics, and engineering. If he is inclined to engineering administration or sales engineering, he will elect courses in the fields of economics and business administration. The electric power engineer may be particularly interested in inductive interference or carrier frequency telephony on transmission lines and will select courses from both the power and communication fields. He will usually complete his program with courses in mechanical and civil engineering, such as thermodynamics, mechanics, statics or kinematics, or hydraulics.

The foregoing elective program appears to solve the problem of the regrouping of curricula along functional lines as proposed by Edward Bennett.[8] However, the program need not be divided rigidly, but each student may select the technical, economic, or administrative subjects which are in accordance with his own abilities and tastes, provided the program which he arranges is substantial and has a definite purpose.

Objections to Elective Program

Certain objections to this elective curriculum may be raised. A number of possible objections were considered before the plan was put into effect. It was feared by some that students would elect a group of easy subjects but this would not fulfill the requirements for a degree. Actually, instead of electing the easier subjects, the tendency has been for students to undertake too many difficult courses. This is sometimes done against the counsel of the adviser. Later, the majority of such students drop or change courses to balance the program. This method of learning by experience is better for the student than to have the faculty decide for him how extensive a program he should carry. However, some students of unusual ability do carry heavy programs successfully. Their advancement, therefore, is not retarded by their being obliged to keep step with students of lesser ability. As a matter of fact, we find the typical engineering student of today serious and hard working. He realizes that only by achievement that is much above the average will he be able later to find a place under present competitive conditions.

The objection may be raised that with the elective curriculum the student will be deficient in cultural and humanistic studies, tending to make him a narrow technician. In his first 2 years it is difficult for the student to complete his program with technical studies only. Practically all the technical courses require physics and mathematics through the calculus as preparation, so that the number of technical courses which the student can take during his first 2 years is limited. Moreover, if he does elect too many technical courses in a single year, he finds that the accompanying laboratory work requires too much time. He also learns by experience that a program entirely of technical subjects has a danger of becoming dull and monotonous, and that the program may be leavened by the election of a few nontechnical subjects.

Also, it should be remembered that in a university the student does not acquire his broader training entirely from classroom work. He makes contacts with students having other interests, and in some universities, including Harvard, it is arranged that students of widely divergent interests shall live together in a single house. Under such conditions students obtain an added breadth of education over that given in the classroom. In consultations with students, I have seen this contact reflected in their election of certain nontechnical studies because their interest had been aroused in such studies by discussions with nonengineering associates.

It may also be objected that the student is too immature to select wisely his own program, and in the beginning he may not know exactly the field of engineering to which he is best adapted. This last criticism also applies to the fixed curriculum. However, with the elective curriculum the student necessarily consults with his adviser when he enters his freshman year, and he immediately obtains a much clearer picture of the engineering profession than he would by the usual formal registration in a number of listed subjects. As is true in most engineering schools, the preparatory subjects of the first year, and to a large extent those of the second year, are common for several fields of engineering and no harm is done if the student does not select his specific field during his first or second year. As a matter of fact, many engineers have attained success in fields of engineering quite different from those in which they were specifically trained.

However, with the elective curriculum the student realizes that the responsibility of arranging the program is his and he starts immediately to make inquiries and to gather facts. He consults his fellow students, particularly the upper classmen, his adviser, his parents, and frequently graduates and practicing engineers. From these various sources of information he usually comes to a tentative decision and then discusses with his adviser the basis on which his decision rests. This development of inquisitiveness and self-analysis on the part of the student is far more important educationally than following blindly a ready-made synthesized program, however carefully it has been prepared. It is natural for the student to take far more interest in subjects which he himself has selected than in those which he is compelled to take.

Incidentally, the entire procedure is stimulating to the faculty. Students are keen to appraise courses at their true value and they are not likely to register in those courses which have little merit.

Reading Period

In 1927 Harvard adopted the reading period whereby, in courses not regularly open to freshmen, formal classroom work at the option of the instructor could be terminated approximately 3 weeks before the end of the term. By reading and other assignments the student completes the course by himself, although he is encouraged to consult with his instructors when he finds it desirable to do so. The primary object of the reading period is to develop the habit of self-education.

At first the reading period was not adopted widely by the engineering faculty. It was felt that at best the entire term was too short a time for imparting the amount of scientific material that the student should know, and that the rate of assimilation is higher under the close supervision of the classroom. However, on reflection, it was realized that the development of self-education and responsibility in the student is far more important than an added number of scientific relationships, and so now the reading period is employed in a majority of the electrical engineering courses above elementary grade.

Reading period assignments are necessarily varied in character. However, most teachers attempt to assign work which requires the students to study current technical publications and reference books, and thus to use the libraries. Students know that in the examination, emphasis will be placed on the reading period assignment and it is found that they actually master their assignments. They assert that they work harder during the reading period than during the other part of the term. A surprisingly rapid development in the student usually occurs during this reading period, due to the fact that instead of regarding the course as consisting of so many designated hours per week in which installments are written in his notebook, he now looks at it in perspective and is able to see it as an integrated whole. Undoubtedly relief from regular attendance in the classroom, which toward the end of the term may become a bit monotonous, has a stimulating influence.

Coördinated Program as Requirement for Degree

Although in a large university it is difficult to teach diverse subjects except as separate units, under the present plan at Harvard the degree is awarded not for completion of a definite number of distinct courses, but rather for satisfactory completion of a coördinate program of studies. The following is quoted from the catalog:

"The degree of bachelor of science in engineering will be conferred on students who complete a program of study, arranged with a definite purpose, ordinarily requiring 4 years of study and consisting largely of mathematics and science."

Electrical Laboratory Work

The object of laboratory work is threefold; to supplement the classroom theory with engineering experience; to familiarize students with the actual manipulation and the practical connections of electrical apparatus; to train students in the methods of planning and conducting an engineering project.

Laboratory work is usually conducted by assigning definite experiments to be performed weekly or at regular short intervals. The plan of issuing direction sheets specifying the laboratory procedure in detail has been discarded at Harvard as not adapted to the development of initiative and resourcefulness in the student; although even with this method the student must necessarily gain some engineering experience and familiarity with the apparatus. An improved method, employed to a considerable extent, is first to require students to study the test apparatus and with a little guidance from an instruction sheet, to submit a preliminary report before the experiments can be performed. This method trains students in the methods of planning and conducting engineering projects. The procedure at Harvard, however, goes farther. As soon as the student has become sufficiently well acquainted with the laboratory equipment and procedure, the laboratory work, instead of consisting of a number of single experiments each performed in one short laboratory session, consists of a few projects which are relatively comprehensive in extent. An instruction sheet designates briefly the particular apparatus, the assignment, and the date on which the final report is due. The student is required to submit a satisfactory preliminary report before he is permitted to perform the experiment. He is free to write the preliminary and final reports when and where he sees fit, except that the final report must be submitted on the date specified. He plans the experimental work and makes the arrangements for the use of the apparatus. Since the experimental work usually involves longer periods of time than the usual laboratory session, it devolves on the student to plan with some care the tests which are to be made and to coördinate the experimental work so that there is no unnecessary duplication, and so that the laboratory time is used in the most efficient manner. There is every incentive for the student to do the work efficiently since he can use the time saved to considerable advantage.

As one example of the method, the separate tests which are usually conducted on a dynamo, such as the saturation curve, the shunt generator characteristic, the compound generator characteristic, the shunt motor characteristic, the compound motor characteristic, the stray power and the determination and separation of losses, are conducted as a single comprehensive project rather than as a number of separate experiments.

Combining Reading and Laboratory Work

An example of combining the reading period assignment with the laboratory work is our requirement that in the reading period occurring at the end of the first semester, the students write the preliminary report for an experiment on a grid-controlled mercury-vapor rectifier and inverter. When they begin their study, the apparatus and its principles of operation are entirely new to them and their only

sources of information are the current technical books and periodicals. Yet, of themselves, they acquire sufficient understanding of the underlying principles of the tube and its methods of operation to write a comprehensive preliminary report and, as part of the midyear examination, to analyze the apparatus and its operation. The experimental work of the project is performed during the first half of the second semester.

At all times students are encouraged to suggest or arrange laboratory experiments on apparatus or subjects which interest them personally, and many students do this.

The advantages of this system of conducting laboratory work are many; it develops initiative and planning in the student; his sense of responsibility is developed; he comes to consider the apparatus which he tests and the laws governing its action as a coordinated whole rather than as a number of separate entities. Moreover, the student can arrange the hours to fit with his other activities. Also, freedom of schedule is quite important in some cases since it gives students opportunity to earn money by outside work and to engage in other activities which regular laboratory hours would prevent.

Conclusions

The foregoing plan of engineering training has been in full operation for nearly 2 years so that its ultimate effects, particularly after graduation, cannot be determined positively yet. Some desirable changes in the attitude of the students have been noticed, however. Frequent consultations make both the students and the faculty better acquainted; the students know themselves much better; they go about their work with a more serious and more mature attitude; there is a distinct improvement in the general scholastic standing. This last, of course, might be attributed to a more intelligent student body. It is not claimed that the methods which are described are the best, although no one will dispute the desirability of the objects. With experience changes will undoubtedly be made, for engineering education can be improved only by continued trial and experiment. It is realized that so single method may be best for all engineering schools. However, this plan is admirably adapted to the educational system of Harvard College and the other departments of the University, also on the elective basis, and they offer many subjects from which the engineering students may choose.

References

1. Engineering Schools and the Changed Conditions, V. Karapetoff. Elec. Engg., Sept. 1933, p. 604–5; "Letters to the Editor," C. L. Dawes, Sept. 1933, p. 647 and Feb. 1934, p. 364; J. G. Brainerd, Dec. 1933, p. 936; Training of Engineers in the Power of Expression, Sidney Withington, Nov. 1933, p. 799.

2. The Pitt-Westinghouse Program, H. F. Dyche and R. E. Hellmund. Elec. Engg., Jan. 1934, p. 103–8.

3. Report of the Investigation of Engineering Education, Soc. for the Promotion of Engg. Education, v. 1, 1928–29.

4. First Annual Report for the Year Ending October 1933, Engineers' Council for Professional Development.

5. Engineering Courses for the Functional Rather Than the Industrial Divisions of Engineering, Edward Bennett. *Engg. Education*, June 1924, p. 582. (See also p. 640 of report mentioned in ref. 3.)

Split Winding Transformers

A discussion of the application of and advantages derived from the use of split winding transformers for separating bus sections and for avoiding undue concentration of power from high voltage lines. An explanation is given of the characteristics of these units with respect to the reactances and the effect of load unbalance on the windings.

By
D. D. CHASE
ASSOCIATE A.I.E.E.
General Elec. Co.
Schenectady, N. Y.

A. N. GARIN
ASSOCIATE A.I.E.E.
General Elec. Co.
Pittsfield, Mass.

INCREASE in the size of units and power systems and in the number of interconnections has resulted in operating conditions much more complicated than were encountered in the days of small individual systems. This additional complication in operation can only be justified by improving the over-all efficiency of the system so that power can be sold more cheaply and by the ability of the power company to give more and better service.

Naturally the tying together of larger units or systems results in more concentration of power as well as a greater area being controlled. If tying together these power areas does not result in an improved service, the gain of the interconnection is only partially realized.

One of the principal difficulties of the larger systems has been that of keeping the disturbances resulting from system short circuits within the desired limits. This can be accomplished in several ways:

1. By improving the operating performance of the oil circuit breakers and relays so as to remove the source of trouble as quickly as possible.

2. By increasing system reliability by improvements in design and construction of the component parts, so that the actual number of failures is decreased.

3. By laying out the system so that only a limited area can be affected by the faults which do occur.

There have been several articles published on the first in the last few years showing the improvements made in oil circuit breakers and relays so that there

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 22, 1934; released for publication April 10, 1934. *Not published in pamphlet form.*

is no need to discuss this subject here. Similarly, the manufacturers have been improving the quality of their products, and the power company their installations, so that the failures per hour of service per kva have been decreased.

It is the purpose of this paper to discuss the split winding transformer and to illustrate what a practical device it is for use in the third method by limiting the effects of the faults that do occur.

Split Winding Transformer and Its Application

The split winding transformer is a multiwinding transformer in which 2 or more of the circuits are for the same voltage and intended for connection to independent sources of loads. The split circuits are normally arranged so that they have approximately the same reactance to the other windings. Care also is taken to have a relatively high reactance between them to act as a transfer reactance to limit the transfer of current during disturbances.

There are three major system arrangements in which the split winding transformer may give important advantages in system design. These are:

1. One large split winding transformer may be used in place of smaller banks of straight transformers for feeding 2 or more transmission lines.

2. A split winding transformer may be used to divide large blocks of transmitted power among low voltage buses and thus eliminate the concentration of energy.

3. The split winding transformer may be used to obtain bus sectionalization just as the double winding generators have in stations for lower voltage.

Power system ties have been increasing in size and voltage so that an appreciable amount of power can be exchanged between systems if necessary. These ties can be made using straight 2-winding transformers and 1-circuit transmission with the power taken from one point on each system, or the ties can be made with 2 completely independent lines and transformers or, finally, transformers with split high voltage windings can be used with 2 transmission lines connecting the systems.

The comparison of 2 lines with the split winding transformer, or with 2 independent transformers, brings out the following salient features. Larger transformers may be used with resultant lower costs, losses, and weight per kva for the split winding arrangement. The one circuit reactance can be made higher than the reactance of the smaller individual transformer, with the result that the fault kva will be less for line faults. At the same time, the split winding transformer can be so designed that the power transmitted through one line only, with the other line out of service, can be as large as that which could be transmitted through one of the lines used with independent transformers. However, the 2 lines using independent transformers have the advantage that transformer outage affects only one circuit.

In making a comparison between one power line and transformer with the same capacity as 2 lines with a split winding transformer, it becomes simply a comparison of costs versus reliability with costs favoring the one single transmission line and reliability in favor of the split winding transformer and 2 lines.

The split winding transformer also has been used with one high voltage winding and the low voltage winding split into 2 circuits. The power systems are tied together on the high side with a single transmission line, and the low voltage windings are connected to different bus sections of the station at the distribution load centers. With transmission lines capable of carrying 100,000 kva or more it becomes increasingly advantageous to be able to divide this power among different bus sections for good operating conditions. Also, by this method the size of circuit breakers both as to current rating and interrupting capacity can be decreased. The reduction in the current carrying capacity of these large breakers may be necessary in some cases since the actual current to be handled otherwise is beyond that for which any breaker has yet been designed.

In some power systems where the distribution of energy has been at from 24 to 27 kv the autotransformer has been used to step up the voltage from the generator to that required for the distribution system. With this type of system arrangement the use of the split winding transformer has the same application as the double winding generators have for systems of lower voltage.[1,2,3]

The Brooklyn Edison Company uses autotransformers in its 770,000-kw Hudson Avenue station to step up the generator voltage to 27.6 kv. This station, which was designed initially in 1922–23, has at the present time 3 50,000-kw single-shaft units, an 80,000-kw and 2 110,000-kw cross-compound units, and 2 160,000-kw single-shaft units. The last 2 units use split winding autotransformers in stepping up the generator voltage whereas the earlier units used standard autotransformers. Even with the installation of the last 2 units, which have more than 3 times the rating of the original units, the interrupting requirements of the oil circuit breakers have been kept the same, due to the rearrangement of the station and to the use of the split winding autotransformers.[4]

The application of the split winding transformer can best be shown by the fact that more than 1,250,000 kva of this type have been built in the few years that they have been available. Some 750,000 kva of these units are in autotransformers or straight transformers with the high voltage winding split. The voltage classifications used are 15, 25, and 37 kv.

The high voltage power transformers so far built have had the low voltage windings split, the split winding used varying from 22 to 132 kv. The high voltage windings varied in voltage from 110 to 230 kv. Methods of connecting these transformers are shown in Figs. 1 and 2.

Operating Characteristics

Whether a winding is split to reduce the short circuit kva, to permit maintaining voltage and carrying load on one circuit when the other circuit is short circuited, or for any other purpose described above, these results are obtained by a proper selection of transformer reactances. Both circuits of the split

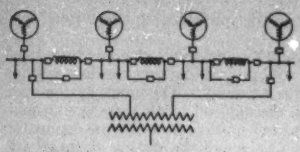


Fig. 1. Split winding transformer for transmitting a large block of power

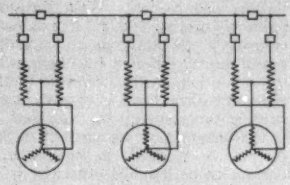


Fig. 2. Split winding autotransformer used in station bus arrangement

The transformer is applicable to either the star or ring bus

winding of a typical split winding transformer are of equal capacity and have the same reactive characteristics; that is, they have the same regulation drop when equally loaded, carry equal currents when connected to the same bus, draw the same kva when short circuited, etc. As a result of this symmetry, a few simple equations tie together the reactive characteristics of split winding transformers in such a manner that none of them can be changed without changing some other one. These equations are perfectly general in the sense that they apply regardless of the internal connections and construction of transformers. The same equations apply for autotransformers provided all reactances are taken as effective values at terminals.

Throughout this paper the following terminology will be used as indicated in Fig. 4. For a transformer with a single circuit winding *A* and with winding *B* split into 2 circuits, *B1* and *B2*, the total power transmitted from *A* to *B* will be called the "through" power or load. The power flowing from *B1* to *B2* will be called the "transfer" power or load. Operation from *A* to *B1*, with *B2* idle, will be called "1-circuit" operation, and the corresponding load "1-circuit" load. The expressions "balanced load" or "balanced operation" will be used to describe operation with *B1* and *B2* equally loaded at the same power factor. "Unbalanced load" and "unbalanced operation" will mean operation with *B1* and *B2* unequally loaded. "Unbalanced" operation may be viewed, of course, as the result of superposition of a "through" load and a "transfer" load, and the degree of unbalance can be specified clearly by specifying these simultaneous loads. Since, however, the *B1* and *B2* loads are usually of the same power factor so that the load on *A* is equal to their arithmetical sum, this load may be taken as 100 per cent and the degree of unbalance then may be specified conveniently by stating the percentage of total power flowing through each circuit. As an example 45//55 per cent load division will mean that 45 per cent of the total load, and consequently of load on *A*, is carried by *B1* and 55 per cent by *B2*.

The reactance from *A* to *B1* and *B2* in multiple will be called the "through" reactance and will be denoted by $X_{A-B1//B2}$. The reactance from *B1* to *B2* will be called the "transfer" reactance X_{B1-B2}. The reactance from *A* to *B1* will be called the "1-circuit" reactance X_{A-B1}. All reactances will be expressed in per cent based on some reference kva. In using the curves and formulas of this paper care must be exercised to have all reactances reduced to some common kva basis.

Reactances

Split winding transformers have been built with ratios of transfer to through reactance ranging from a little less than 4 up to approximately 18. Theoretically this ratio can have any value from zero to infinity. This flexibility is a striking advantage over older methods of splitting a circuit. Thus if 2 separate lines were connected through reactors to the same terminals of an ordinary transformer the total theoretically possible range of values of the ratio of transfer to through reactance would be contained between the limits of zero and 4, with the upper limit unobtainable in practice as it could be reached only if transformer reactance were zero. If 2 similar transformers of ordinary type were used, permanently connected in multiple on the single circuit side and connected to 2 separate circuits on the split side of the system, the ratio of transfer to through reactance would be equal to 4 and could have no other value.

The through, the transfer, and the 1-circuit reactances of a split winding transformer must satisfy the relations shown in Fig. 5 and given by the following equation:

$$X_{A-B1//B2} = X_{A-B1} - {}^1/_4 X_{B1-B2} \qquad (1)$$

Several important conclusions can be drawn from eq 1. If any 2 of the 3 reactances involved are specified, the third reactance becomes fixed, so that one cannot assign arbitrary values to all 3 reactances. Thus, for instance, if the through reactance $X_{A-B1//B2}$ is specified as 8 per cent and the transfer reactance X_{B1-B2} as 40 per cent, the 1-circuit reactances X_{A-B1} and X_{A-B2} must be 18 per cent, and cannot have any other values.

Even assigning arbitrary values to 2 out of 3

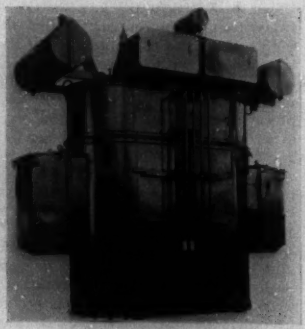


Fig. 3. Split winding transformer rated "WC - 60 - 20,000 kva, 110,000-13,-700 / 23,750 V // 13,700/ 23,750 V" with independent load ratio control on the 2 low voltage circuits

reactances involved in eq 1 may lead to a physically impossible or to an economically impracticable design, depending on the resultant value of the reactance left unspecified. Assume for instance that the 1-circuit reactance and the transfer reactance have been specified as 15 per cent and 64 per cent, respectively. These values, substituted in eq 1, give -1 per cent for the through reactance. Therefore, it is physically impossible to obtain the specified reactance values. If the 1-circuit and the transfer reactances are specified as 15 per cent and 52 per cent, respectively, eq 1 gives $+2$ per cent for the through reactance. This value, although theoretically speaking a possible one, is unreasonably low and in most cases would necessitate an extremely expensive design, so that the specified reactance values would be, practically speaking, unobtainable.

Referring once more to eq 1, 1-circuit reactance cannot be lower, and in most cases will be considerably higher, than the through reactance. On the basis of constant through reactance, the higher the specified value of transfer reactance is the higher will be the 1-circuit reactance. This is important when 1-circuit operation is expected, because excessive values of 1-circuit reactance may result in unsatisfactory 1-circuit operation due to excessive voltage regulation and load losses.

Short-Circuit Conditions

Two conditions of symmetrical 3-phase short circuit on *B1* will be considered: first, when voltage is maintained only on the single circuit winding *A*; second, when voltage is maintained not only on *A*, but also on *B2*. For all ratios of transfer to through reactance, except 4, short circuits will be heavier with voltage maintained on both *A* and *B2* than with voltage maintained only on *A*.

The reactance limiting the short-circuit kva, when *B1* is short circuited and full voltage maintained on *A* only, is found by rewriting eq 1 as:

$$X_{A-B1} = X_{A-B1//B2} + {}^1/_4 X_{B1-B2} \qquad (2)$$

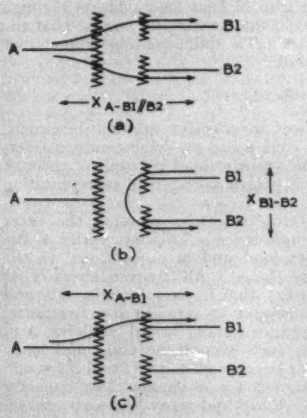


Fig. 4. Loads and reactances

(a) Through load and through reactance
(b) Transfer load and transfer reactance
(c) One-circuit load and one-circuit reactance

This equation shows that with a given through reactance, short circuit kva always is reduced by splitting winding *B*. With transfer reactance equal to 4 times the through reactance the short circuit

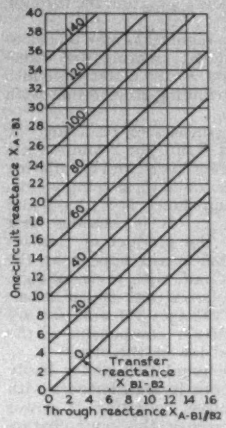


Fig. 5. Relation of reactances

All reactances in per cent on common reference kva

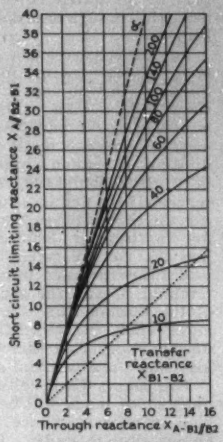


Fig. 6. Short-circuit limiting reactance. Short circuit on B1, voltage maintained on A and on B2

kva is just half what it would be if the *B* winding were not split, and further reduction in short-circuit kva down to any desired value can be obtained by increasing the transfer reactance.

The reactance limiting the short-circuit kva when *B1* is short circuited and voltage maintained on both *A* and *B2* is given by the following equation, represented graphically in Fig. 6:

$$X_{A//B2-B1} = \frac{4X_{A-B1//B2}\,X_{B1-B2}}{4X_{A-B1//B2} + X_{B1-B2}} \qquad (3)$$

As shown by the straight dotted line on Fig. 6, for a given through reactance short circuit kva is reduced by splitting winding *B*, provided the transfer reactance is greater than $^4/_3$ of the through reactance. With the transfer reactance 4 times the through reactance the short-circuit kva is half what it would be if the *B* winding were not split. A rapid increase in the transfer reactance will be required to obtain a further reduction in short-circuit kva. Transfer reactance equal to 12 times the through reactance will give short-circuit kva equal to $^1/_3$, and, as an absolute limit, transfer reactance equal to infinity will give short-circuit kva equal to $^1/_4$ of what it would be if the *B* winding were not split. If still lower values of short-circuit kva are required the *B* winding will have to be split into more than 2 circuits.

Regulation

Under balanced load the regulation from the terminals of the single circuit winding A to the terminals of each circuit of the split winding B is the same, and may be calculated as for any 2-winding transformer using the through impedance $Z_{A-B1//B2}$ and the through load.

For unbalanced loads the regulation may be calculated by well known methods, treating the transformer with windings A and B, the latter split into circuits $B1$ and $B2$, as a 3-winding transformer with windings A, $B1$, and $B2$.[5]

An alternative method consists of resolving the unbalanced load on winding B into the 2 components of the through and the transfer loads, and calculating separately the voltage drops due to these components. For the through load the impedance is $Z_{A-B1//B2}$ and for the transfer load Z_{B1-B2}. It is obvious that half the voltage given by the product of transfer load times transfer impedance will appear at the terminal $B1$ and the other half, with reversed sign, at the terminal $B2$. It follows that under unbalanced loads the terminal voltages $B1$ and $B2$ are unequal, and that the transfer component of the load raises one of them and lowers the other.

This shows that voltage regulation under badly unbalanced loads will be poor in transformers with high transfer reactance, unless operating at power factors close to unity. However, this same characteristic may be taken advantage of to design split winding transformers such that with one circuit of the split winding short circuited the terminal voltage of the other circuit is kept up, thus retaining the load on that circuit.

Neglecting resistances, with 100 per cent voltage maintained on terminals A, and with $B1$ open circuited and $B2$ short circuited, the voltage rise at the terminals $B1$, expressed in per cent of rated voltage, is:

$$\Delta E = \frac{X_{B1-B2} - 4X_{A-B1//B2}}{X_{B1-B2} + 4X_{A-B1//B2}} \times 100 \qquad (4)$$

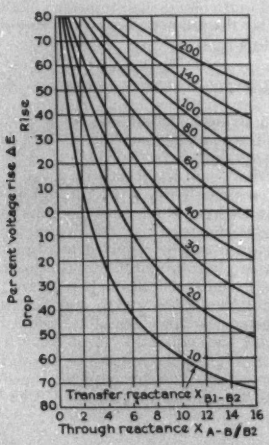


Fig. 7. Voltage rise or drop under short circuit. Voltage rise or drop at B1 with B2 short-circuited and voltage maintained on A. All reactances in per cent on common reference kva

This rise may be found to be negative, indicating a drop in voltage.

Figure 7 is a graphical representation of eq 4 which shows that if the transfer reactance is more than 4 times the through reactance a short circuit on $B2$ will be accompanied by a voltage rise at terminals of $B1$. A moderate rise is usually desirable as it helps to retain the load on $B1$. Extra high values of transfer reactance may give excessive values of voltage rise. As an example, a design with 10 per cent through reactance and 100 per cent transfer reactance will give a rise of 43 per cent, which may be altogether too high for the connected apparatus. The full value of this rise will appear at $B1$ terminals only if negligible load is connected to $B1$ and if the voltage on A is maintained during a dead short circuit on $B2$. Usually this is not the case.

When the ratio of transfer to through reactance equals 4, a short circuit on $B2$ will leave the terminal voltage of $B1$ unaffected. As an example, a design with 10 per cent through reactance and 40 per cent transfer reactance will have zero voltage rise at terminals of idle circuit $B1$ when circuit $B2$ is short circuited and 100 per cent voltage is maintained at terminals of winding A.

If the transfer reactance is less than 4 times the through reactance a short circuit on $B2$ will be accompanied by a voltage drop at the terminals of $B1$. This may be objectionable if the voltage drop is excessive. For example, a design with 10 per cent through reactance and 20 per cent transfer reactance will give a voltage drop of 33 per cent.

Losses

The no load loss and the load losses for balanced loads present no peculiarities and are usually only slightly higher than the normal losses of transformers of the same rating but without split windings.

Under unbalanced loads the load losses always are higher than under balanced loads of the same total kva. In fact, under unbalanced loads the load losses are given by the sum of load losses due to through load plus load losses due to transfer load so that the effective resistance of a split winding transformer may be expressed as:

$$R_{eff} = R_{A-B1//B2} + t^2 R_{B1-B2} \qquad (5)$$

where all resistances are effective values at terminals, expressed in per cent based on some common reference kva; t is the transfer load per unit of through load. In Fig. 8 is shown a graphical representation of eq 5.

In eq 5 the term t^2R_{B1-B2} represents the extra loss due to load unbalance. This loss varies as the square of transfer load and is proportional to the transfer resistance R_{B1-B2}. All the resistances of eq 5 are a-c resistances; that is, they include eddy and stray losses in addition to straight d-c resistance. The transfer resistance usually would be higher than the through resistance even if no eddy and stray losses were present because circuits $B1$ and $B2$ would normally be designed for a smaller kva capacity than winding A. Eddy and stray losses are caused

by leakage flux; since transfer reactance is usually higher than through reactance there usually will be more leakage flux per kva of load for transfer loads than for through loads. If, therefore, eddy and stray losses are taken into account as they must be in any practical design, it will be found that in most cases transfer resistance is much higher than through resistance, and that increasing the ratio of transfer to through reactance will increase the ratio of transfer to through resistance.

It follows, therefore, that in transformers with a high ratio of transfer to through reactance the load losses will increase faster with load unbalance than in designs with a moderate ratio.

Design Features

Split winding transformers may be built as 3-phase or as single phase units, with windings connected Y or delta, as straight transformers or as autotransformers. The split winding may consist internally of 2 entirely independent circuits, or it may be only partially split. Fig. 9 shows, on a single phase basis, 5 fundamental internal connection diagrams. In practice, in addition to these schemes, their various modifications and combinations may be used.

The arrangement of Fig. 9a is the simplest possible arrangement and may be used for all values of the ratio of transfer to through reactance by properly interlacing circuits *B1* and *B2*. If the required degree of interlacing is difficult to obtain, the scheme of Fig. 9b may be used to advantage. The transfer reactance may be reduced to any desired value by reducing the percentage of turns in the split portion of the winding, so that no interlacing whatever is required. Another scheme of avoiding the necessity of interlacing the 2 circuits of the split winding is shown in Fig. 9c. If coils Nos. 1 and 4 are electromagnetically remote from coils Nos. 2 and 3, the ratio of transfer to through reactance is 4. Both higher and lower ratios can be obtained by other groupings of the 4 coils.

The simplest internal connection diagrams for autotransformers, split on the high voltage and on the low voltage side respectively, are shown in Figs. 9d and 9e. Figure 9d is an adaptation of the scheme of Fig. 9a to an autotransformer split on the high voltage side. In fact, Figs. 9a, 9b, and 9c can be applied for autotransformers split on the high voltage side, by simply connecting the single winding *A* in series with the split winding *B*. Winding *A* will become then the common winding and winding *B* the split series winding of the autotransformer. Figure 9e is an adaptation of the scheme of Fig. 9c to an autotransformer split on the low voltage side.

Split winding transformers may be provided with taps, with or without load ratio control, for independent voltage control in both circuits of the split winding. If independent control is not desired, internal connections such as that shown in Fig. 9b permit varying the terminal voltages of both circuits by means of only one set of taps located in the unsplit portion of the split winding.

From the viewpoint of voltage stresses, both of operating frequency and of high frequency, each circuit of a split winding must be considered as an independent winding and must be insulated accordingly.

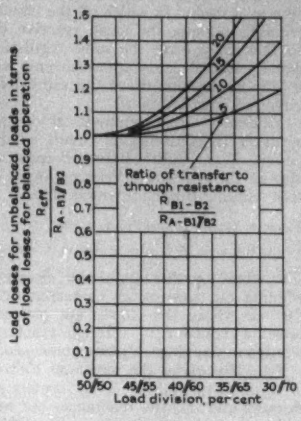


Fig. 8. Effect of load unbalance on load losses. All resistances in per cent on common reference kva

Transformers With 2 Split Windings

Transformers have been built with a single circuit primary, a double circuit secondary, and a double circuit tertiary; with symmetrical reactances from the primary to the secondary circuits and also from the primary to the tertiary circuits.

Depending on the degree of symmetry and on the values of reactances between various circuits, transformers with 2 split windings may have strikingly different operating characteristics. Thus a 2-winding transformer with 2 circuits *A1* and *A2* in the primary *A* and 2 circuits *B1* and *B2* in the secondary *B* may be designed with symmetrical reactances

$$X_{A1-B1} = X_{A1-B2} = X_{A2-B1} = X_{A2-B2}$$

In this transformer, current unbalance on the *A* side does not produce any current unbalance on the *B* side and *vice versa*. Hence, for any unbalanced loads, including short circuits, the transformer behaves as though it were split only on the side carrying the unbalanced load.

Entirely different characteristics are obtained by locating windings *A1* and *B1* electromagnetically remote from windings *A2* and *B2*. In this case, so far as reactances are concerned, there are in effect 2 transformers, one with windings *A1* and *B1* and the other with windings *A2* and *B2*; and this result is achieved without an appreciable sacrifice of the advantages of large unit size. Any load unbalance on the *A* side tends to be reflected on the *B* side and affects all the apparatus connected to the *B* side, depending on its characteristics, as a current or a voltage unbalance.

A variety of intermediate designs can be worked out between these extremes.

Windings Split Into 3 or More Circuits

In some rather special cases it may be advantageous to split a winding into more than 2 independent circuits. Let us define a symmetrical design as a design in which all the circuits of the split winding possess the same reactive characteristics, so that they have the same regulation drop when equally loaded, carry equal currents when connected to the same bus, draw the same kva when short circuited, etc.

Evidently, in a symmetrical design, all the reactances from the single circuit winding A to any circuit of the split winding B must be equal, and also all the reactances between any 2 circuits of the split winding B must be equal, that is:

$$X_{A-B1} = X_{A-B2} = X_{A-B3} = X_{A-B4}, \text{ etc.}$$

$$X_{B1-B2} = X_{B1-B3} = X_{B1-B4} = X_{B2-B4} = X_{B3-B4}, \text{ etc.}$$

The effect of the number of circuits in the split winding on transformer characteristics is shown in Fig. 10 where the curves are plotted against the ratio of transfer to through reactance, with the number of circuits as a parameter.

Fig. 10a gives the ratio of 1-circuit reactance to through reactance. Transformers with the same through and transfer reactances but with a different number of circuits in the split winding will have different values of 1-circuit reactance. For example, a transformer with 10 per cent through and 40 per cent transfer reactances will have 20 per cent 1-circuit reactance if it has 2 circuits in the split winding, 25 per cent with 4 circuits, and 27.5 per cent with 8 circuits.

A symmetrical design with several circuits in the split winding retains its symmetry when operating with some of the circuits idle. The reactance for such operation also can be obtained, therefore, from Fig. 10a. As an example, a transformer with 3 circuits in the split winding, with 10 per cent through reactance and 48 per cent transfer reactance, will have the following reactances:

Operating on all 3 circuits	10 per cent
Operating on any 2 circuits	14 per cent
Operating on any one circuit	26 per cent

Having found the reactances as in the examples above, regulation and short-circuit kva, are readily determined on the assumption that voltage is maintained only on the single circuit winding.

Fig. 10b shows that with one circuit of the split winding short circuited and voltage maintained on the remaining circuits of the split winding and on the single circuit winding, for designs with any number of circuits the short-circuit limiting reactance increases with increasing transfer reactance, following a curve that gradually flattens out and approaches a horizontal line. So far as short-circuit protection is concerned, there is little to be gained from any further increase in the ratio of transfer to through reactance. If a higher ratio of short-circuit limiting reactance to through reactance is desired, it will have to be obtained by increasing the number of circuits in the split winding.

Fig. 10c shows that the ratio of transfer to through

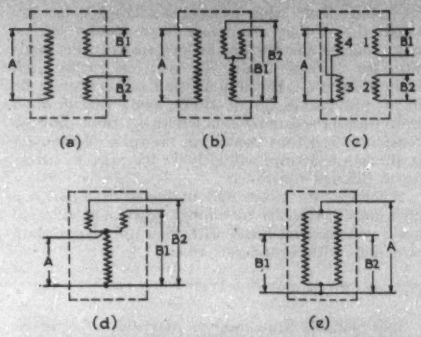


Fig. 9. Internal connections for split winding transformers (above) and autotransformers (below)

reactance must be equal to at least twice the number of circuits in the split winding if a drop in terminal voltage of all circuits, when one of them is short circuited, is to be avoided. It is obvious from design considerations that any increase in the number of circuits would naturally be accompanied by an increase in transfer reactance so that, as a rule, the above requirement is easily met.

If a certain rise in voltage is specified the corresponding ratio of transfer to through reactance is readily determined for any number of circuits. It will be observed that for a given voltage rise the required ratio of transfer to through reactance increases very fast as the number of circuits is increased. In fact, there is a definite limit to maximum voltage rise obtainable with a given number of circuits, and the greater the number of circuits the lower the limit is. It is very fortunate, therefore, that operating requirements usually do not call for a large voltage rise when there are more than 2 or 3 circuits in the split winding.

Curves of Fig. 10 will be exact only for exactly symmetrical designs. Exact symmetry may be difficult to obtain in a practical design, and even approximate symmetry may be difficult to obtain when the number of circuits is large, especially if windings are provided with taps. When applied to approximately symmetrical designs the curves of Fig. 10 will be only approximations.

In many cases there is little justification for specifying a symmetrical or even an approximately symmetrical design. Thus, for instance, when the circuits of the split winding are connected to entirely independent lines, to separate buses, or to separate generators the current division and the regulation drop are obviously controlled by the connected load or by the governor setting and the excitation of the generators. In such cases symmetrical reactances are no more necessary than in any multiwinding transformer. When the circuits are connected to separate lines and these lines are tied together at some distance from the transformer, or when the circuits are connected to a split winding

generator, the reactances of the lines or the reactances of the generator windings will be sufficiently high, as a rule, to make any reasonable departure from exact symmetry in transformer reactances a matter of no practical significance. Even in the rather unusual case when the circuits of the split winding are connected to a common bus equal current division can be obtained without symmetrical reactances provided there are more than 2 circuits in the split winding. Although such a design will not divide currents equally when operating with some of the circuits idle, will not draw the same short-circuit kva regardless of which circuit of the split winding is shorted, and will not give the same voltage rise at terminals of all non-short-circuited circuits, the variations in these characteristics can be usually held within permissible limits.

Summarization

Although the split winding transformer is a relatively new tool for power system design, more than 1,250,000 kva of these units have been built.

By using transformers of this type large blocks of transmitted high voltage power have been divided among bus sections on the low voltage side to eliminate power concentration and improve the normal system operating conditions.

These transformers have been used in station bus arrangements to obtain bus sectionalization with a resultant reduction in the size of circuit breakers required and the elimination of the bus sectionalizing reactors.

Since existing systems in increasing their capacity have used split winding transformers where transformers were required to obtain the proper voltage without increasing the interrupting duty on the existing breakers, there is every reason to believe that these transformers will be advantageous in other existing stations when increased capacity is required, as well as be useful in the building of new stations.

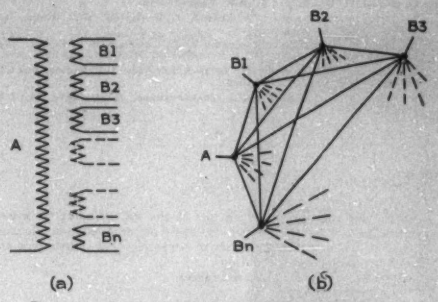


Fig. 11. Equivalent circuit for symmetrical design with "n" circuits in the split winding

(a) Transformer (b) Equivalent circuit

The power companies in deciding on the desirable characteristics of a split winding transformer should obviously study the adjacent parts of the system so as to obtain the best coördination possible between the system and the new installation. This is especially true in determining the number of circuits in the split winding.

As far as the transformer itself is concerned, the desirable characteristics may be briefly outlined as follows:

1. Although transformers can be built with windings split into any reasonable number of circuits, designs with more than 2 circuits in the split winding necessarily are more complicated and expensive and should not be specified unless the system itself is split into more than 2 circuits, or an extraordinary reduction in short-circuit kva is required.

2. The best ratio of transfer to through reactance for transformers with 2 circuits in the split winding is approximately 4. If this ratio is less than 3, the effectiveness of split circuit construction in preventing the spread of trouble from one circuit to another is seriously reduced; on the other hand, ratios much higher than 10 are suitable only when no appreciable load unbalance is expected, and when system characteristics are such that over-voltages caused by short circuits present no danger.

3. Transformers with 2 circuits in the split winding have been built with load division ranging in limits from 50//50 per cent to 33//67 per cent. If necessary, transformers can be built for a greater load unbalance. Naturally such designs will be more expensive.

4. Transformers with 2 circuits in the split winding are inherently symmetrical. In transformers with more than 2 circuits, symmetry can be obtained but may require a special design. In many cases, approximate symmetry will meet operating requirements. There-

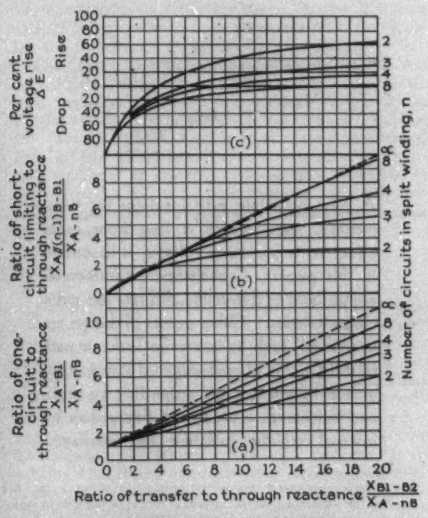


Fig. 10. Characteristics of transformers with one winding split into several circuits

(a) Relation of reactances
(b) Short circuit limiting reactances
(c) Voltage rise or drop under short circuit
All reactances in per cent on common reference kva

fore, for transformers with several circuits in the split winding, a permissible range of reactance values, rather than definite values, should be specified.

References

1. Double Windings for Turbine Alternators, P. L. Alger, E. H. Freiburghouse, D. H. Chase. A.I.E.E. Trans., v. 49.
2. The Double Winding Generator, T. F. Barton. *G.E. Review*, June 1929.
3. The Double Winding Generator, D. D. Chase and H. C. Forbes. *Elec. Wld.*, Dec. 15, 1928.
4. Providing Reliability in a 770,000-Kw Station, J. F. Fairman and Carl M. Gilt. *Elec. Wld.*, May 21, 1932.
5. Theory of Three Circuit Transformers, A. Boyajian. A.I.E.E. Trans., v. 43.

Appendix

Denoting the number of circuits in the split winding by n and expressing all reactances in per cent based on some common reference kva, the reactive characteristics of a symmetrical transformer are given by the following equations.

Relation connecting the 3 reactances:

$$X_{A-nB} = X_{A-B1} - \frac{n-1}{2n} X_{B1-B2} \tag{6}$$

wherefrom:

$$\lim (X_{A-B1}) = X_{A-nB} + {}^1/_2\, X_{B1-B2} \tag{7}$$

when $n \longrightarrow \infty$

Relation between reactances and short circuit kva, or short circuit on $B1$ and maintained voltage on $B2$, $B3$, $B5$, etc., and on A

$$X_{A//(n-1)B-B1} = \frac{n^2 X_{A-nB}\, X_{B1-B2}}{2n(n-1)\, X_{A-nB} + X_{B1-B2}} \tag{8}$$

wherefrom:

$$\lim \left[X_{A//(n-1)\,B-B1} \right] = n^2 X_{A-nB} \tag{9}$$

when $\dfrac{X_{B1-B2}}{X_{A-nB}} \longrightarrow \infty$

Relation between reactances and terminal voltage rise of non-short-circuited circuits of a split winding when 1 circuit is short-circuited

$$\Delta E = \frac{X_{B1-B2} - 2nX_{A-nB}}{(n-1)\, X_{B1-B2} + 2nX_{A-nB}} \times 100 \tag{10}$$

Wherefrom:

$$\lim (\Delta E) = \frac{1}{n-1} \times 100 \tag{11}$$

when $\dfrac{X_{B1-B2}}{X_{A-nB}} \longrightarrow \infty$

Referring to Fig. 10, in the equivalent mesh network of a symmetrical split winding transformer all branch reactances from the terminal A to any B terminal are equal to

$$nX_{A-nB} \tag{12}$$

and all branch reactances between B terminals are equal to

$$\frac{n^2 X_{A-nB}\, X_{B1-B2}}{2n\, X_{A-nB} - X_{B1-B2}} \tag{13}$$

A New Porcelain Post Insulator

By
G. W. LAPP
ASSOCIATE A.I.E.E.

Lapp Insulator Co., Inc.,
LeRoy, N. Y.

A new porcelain post insulator for transmission lines, which is free from radio effect at its operating voltage, is described in this paper. Capacitance measurements are utilized to determine and rate the radio characteristics. Other points of design are described, such as improved leakage path to resist arcing in contaminated atmosphere, greater height to avoid grounding by birds, and increased resistance to destruction by internal cracking, puncture, and breakage.

NEW requirements necessitate the reconsideration of the specifications for pin type transmission line insulation. The following points are submitted as an adequate basis for judging the merits of such insulators.

1. Long life should be insured by a design inherently free from puncture or cracking, with few special details to be watched during manufacture, assembly, and testing. Lack of internal soundness has produced most failures.

2. Resistance to shattering by power arcs, stones, and bullets should be assured. Material should be distributed to avoid extended fragile parts especially if they permit propagation of cracks into the body of the insulator. At all hazards it should be possible to maintain or restore service on the damaged insulator.

3. Accepted ratings and flashover standards should be met.

4. Operation in dirty atmospheric conditions without cleaning is frequently of critical importance.

5. Permanent freedom from radio effects at voltages safely above neutral operating voltage presents the latest problem. This result

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 9, 1934; released for publication April 30, 1934. *Not published in pamphlet form.*

should preferably be accomplished by a design that reduces the cause instead of by the use of superficial coatings or attachments that may deteriorate and aggravate the trouble.

6. Cost must be reasonable for general use.

The degree to which these qualifications have been met by a new porcelain line post is the subject of this paper.

The Line Post Development

In Figs. 1 and 2 are shown the developed form of a porcelain post with recessed tie head. A similar line post with conventional tie head is shown in Fig. 3. A standard pin type line insulator is shown in Fig. 4 for comparison.

The line post insulator consists of a hollow porcelain column having an integral closed end at the top or live end and a hermetically sealed plug in the bottom or open end which is solidly cemented into a rigid metal base. (See Fig. 1.) The porcelain is covered on the outside with numerous small leakage flanges producing what is known as "fog type." In its developed form shown in Figs. 1 and 2, the tying head is formed with an undercut or recessed groove below the tie wire groove, which latter is located in the outer rim of the head. This head permits the conventional method of tying. This modified form is employed to reduce the capacitance of the insulator, by interposing air between the tie wire and the main body of the insulator, a region in which the flux density is relatively high. Large diameter of the tie loop permits low concentration of flux leaving the tie wire.

The degree to which corona and radio effects can be reduced in this low capacitance type of porcelain post insulator makes it unnecessary to resort to special conductive or dielectric coatings around the tie wire. It is also possible to use the conventional form of tire wire without special attention to tightness and kind of material or to surface condition of the wire. In the usual high capacitance insulators, unless specially treated, these factors may cause sparking and reduction of the critical voltage.

Radio Characteristics

Radio effects may be encountered where radio frequency voltages appear as a result of concentrated corona or sparking present through the air, usually between a metal part and the porcelain, and particularly between the tie wire and the porcelain. The problem of eliminating this degree of concentration may be attacked in 2 ways. First, by reducing the flux from tie wire to porcelain, and second, by inreasing the equivalent area of contact or replacing the overstressed air by a non-gaseous filler. Along this second line of attack various coatings and fillers, both conductive and insulating, have been tried, but they are usually subject to deterioration or change, and by increasing the capacitance of the insulator they may cause critical concentration at the pin or between shells.

Reducing the amount of electrostatic flux or charging current passing from the tie wire to the insulator is a more fundamental method of removing the trouble. This can be limited by reducing the capacitance of the insulator. The capacitance of the insulator can be reduced most by removing the conventional pin and supporting the conductor and tie wire on a porcelain post of maximum length above the grounded base and of minimum cross section, since porcelain has a high dielectric constant. It is advantageous to make the porcelain body, especially at the top, as small as practicable.

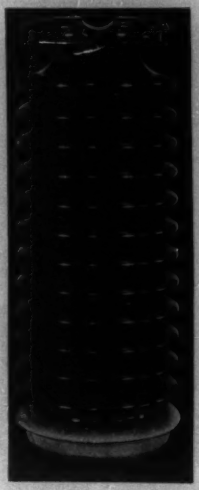


Fig. 1. The new line post insulator for transmission lines

Determination of Radio Effects by Capacitance Measurements

Measurement of electrical capacitance of the insulator affords a possibility of quantitative statement of the effectiveness of different types of insulators in respect to their freedom from radio characteristics. Intensity of electrostatic flux passing from the tie wire into the porcelain is the critically important factor. A significant indicator of the flux entering the porcelain is the capacitance added when the porcelain is placed in position between the tie wire and the ground terminal. Capacitance of line conductor and tie wire are measured while these metal parts are supported in normal relation. Then, the porcelain is put in place between the hardware, and capacitance readings are taken showing a small increase for the porcelain post and a large increase for the pin type. The total capacitance through the porcelain, C_p, can be found by multiplying this added capacitance by the factor $K/(K-1)$ in which K is the dielectric constant. This factor for porcelain is approximately 1.19.

The total flux entering the porcelain from the tie

Table I—Determination of Criterions for Radio Effect

Insulator Type	Point on Curve	Rated Voltage, Kv	Line Voltage to Ground, Kv	Lowest Radio Voltage, Kv	Capacitance, Micromicro farads: Total C_T	Capacitance, Micromicro farads: Porcelain Removed C_A	Capacitance, Micromicro farads: Through the Porcelain $C_P = \frac{C_T - C_A}{(K-1)K}$	Length of Tie-wire Contact Inches L $L = \pi d$	L/C_P
Standard head pin	1	35	20	7	16.6	8.55	9.56	11.1	1.16
Standard head pin	1	45	26	9	18.2	8.08	12.00	11.1	.915
Standard head pin	3	66	38	10.5	16.6	5.25	13.50	15.7	1.16
Standard head line post	4	20	11.5	22	9.32	8.14	1.41	6.28	4.45
Standard head line post	5	66	38	29	5.66	3.90	2.09	14.2	6.8
Recessed head line post	6	66	38	41	5.96	4.54	1.688	18.9	11.2

wire divides into 2 paths. One portion traverses the porcelain directly to the lower metallic grounded terminal, pin, or base. The second part of this flux passes through the porcelain and is diffused to space. This latter fraction is a major portion of the very small amount of flux entering the porcelain in the case of the porcelain post and is a minor portion of the large amount of flux in the case of a standard pin type insulator.

Returning to the total flux entering the porcelain, it is found that if the measured value of this capacitance is low per unit length of tie wire, or circumference of tie-wire groove, the intensity at the contact is low and the voltage for initial radio effect is high. Reciprocals of this ratio are listed in Table I under L/C_P and plotted in Fig. 5, using lowest radio voltages as ordinates. This places the relation on a quantitative basis and shows in a specific way the improvement accomplished by the porcelain line post.

The quantity L/C_P may be taken as a merit figure for the insulator, as shown by the fact that it produces a smooth graph with lowest radio voltages as ordinates. The higher this merit figure, the lower is the flux intensity and therefore the higher the voltage on which the insulator can be used without radio effects.

It will be noted that this graph, when extended, does not pass through the origin, but indicates a positive intercept on the ordinate axis and some value of negative intercept on the L/C_P axis. It is probable that this is due to a small amount of flux leaving the line conductor that does not flow through the critical contact between the tie wire and porcelain. Capacitance measurements made with the line conductor removed tend to confirm this explanation of the intercepts.

Minimum radio voltages and capacitances were measured using 2 turns of No. 8 tie wire and a piece of one-inch conductor about 22 in. long. With 3 turns of tie wire on the recessed line post, the lowest detectable voltage is raised to about 50 kv, which is the greatest increase shown by the additional turn for any type. In general, a greater number of tie-wire turns or larger diameter of wire give higher values of minimum radio voltage.

Table II presents a comparison between conventional and line post insulators on the basis of lowest or starting voltage for radio effects. In Table II, values correspond to 2 turns of No. 6 tie wire. It is found that a practical margin of voltage for minimum radio effect voltage above neutral or operating voltage is available in these post types to offset well-known effects of different kinds of tie wire and different conditions of looseness or roughness of surface or oxidation of the surface of the wire. These factors are of less importance in this type since the flux is reduced to such a very low value.

Values of minimum radio voltage given are conservative as they represent the point at which the initial detectable effect occurs. This is at the start of audibility with maximum volume adjustment on the receiver and with 12 ft of pick-up antenna parallel to the line conductor at 4 ft distance. The start is easily detected audibly or simultaneously on an output meter between the receiver and the speaker. In this way there is no need to be concerned with a calibrated degree of audibility which has been the basis of most of our thinking about radio effects. The practical point at which actual effects would be noticed on a line would occur at some higher voltage and afford another margin of safety. In making these tests for radio effect, the outside disturbances and transformer noise were absent.

Auxiliary devices were not used and are not reported in these tests although any kind of auxiliary treatment that would provide an improvement in usual types should produce some still higher values when applied to this type of recessed tie head line post. This statement is made to emphasize the fact that the method of eliminating concentration by reduction of capacitance is distinct from the remedies which spread the flux or fill in the air

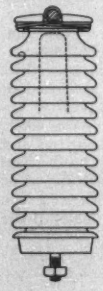


Fig. 2 (left). Line post insulator with recessed head, 66-kv rating

Fig. 3 (right). Line post insulator with standard tie head, 66-kv rating

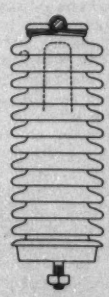


Table II—Comparison of Radio Characteristics

X_T Rating	Neutral Rated Voltage	Minimum Radio Voltage Conventional Pin Type	Minimum Radio Voltage Line Post, Recessed Head
20	11.5	5.5	22
25	14.5	6	33
35	20	7	36
45	26	9	40
55	32	10	43
66	38	10.5	47

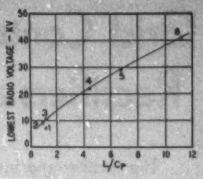


Fig. 5. Curve relating flux concentration to lowest radio voltage

space where the flux tends to produce corona breakdown, whether by the use of conductive coatings and fillers or by dielectric or porcelain filling.

Electrical Characteristics

Electrical considerations also involve dry and wet flashover voltages, freedom from short circuit by birds, freedom from puncture, resistance to flashover under contaminated atmosphere, and maintenance of electrical values after damage by power arc or mechanical breakage. On account of decreased diameter, normal ratings of flashover distance and voltage are attained by slightly greater height than in standard pin types. This increased height from the crossarm to the line conductor affords greater insurance against bird troubles.

Since the length of the puncture path is equal to the flashover distance and has in series at its live end a wall of porcelain of full thickness, this type is inherently free from puncture. The internal air path is a region of negligible dielectric stress.

Radio tests cited in Table I indicate a maximum flux density of very low concentration at the tie wire. The stress in the porcelain adjacent is still lower and the relative degree of freedom from dielectric stress in the porcelain also may be measured by the same figure of merit L/C_p or directly by the lowest voltage for radio effect. This holds for normal voltages. For pre-flashover voltage the relative concentration is diffused by the appearance of conductive corona.

Resistance of this type to flashover initiated by dirty leakage surface is a matter of experience in many extreme cases of contaminated atmosphere. It is this quality that has chiefly recommended the "fog type." The extra height of this type makes it possible to have a long uniform leakage path by the use of many small corrugations on the outside of the insulator. By the elimination of the long dry internal portion of the leakage path from the fog type pin-supported insulator it is possible to extend the same effective style of corrugated leakage surface all the way to the ground terminal. Electrical advantages result from these many small flanges since they cause splashing of rain water, to wet and wash the entire external surface regularly. This makes it unnecessary to wash the insulators in most cases even where atmospheric contamination is severe.

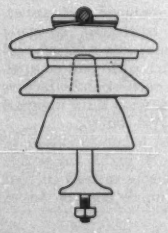


Fig. 4. Pin type insulator, 66-kv rating

Mechanical Characteristics

Mechanically, these small, closely spaced corrugations surrounding the main body of the insulator act as circular reinforcement flanges to strengthen the porcelain wall. They provide non-resonant buffer material to break the shock of any crushing blow and so to prevent an impact from cracking the main wall. Petticoats are so proportioned that these corrugations will break away clean and not propagate the cracks into the main body. The breakage of a corrugation or 2 has a negligible effect in reducing the electrical or mechanical reliability of the support. The fact that the lower end of the porcelain is surrounded and protected by the metal base, removes the open bell effect and eliminates vulnerability at this point. The base produces external compressive forces on the hollow porcelain, consolidating the heavy wall at the bottom. There are no internal parts to cause possible bursting strains. Since the design is ideally adapted to manufacture in one piece, it can be free from the problems of articulated porcelain and metal parts. Testing and assembly follow routine methods and are free from delicate precautions usually considered necessary in conventional types.

Mechanically these porcelain posts are strong and far more rigid than equivalent pin supported insulators. It is possible to produce designs to meet any likely requirements for cantilever strength and rigidity. When fitted with a switch type cap, the post has equal strength upright or inverted.

Merits of the New Insulator

An attempt has been made in this paper to evaluate the merits of this insulator with reference to primary modern requirements for general use on transmission lines on an engineering and test basis. In the past it has been considered necessary to form final judgment of a new insulator only after several years field experience. At present 2 years successful operation are reported on a conventional tie head line post insulator.

Grid Controlled Rectifiers and Inverters

The rectifier and inverter characteristics of the grid controlled mercury arc rectifier of the 6-phase and 12-phase types are considered in this paper. The analysis of rectifier circuits has been extended to cover the effect of grid control on the output voltage, power factor, efficiency, wave forms, and other characteristics; and the characteristics of the grid controlled rectifier operating as an inverter have been determined. Several schemes for applying these rectifiers to railway electrification requiring regeneration are considered.

By
C. C. HERSKIND
ASSOCIATE A.I.E.E.

General Electric Co.,
Schenectady, N. Y.

IN THE past few years the mercury arc rectifier has come into general use as a means for changing power from alternating current into direct current. The advantages of the rectifier over other types of conversion apparatus, due to its desirable structural features and operating characteristics, have led to the development of rectifier units of high capacity. As an integral part of this development, the design of control grids has also been perfected so that high capacity rectifiers with grids which are suitable for applications requiring grid control are now available.

The field for applications of the mercury arc rectifier is considerably enlarged by the use of control grids. Grids provide a simple means for controlling the rectifier output voltage so that the rectifier will have voltage characteristics similar to those of a d-c generator with field control. Such a controlled unit has a variety of industrial uses. Also, by reversing the d-c connections and providing suitable excitation to the grids, the rectifier tank may be operated as an inverter for changing power from direct to alternating current. Other applications making use of various combinations of rectifier and inverter operation have been suggested.

In order to determine the suitability of the mercury arc rectifier for the various applications, it is essential that its operating characteristics and limitations be known. This paper covers some of the principal characteristics of the mercury arc rectifier when functioning with grid control. The theory of rectifier circuits, which has been presented in numerous papers and books[1–10] for the case of the simple rectifier, is here extended to the grid controlled rectifier by the introduction of the grid control angle as an additional factor.

The characteristics of a simple inverter have been determined by the same method of analysis as is used for the grid controlled rectifier. The equations are similar in form and the regulation characteristics are the same. A number of conditions not required in the case of the rectifier must be met in order to operate as an inverter. These arise as a result of the commutation processes taking place during inversion. An analysis of these requirements has been made from the equations.

A part of this paper covers the application of the grid controlled rectifier-inverter unit to railway electrification where regenerative braking is required and discusses the operating characteristics of such a unit.

Part I—The Grid Controlled Rectifier

It is well known that the output voltage of a rectifier may be controlled by means of grids. Also, that the grids function through their ability to control the time at which the anodes may fire, and that by means of the grids the anode firing may be postponed so that the anode current flows at a time when the anode voltage is reduced. However, there has been no general treatment covering the voltage, power factor, efficiency, wave forms, and other characteristics of a rectifier with grid control. The effect of grid control upon each of these factors will be considered; also the additional duty imposed upon the rectifier by the use of grid control.

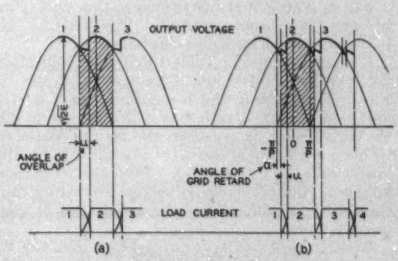


Fig. 1. Output voltage and current waves

(a) Six-phase rectifier without grid control
(b) Six-phase rectifier with grid control

This paper will be limited to a consideration of those rectifier circuits having a highly inductive d-c circuit so that the instantaneous output current is essentially constant and the anode current waves

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 20, 1934; released for publication March 26, 1934. *Not published in pamphlet form.*

1. For all references see list at end of paper.

are flat topped. This is the most important case, being the type of circuit most frequently encountered in practice.

Output Voltage

In Fig. 1 (*a*) are shown the d-c voltage and current waves of a 6-phase rectifier of the usual type without grid control, while Fig. 1(*b*) shows those for a grid-controlled rectifier.

It has been shown[1,2] that the net output voltage of a rectifier without grid control is given by the expression

$$E_d = \sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p} - \frac{IXp}{2\pi} - E_{arc} - \frac{W_t}{I} \tag{1}$$

where the first term represents the d-c voltage at no load, the second term is the voltage drop due to transformer reactance (overlap), and the third and fourth terms are the rectifier arc drop and the transformer winding resistance drop, respectively,
and where

E_d = d-c voltage
E = effective value of transformer secondary voltage to neutral
p = number of secondary phases in each group;
also defined $p = \dfrac{360 \text{ deg}}{\text{degrees conducting period-degrees overlap}}$
I = load current in each group of secondary windings
X = commutating reactance from anode to neutral
E_{arc} = rectifier arc drop
W_t = transformer resistance loss in each group of secondary windings.

In order to facilitate frequent reference to the d-c voltage obtained at no load without grid control, the expression

$\sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p}$ will be denoted by the symbol E_{do}.

When the rectifier firing is postponed by the angle α by means of grid control, as shown in Fig. 1(*b*), the d-c output voltage is reduced. If it is assumed that the rectifier is operating at no load, that is, that the angle of overlap u is zero, and if the rectifier arc drop and transformer winding resistance drop are neglected, the d-c voltage with grid control is

$$E_d = \frac{\displaystyle\int_{-\frac{\pi}{p}+\alpha}^{\frac{\pi}{p}+\alpha} \sqrt{2}\, E \cos \omega t \, d\omega t}{\displaystyle\int_{-\frac{\pi}{p}+\alpha}^{\frac{\pi}{p}+\alpha} d\omega t} = \sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p} \cos \alpha \tag{2}$$

If this expression is substituted for the no load term in eq 1 the net output voltage of a grid controlled rectifier is obtained.

$$E_d = \left[\sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p}\right] \cos \alpha - \frac{IXp}{2\pi} - E_{arc} - \frac{W_t}{I} \tag{3}$$

The arc drop E_{arc} is the same with or without grid control as it depends only upon the load current passing through the rectifier. The voltage drop $\frac{W_t}{I}$ due to the transformer copper losses may usually also be considered to be the same, though the transformer copper losses are changed to a small extent by the variation in the angle of overlap with grid control. At first sight it is not evident that the voltage drop due to transformer reactance, that is, overlapping, is not changed with grid control. However, the truth of this statement may be verified by the analysis which follows.

Calculating the output voltage on the assumption that u is not zero, we obtain from Fig. 1(*b*)

$$E_d = \frac{\displaystyle\int_{-\frac{\pi}{p}+\alpha}^{-\frac{\pi}{p}+\alpha+u} \frac{\sqrt{2}\, E \left[\cos\left(\omega t + \frac{2\pi}{p}\right) + \cos \omega t\right]}{2} d\omega t}{\displaystyle\int_{-\frac{\pi}{p}+\alpha}^{\frac{\pi}{p}+\alpha} d\omega t} + \frac{\displaystyle\int_{-\frac{\pi}{p}+\alpha+u}^{\frac{\pi}{p}+\alpha} \sqrt{2}\, E \cos \omega t \, d\omega}{\displaystyle\int_{-\frac{\pi}{p}+\alpha}^{\frac{\pi}{p}+\alpha} d\omega t}$$

$$= \sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p} \left[\frac{\cos \alpha}{2} + \frac{\cos (u + \alpha)}{2}\right] \tag{4}$$

In order to show that this is equivalent to the first 2 terms of eq 3 it will be necessary to analyze the commutation process.

The transfer of current from one anode to the succeeding anode of the same group takes place during the overlapping or commutating period denoted by u [Figs. 1(*a*) and 1(*b*)]. The angle of overlap for a rectifier without grid control is given by the relation[1,3]

$$\cos u = 1 - \frac{IX}{\sqrt{2}\, E \sin \frac{\pi}{p}} \tag{5}$$

When the firing of the anodes is retarded by the grid control, the angle of overlap is reduced because a higher voltage is available for forcing commutation. An expression for the angle of overlap with retarded firing similar to the above relation may be derived from an analysis of the commutating circuit.

Referring to Fig. 1(*b*), during commutation from anode 1 to anode 2, a circulating current is set up in the loop formed by these 2 anodes and their connected transformer windings. This current flows as a result of the voltage difference between the 2 phases. The value of the voltage available for commutation is

$$2\sqrt{2}\, E \sin \frac{\pi}{p} \sin (\omega t + \alpha)$$

where time $t = 0$ is taken as the instant at which commutation begins. As a result of the inductance of the transformer windings a voltage is induced in the commutation circuit opposing the transfer of current. This induced voltage is equal and opposite to the commutating voltage. Applying Kirchoffs' second law to the closed loop forming the commutating circuit

$$L \frac{di_2}{dt} = \sqrt{2}\, E \sin \frac{\pi}{p} \sin (\omega t + \alpha) \tag{6}$$

in which L is the inductance of the circuit between anode and neutral and i_2 is the instantaneous current in anode 2.

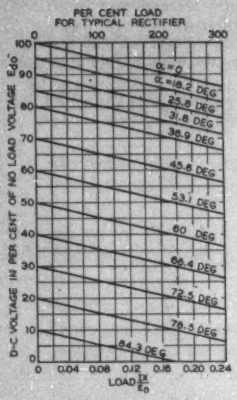
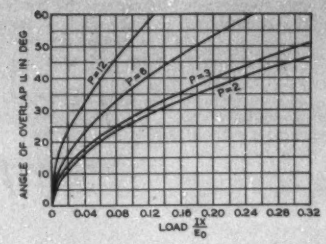


Fig. 2. Voltage regulation characteristics of 6-phase and 12-phase grid controlled rectifiers with interphase transformers (p = 3) and highly inductive d-c circuit

α = angle of grid retard



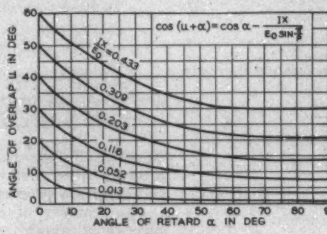


Fig. 3 (above). Angle of overlap for rectifiers without grid control plotted as a function of load

Fig. 4 (below). Variation in angle of overlap with the angle of grid retard for a grid controlled rectifier (p = 3)

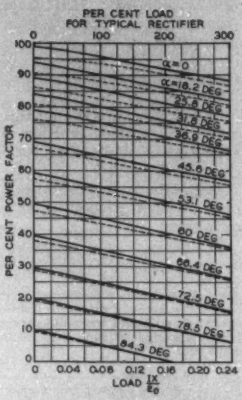


Fig. 5. Power factor characteristics of 6-phase and 12-phase grid controlled rectifiers with p = 3 and highly inductive d-c circuit

Solid lines—power factor of 12-phase rectifier
Dash lines—power factor of 6-phase rectifier
α = angle of grid retard

Integrating the above equation and substituting $i_2 = 0$ at time $t = 0$, we obtain

$$i_2 = \frac{\sqrt{2}\,E \sin\frac{\pi}{p}}{X}\,[\cos\alpha - \cos(\omega t + \alpha)] \tag{7}$$

where $X = L\,\omega$

Upon the completion of commutation $\omega t = u$ and $i_2 = I$. Then the angle of overlap with grid control is given by[4]

$$\cos(u + \alpha) = \cos\alpha - \frac{IX}{\sqrt{2}\,E \sin\frac{\pi}{p}} \tag{8}$$

It will be noted that this equation is of the same form as eq 5 for the simple uncontrolled rectifier and that it reduces to eq 5 when $\alpha = 0$. Equation 4 may be reduced to the form of eq 3 by substituting the value of $\cos(u + \alpha)$ given by eq 8.

The drop in d-c voltage due to overlapping of anodes arises from the inductive voltage produced by the commutating current.

The instantaneous inductive voltage drop e_L is

$$e_L = L\,\frac{di_2}{dt}$$

The average d-c voltage drop due to overlapping, ΔE_d, may be calculated by integration of the inductive voltage drop e_L over the angle u

$$\Delta E_d = \frac{1}{2\frac{\pi}{p}} \int_0^u e_L\, d\omega t$$

Substituting the values of e_L from eq 6 this becomes

$$\Delta E_d = -\sqrt{2}\,E\,\frac{p}{\pi}\,\sin\frac{\pi}{p}\left[\frac{\cos(u + \alpha) - \cos\alpha}{2}\right] \tag{9}$$

The replacing the bracketed terms by $-\dfrac{IX}{\sqrt{2}\,E \sin\frac{\pi}{p}}$ from eq 8 we obtain

$$\Delta E_d = \frac{IXp}{2\pi} \tag{10}$$

This relation shows that the voltage drop due to transformer reactance (overlapping) is independent of the use of grid control.

The d-c voltage regulation characteristics of a grid controlled rectifier, calculated by means of eq 3, are shown graphically on Fig. 2. The voltage drops due to arc drop and resistance drop are not included in these curves. A constant grid retard, angle α, is assumed for each curve. Values of α are chosen so that the reduction in d-c voltage at no load, that is, $\cos\alpha$, varies in steps of 5 and 10 per cent of the voltage at no load without grid control.

The curves on Fig. 2 apply to either 6-phase or 12-phase rectifiers with interphase transformers giving double wye or quadruple zigzag operation, that is, where $p = 3$. The load is expressed in terms[5] of $\dfrac{IX}{E_0}$ where I and X have the same values as in eq 1 and $E_0 = \sqrt{2}\,E$.

Calculation of Angle of Overlap

The angle of overlap of a rectifier without grid control is given by eq 5. In Fig. 3 is shown the

overlap plotted as a function of load $\frac{IX}{E_0}$ for different types of rectifiers having various values of p.

When the anode firing is retarded by grid control the angle of overlap may be determined from eq 8. The variation in the angle of overlap with the angle of grid retard for a grid-controlled rectifier is shown by Fig. 4. These curves apply to rectifiers operating with interphase transformers so that $p = 3$.

Power Factor

The effective value of the a-c line current to a rectifier is directly proportional to the d-c output current (neglecting the effect of overlap) and is determined by the transformer connections. When the anode firing is retarded the line current is caused to lag in phase, but its value remains substantially the same. As the a-c line voltage is usually practically constant, the primary kilovoltampere input to a rectifier does not change appreciably as the d-c voltage is varied by grid control, the d-c current being held constant. This means that the rectifier output voltage is varied at the expense of a-c line power factor and that the power factor is approximately equal to the ratio of the d-c voltage with grid control to the voltage which would be obtained without grid control.

It has been shown[6] that the power factor of a rectifier without grid control may be expressed by the general equation

$$\text{Power factor} = K \frac{\cos^2 \frac{u}{2}}{\sqrt{1 - Cf(u)}} \tag{11}$$

where constants K and C are characteristic of the type of connection used and $f(u)$ is a function of the angle of overlap. A similar equation has been derived for the power factor of a grid controlled rectifier (see appendix A of this paper). This equation has the form

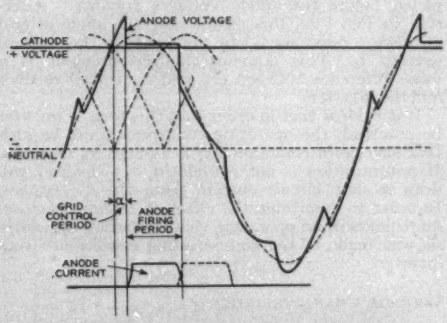


Fig. 6. Anode to cathode voltage wave form of a 6-phase grid-controlled rectifier without interphase transformer

$$\text{Power factor} = K \frac{\frac{1}{2}[\cos \alpha + \cos (u + \alpha)]}{\sqrt{1 - Cf_1 (u, \alpha)}} \tag{12}$$

where constants K and C have the same values as in eq 11 and $f_1 (u, \alpha)$ is a function of both the angle of overlap and the angle of retard. The term $\frac{1}{2}[\cos \alpha + \cos (u + \alpha)]$ is the ratio of the d-c voltage under load with grid control E_d (neglecting arc drop and resistance drop) to the d-c voltage at no load without grid control, E_{do}. Expressing the power factor in terms of the ratio of these 2 voltages we obtain

$$\text{Power factor} = K \frac{\frac{E_d}{E_{do}}}{\sqrt{1 - C f_1 (u, \alpha)}} \tag{13}$$

For a 6-phase rectifier of the usual type this equation becomes

$$\text{Power factor} = 0.955 \frac{\frac{E_d}{E_{do}}}{\sqrt{1 - 3 f_1 (u, \alpha)}} \tag{14}$$

While for a 12-phase rectifier it is

$$\text{Power factor} = 0.988 \frac{\frac{E_d}{E_{do}}}{\sqrt{1 - 1.61 f_1 (u, \alpha)}} \tag{15}$$

The values of $f_1 (u, \alpha)$, $\sqrt{1-3 f_1 (u, \alpha)}$ and $\sqrt{1-1.61 f_1 (u, \alpha)}$ may be obtained by referring to Fig. 13 in appendix A of this paper.

The power factors for both 6-phase and 12-phase rectifiers having the regulation characteristics shown on Fig. 2 are given by the curves on Fig. 5. The same values of α have been chosen for both sets of curves so that the power factor corresponding to any voltage regulation curve may be determined directly. The effect of transformer magnetizing current has been neglected in these curves. Also it has been assumed that the arc drop and transformer winding resistance drop constitute a part of the d-c load.

Efficiency

The losses in a rectifier tank equipped with control grids will not be changed appreciably by the use of grid control, the load current remaining the same. There will be a fractional increase in the main transformer losses due to the reduction in the angle of overlap.[7] However, this will usually be so small that it may be neglected. The most important increase in losses will occur in the interphase transformer due to the increase in interphase voltage.

As the interphase transformer constitutes only a minor part of the total losses, it is seen that at a given load current the losses remain practically constant with grid control and that the reduction in the efficiency is only that resulting from the smaller output due to reduction in d-c voltage.

Wave Form

It is apparent from Fig. 1(*b*) that as the angle of grid retardment is increased, the magnitude of the ripple in the d-c output voltage wave is also increased.

The coefficients of the sine and cosine terms of the harmonics in the output waves are respectively as follows:

$$a_m = \frac{E_{dn}}{2} \cos m\pi \left[\frac{\sin(mp'+1)(u+\alpha) + \sin(mp'+1)\alpha}{mp'+1} - \frac{\sin(mp'-1)(u+\alpha) + \sin(mp'-1)\alpha}{mp'-1} \right] \quad (16)$$

$$b_m = \frac{E_{dn}}{2} \cos m\pi \left[\frac{\cos(mp'+1)(u+\alpha) + \cos(mp'+1)\alpha}{mp'+1} - \frac{\cos(mp'-1)(u+\alpha) + \cos(mp'-1)\alpha}{mp'-1} \right] \quad (17)$$

The effective values of the various harmonics are then

$$h_m = \frac{1}{\sqrt{2}} \sqrt{a_m^2 + b_m^2}$$

where m has values 1, 2, 3, 4, etc., p' is defined as the number of secondary phases, a_m = coefficient of sine term of the harmonic of the order mp and b_m = coefficient of cosine term of the harmonic of the order mp.

The wave form of the primary line current is also affected by the retardment of anode firing. However, in this case the effect is only that due to the shortening of the angle of overlap. As the amount the grid is retarded is increased and the angle of overlap becomes shorter, the primary current wave form approaches that for the case of no load where there is zero overlap.

Duty on Rectifier

When the output voltage of a 6-phase rectifier is controlled by means of grids, the voltage on the anodes has the wave form shown on Fig. 6.

It will be noted that the anode voltage wave differs from that of a rectifier without grid control in 2 important respects. First, during the control period, indicated by the angle α, the anode voltage is positive by an amount greater than the arc drop voltage although the anode carries no current. The second effect of grid control is to increase the rate of rise of inverse voltage on the anode. This is indicated by the part of the curve immediately following the firing period. Both of these effects increase the duty on anodes and grids over that imposed when operating as a rectifier without grid control.

Part II—The Inverter

A grid controlled mercury arc rectifier may be operated as an inverter by reversing the d-c connections and providing suitable excitation voltage to the grids.[8] The connection diagram for a 6-phase inverter is shown on Fig. 7(*a*). The operation of an inverter having a highly inductive d-c circuit may be understood by reference to Fig. 7(*b*) which shows the voltage and current wave shapes.

The conversion of power from a d-c system to an a-c system requires that the rectifier anodes carry current when the transformer secondary voltages are negative, that is, that the anode currents flow in opposition to the voltages from the a-c system. In the inverter this is accomplished by controlling the anode firing by means of the grids.

Referring to Fig. 7, anode 1 carries current during

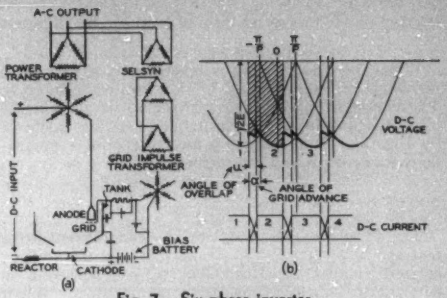


Fig. 7. Six-phase inverter

(a) Connection diagram
(b) Current and voltage waves

the time that its transformer voltage is negative. The other anodes are prevented from firing by exciting their grids with a negative voltage. The transfer of current from anode 1 to anode 2 is initiated by exciting the grid of anode 2 positively. Commutation must be started while the counter electromotive force in the transformer winding connected to anode 2 is less than that in the winding connected to anode 1. The counter electromotive force *voltage difference* in the circuit made by these 2 anodes forces the transfer of current from anode 1 to anode 2 and overcomes the commutating impedance of the transformer windings. The total current in the d-c system is maintained substantially constant during commutation by means of a reactor in the d-c line. In order that the current be commutated successfully, it is necessary that the firing of anode 2 be initiated early enough so that commutation is completed before the anode voltages equalize. Referring to Fig. 7(*b*), this means that the angle of grid advance α must always be greater than the angle of overlap u. This commutation requirement is a basic difference between the grid controlled rectifier and the inverter.

It is evident that in order that this type of inverter be practical, the operating conditions must be such that successful commutation is assured at all times. If commutation is not completed, the inverter will draw a short-circuit current from the d-c system. In order to determine the effect of commutation requirements upon operating characteristics, an analysis was made of the commutating conditions in an inverter.

Voltage Characteristics

The relation between the a-c and d-c voltages for an inverter may be expressed by an equation similar to that which was derived for the voltage relations of a grid controlled rectifier. In the case of the inverter, the voltage drops, due to (1) overlapping, (2) rectifier arc drop, and (3) transformer winding resistance drop, add to the d-c voltage which would appear at no load instead of subtracting as in the case of the rectifier, since the direction of current flow is

reversed with respect to the d-c voltage when inverting. The voltage equation for the inverter is

$$E_d = \left[\sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p}\right] \cos \alpha + \frac{IXp}{2\pi} + E_{arc} + \frac{W_1}{I} \tag{18}$$

Where α is the angle of grid advance [Fig. 7(b)], and the other terms have the same values as for eq 3.

The first and second terms in eq 18 may be derived in the same manner as the corresponding term in eq 3 for the rectifier. The relation between these equations will be seen by a comparison of Figs. 1(b) and 7(b). Referring to these figures, if the angle of overlap u is zero, the d-c voltage will be the same in both cases and will have the value $\sqrt{2}\ \frac{P}{\pi}\ \sin \frac{\pi}{p} \cos \alpha$, where α is the angle of retard for the rectifier and the angle of advance for the inverter. Overlapping causes the anode firing to be delayed in phase, which tends to lower the d-c voltage of the rectifier and raise the d-c voltage of the inverter. The rectifier d-c voltage drop due to overlapping is given by eq 10. It will be noted that this voltage drop depends only upon the current to be commutated and the commutating reactance and remains the same regardless of the time at which commutation occurs and the length of the overlap period. Therefore, it will have the same value for the inverter as it does in the case of the rectifier.

The voltage regulation characteristics for this inverter are shown on Fig. 8. These curves apply to both 6-phase and 12-phase inverters with interphase transformers (p = 3). The voltage drops due to arc drop and resistance drop have been neglected and only the voltage drop due to overlap has been considered. Also, the d-c circuit is assumed to be highly inductive so that the instantaneous input current is essentially constant.

These regulation curves are based on the assumption that the a-c voltage is held constant. The d-c voltage is expressed in per cent of the maximum d-c voltage at which the inverter might operate assuming no overlap and no grid advance. This voltage is equal to the no load voltage of a rectifier without grid control and is $E_{do} = \sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p}$.

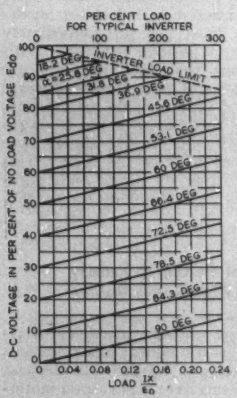


Fig. 8. Voltage regulation characteristics of 6-phase and 12-phase inverters with p=3 and highly inductive d-c circuit

α = angle of grid advance

The manner in which the inverter load is determined may be understood from the regulation curves. Assume, for example, that the inverter is connected to the a-c system with the grid excitation advanced 36.9 deg (Fig. 8). If a low voltage is applied on the d-c side and gradually increased, the inverter will not pick up load until the d-c voltage attains a value of 80 per cent. That is, the inverter will not pick up load until the impressed d-c voltage becomes greater than the d-c counter electromotive force generated in the inverter by the a-c voltages. If it is desired to invert with a low d-c voltage, less than 80 per cent for example, the grid excitation must be advanced until the counter electromotive force becomes less than the impressed voltage. As the impressed d-c voltage is increased after the inverter has picked up load, the load carried will be determined by the regulation curve for the particular grid setting which is used. The load may be increased, by raising the d-c voltage, until the inverter fails to commutate, as will be explained later under "Commutation and Load Limits."

Calculation of Angle of Overlap

The commutation processes of this type of inverter may be analyzed in the same manner as those of the grid-controlled rectifier. The voltage equation for the commutating circuit of the inverter is

$$L \frac{di_2}{dt} = -\sqrt{2}\, E \sin \frac{\pi}{p} \sin (\omega t - \alpha) \tag{19}$$

Solving this equation, the angle of overlap when inverting is given by the relation

$$\cos (u - \alpha) = \cos \alpha + \frac{IX}{\sqrt{2}\, E \sin \frac{\pi}{p}} \tag{20}$$

In Figure 9 is shown the variation in the angle of overlap with the angle of grid advance for an inverter.

Commutation and Load Limits

It has been pointed out that the angle of advance of the grid excitation for this type inverter must always be greater than the angle of overlap in order that commutation be completed successfully. This requirement limits the load which may be carried and also affects the voltage relations between the a-c and d-c systems.

The load limit of the inverter, as fixed by commutation requirements, may best be expressed in terms of the voltage relations. Let it be assumed that an inverter is operating with a fixed angle of grid advance. As the load current is increased the angle of overlap increases until finally at the limiting load for this grid setting, assuming no time is required for deionization, the angle of overlap is just equal to the angle of advance. When the inverter is operating under these limiting conditions the angle

of overlap will be the same as that when rectifying an equal load with the grids not retarded, and the voltage wave forms will be similar, and the d-c voltages will be equal (neglecting arc drop and resistance drop). The load limiting curve for the

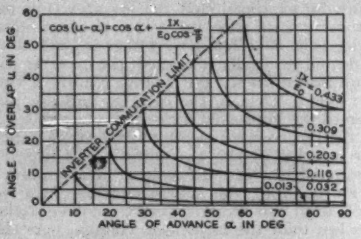


Fig. 9. Variation in angle of overlap with the angle of grid advance for an inverter (p = 3)

inverter is therefore the same as the voltage regulation curve for the rectifier with the grids not retarded. The inverter load limit is shown by the dotted curve on Fig. 8.

These considerations show that in order to invert, the a-c d-c voltage relations, the load, and the angle of advance must all be properly adjusted to each other. It is seen that in order to increase the load limit the grid angle must be advanced to compensate for the increasing angle of overlap and obtain sufficient time for commutation and deionization. However, it should be noted particularly that the inverter will not operate when the d-c voltage is greater than that which would be obtained when operating as a simple rectifier at the same load current without grid control.

These requirements have been verified by test on an experimental 6-phase inverter of the type described. In order to make the inverter operate it was found necessary to reduce the d-c voltage to a value less than that obtained when operating as a rectifier without grid control, the a-c voltage remaining constant.

The voltage required for commutation of this type inverter is supplied by the a-c system. In order to operate, the inverter must be connected to an a-c system capable of supplying this voltage and carrying the commutating current. It will not operate when connected to a pure resistance a-c load.

Wave Forms

The current and voltage wave forms of the inverter are very nearly the same as those of the grid controlled rectifier when both are operated at the same d-c voltage and current.

Power Factor

Since commutation of the anode currents must be completed before the anode voltages become equal (see Fig. 7(*b*)), the anode current waves will always be earlier in phase than the voltage waves. Corresponding currents will flow on the other side of the transformer and therefore the currents in the a-c line will always lead the a-c line voltages and the inverter will deliver power only at a leading power factor.

From a study of the commutation requirements it has been shown that an inverter of this type which is commutated from the a-c system must always operate at leading power factor. The power factor of the inverter may be expressed by equations similar to those for the rectifier. (Refer to appendix B of this paper.) These equations have the form:

$$\text{Power factor} = K\,\frac{{}^1/_2[\cos\alpha + \cos(u-\alpha)]}{\sqrt{1 - C\,f_2(u,\alpha)}} \tag{21}$$

For a 6-phase inverter this equation becomes:

$$\text{Power factor} = 0.955\,\frac{\frac{E_d}{E_{do}}}{\sqrt{1 - 3\,f_2(u,\alpha)}} \tag{22}$$

While for a 12-phase inverter it is

$$\text{Power factor} = 0.988\,\frac{\frac{E_d}{E_{do}}}{\sqrt{1 - 1.61\,f_2(u,\alpha)}} \tag{23}$$

The power factors for both a 6-phase and a 12-phase inverter are given on Fig. 10. These power factors are given for the same values of grid advance as chosen for the regulation curves shown on Fig. 8.

Duty on Rectifier

The anode voltage when inverting will have a wave form similar to that shown by Fig. 11. This curve shows that the anode voltage is always positive except during the small interval allowed for deionization. The grid must acquire control of the anode during this small interval.

It is evident by comparison of the anode voltages that the duty on the grids is much greater in the case of the inverter; first, only a short period is available for deionization and the grid must acquire control of the anode during this interval; second, the grids must function to prevent anode firing during practically the entire inactive period of the anode; and third, the anode must pick up immediately when its grid acquires a positive potential. This last requirement means that the excitation arc must be properly located and must furnish adequate ionization to insure good pick-up of the main anodes at all loads. Since the anode firing period is always only a fractional part of a cycle the grid voltage wave must be negative during most of the cycle. This may be accomplished either by means of a negative bias or by using an impulse voltage for exciting the grids.

Part III—Application of the Unit to Railway Electrifications With Regenerative Braking

The use of mercury arc rectifiers capable of inverting has been proposed for d-c railway electrifications where regenerative braking is required. In the past such electrification systems have mostly used motor-

generator equipment. The motor-generator set will receive power from the d-c system and transfer it to the a-c system when the d-c voltage rises. No other changes are necessary. However, in the case of the rectifier, it is necessary to reverse the d-c leads in order to change from generation to regeneration. This means that the d-c circuit must be opened and closed in order to change over. At the same time the grid excitation and the main d-c a-c voltage relations must be adjusted properly in order to insure commutation when inverting.

Because of the many differences between the operating characteristics of motor-generator equipment and those of regenerative rectifier equipment a careful study has been made of the requirements which must be met in railway applications.

Railway Service Requirements

In practical railroad operation where regenerative braking is employed, the substation must be able to deliver or to receive power as determined by the performance of trains on the road. Regeneration by a train is always initiated by the locomotive engineer, who decides when it should be done and makes the necessary changes to accomplish it. The substation equipment or the substation operator has no knowledge of the engineer's decision until the locomotive is already regenerating. The demand for the substation to receive regenerated power appears first in the form of an increase in the d-c bus voltage at the substation.

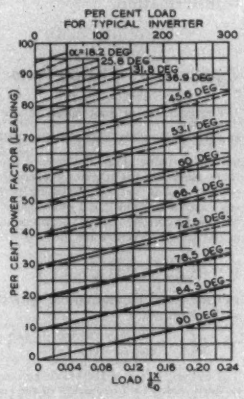


Fig. 10. Power factor characteristics of 6-phase and 12-phase inverters with p = 3 and highly inductive d-c current

Solid lines — power factor of 12-phase inverter
Dash lines — power factor of 6-phase inverter
α = angle of grid advance

Limitations of Rectifier-Inverter Equipment

Because of the changes which must be made in order to change a rectifier tank from rectifier to inverter operation, and *vice versa*, it is seen that a single tank rectifier inverter-unit cannot be expected to float from generation to regeneration easily and inherently like a synchronous motor generator set. It is also evident that some time element is involved in changing the rectifier from one type of operation to the other and that during this time it will be disconnected from the substation bus.

A single rectifier operating with one connection will neither invert itself inherently nor give a reliable indication of the necessity for reversal. For example, assume that the rectifier has been generating and that the railway load changes so that regenerating operation is required. Then the rectifier will simply go to no load and remain at no load until the railway load again requires power for motoring operation. The rectifier will not allow any reverse current to flow and so no indication of the necessity for reversal can be obtained by means of a reverse current relay or other indicating devices of that type. Should a single rectifier tank be operating as an inverter, upon the cessation of regeneration and the recurrence of motoring demand, the conditions will be the same as those just cited.

Proposed Arrangements of Rectifier-Inverter Equipment for Regeneration

In order to meet the requirements for operation in railway service and to overcome the above limitations of the rectifier equipment, a number of different arrangements have been proposed. Some of these schemes will be described in the following paragraphs, together with a description of their operating characteristics. However, no attempt will be made to determine the relative merits of the different schemes.

One scheme which has been proposed uses a single rectifier tank for rectifying and inverting, the d-c connections being reversed when changing from one type of operation to the other. In order to obtain an indication of the necessity for reversal of connections when a single rectifier tank is used, the use of either a relay equipment consisting of a low ca-

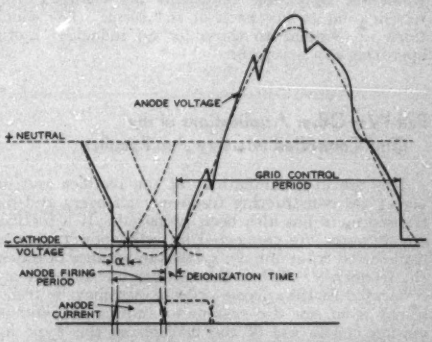


Fig. 11. Anode to cathode voltage wave form of a 6-phase inverter without interphase transformer

pacity rectifier and inverter permanently connected, or of a small synchronous motor generator set floating on the d-c bus has been suggested. By using the latter of these 2 devices, the small motor generator set, a means may also be provided for commutating the inverter in case of failure of the a-c system voltage.

The d-c voltage characteristics of a single tank unit taking into account the effect of rectifier arc drop are shown by Fig. 12. From these curves it will be noted that if the grid excitation angle is held constant both when rectifying and when inverting and the proper angle is chosen for each condition, shunt voltage characteristics such as those of curves aa' and bb' will be obtained. In order that the inverter carry the required loads, the angle of grid advance must be large enough to provide time for commutation and deionization at the maximum inverting load, with a safe margin to assure reliability.

The necessity for reversing d-c connections may be eliminated by using a double tank unit, one tank being connected always as a rectifier and the other as inverter. Such a double unit will have shunt voltage characteristics similar to those of the d-c machine of a motor generator set and will permit a smooth and automatic reversal of power flow.

The fact that the inverter will deliver a-c power only at a leading power factor is not expected to prove a serious disadvantage to its use for railway electrification. As the power factor of the inverter is substantially the same as that of the rectifier when the grid excitation angles are equal, except that it is leading instead of lagging, the reactive kilovoltampere load which must be carried by the a-c system remains approximately the same for a given load whether rectifying or inverting. Stated in other words, only the flow of real power reverses direction when the operating conditions are changed from rectification to inversion or *vice versa*. The conditions are similar to those for an induction motor operating as a generator.

Part IV—Other Applications of the Grid Controlled Mercury Arc Rectifier

The use of combinations of the rectifier and inverter for constructing frequency changers and d-c transformers has also been proposed. If a rectifier and inverter are connected in series, power may be transferred from one a-c system to another of different frequency. When the rectifier and inverter are connected in the reverse order power may be transferred from one d-c system to another of different voltage. The use of the inverter of this type for these applications is seriously restricted by its power factor characteristics. Before the inverter can come into general use for these applications, some means must be devised which will permit operation at lagging power factors.

Frequency changer circuits in which only one rectifier tank is used, the same anodes performing the double function of rectification and inversion have also been proposed. However, up to the present time these circuits have not proved generally practical for use with a 60-25 cycle ratio of frequency transformation.

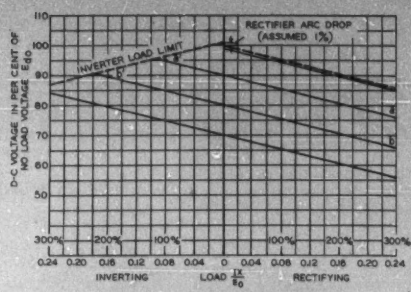


Fig. 12. Voltage regulation characteristics of a rectifier-inverter unit for regeneration

The percentage power factor is approximately the same as the percentage d-c voltage for a 12-phase unit (see Figs. 2 and 5) The upper load scale indicates the percentage load for a typical unit

Appendix A—Power Factor of the Rectifier

The effective or root mean square value of the rectifier anode current wave when there is no overlapping is $\frac{I}{\sqrt{p}}$ where I is the maximum value of the flat topped anode wave. When overlapping takes place and the rectifier is operating with grid control, the anode current during the commutating periods may be calculated from eqs 7 and 8 given in Part I of the paper. Combining these equations the anode current during the commutating period at the beginning of the anode current wave is

$$i_2 = I\left(\frac{\cos\alpha - \cos(\omega t + \alpha)}{\cos\alpha - \cos(u + \alpha)}\right) \tag{24}$$

and the anode current during the commutating period at the end of the wave is

$$i_1 = I\left(1 - \frac{\cos\alpha - \cos(\omega t + \alpha)}{\cos\alpha - \cos(u + \alpha)}\right) \tag{25}$$

The heating effect of the anode current wave with overlapping may be determined by integration of the equation

$$I^2_{eff} = \frac{1}{2\pi}\int_0^u i_2^2\,d\omega t + \frac{I^2}{2\pi}\left(\frac{2\pi}{p} - u\right) + \frac{1}{2\pi}\int_0^u i_1^2\,d\omega t$$

substituting the values of i_1 and i_2 the equation becomes [9]

$$I_{eff} = \frac{I}{\sqrt{p}}\sqrt{1 - p\,\frac{1}{\pi}\int_0^u\left[\left(\frac{\cos\alpha - \cos(\omega t + \alpha)}{\cos\alpha - \cos(u + \alpha)}\right) - \left(\frac{\cos\alpha - \cos(\omega t + \alpha)}{\cos\alpha - \cos(u + \alpha)}\right)^2\right]d\omega t} \tag{26}$$

$$I_{eff} = \frac{I}{\sqrt{p}}\sqrt{1 - p\,f_1(u, \alpha)} \tag{27}$$

where $f_1(u, \alpha)$ represents the value of the integral in eq 26. Solving the integral we obtain

$$f_1(u, \alpha) = \frac{1}{2\pi}\left[\frac{\sin u\,(2 + \cos(u + 2\alpha)) - u\,(1 + 2\cos\alpha\cos(u + \alpha))}{(\cos\alpha - \cos(u + \alpha))^2}\right] \tag{28}$$

When $\alpha = 0$ this function reduces to the value obtained by other authors[10] for the rectifier without grid control.

The factor $\sqrt{1 - p\,f_1(u, \alpha)}$ represents the change in the effective

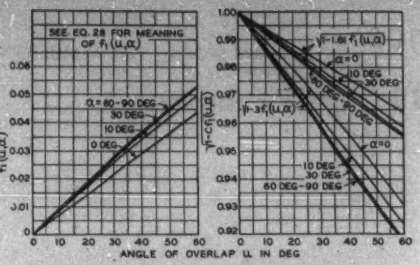


Fig. 13. Curves for grid controlled rectifiers giving the values of $f_1(u, \alpha)$ and $\sqrt{1-Cf_1(u, \alpha)}$ as functions of u for various angles of grid retard

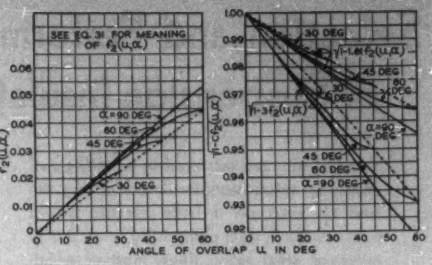


Fig. 14. Curves for inverters giving the values of $f_2(u,\alpha)$ and $\sqrt{1-Cf_2(u, \alpha)}$ as functions of u for various angles of grid advance

value of anode current due to overlapping. A factor of similar form applies to the primary current of the rectifier with overlapping.

The power factor of a rectifier is defined by the ratio, power factor $= \dfrac{\text{power output}}{\text{kilovoltampere input}}$, if the rectifier arc drop and transformer winding resistance drops are assumed to be part of the d-c load. The power factor may be expressed in terms of the various voltage and currents

$$\text{Power factor} = \frac{E_{dc} I_{dc}}{3 E_L I_L}$$

where

E_{dc} = d-c voltage $\qquad E_L$ = primary line to neutral voltage

I_{dc} = d-c current $\qquad I_L$ = primary line current

The d-c voltage may be expressed in terms of the primary line to neutral voltage by eq 4 and the primary line current may be expressed in terms of the d-c current.

$$E_{dc} = \sqrt{2}\, E_L \frac{P}{\pi} \sin \frac{\pi}{P} \left[\frac{\cos \alpha}{2} + \frac{\cos (u + \alpha)}{2}\right]$$

where $E_L = E$

$$I_L = \frac{I_{dc}}{\sqrt{6}} \sqrt{1 - 3 f_1 (u, \alpha)} \text{ for a 6-phase rectifier}$$

$$I_L = I_{dc} \frac{(\sqrt{3} + 1)}{4\sqrt{3}} \sqrt{1 - 1.61 f_1 (u, \alpha)} \text{ for a 12-phase rectifier}$$

Substituting these values we obtain

$$\text{Power factor} = \frac{3}{\pi} \frac{\left[\dfrac{\cos \alpha}{2} + \dfrac{\cos (u + \alpha)}{2}\right]}{\sqrt{1 - 3 f_1 (u, \alpha)}} \text{ for a 6-phase rectifier}$$

and

$$\text{Power factor} = \frac{6\sqrt{2}}{\pi(\sqrt{3} + 1)} \frac{\left[\dfrac{\cos \alpha}{2} + \cos \dfrac{(u + \alpha)}{2}\right]}{\sqrt{1 - 1.61 f_1 (u, \alpha)}} \text{ for a 12-phase rectifier}$$

For convenience in calculating rectifier power factors the values of $f_1 (u, \alpha)$, $\sqrt{1 - 3 f_1 (u, \alpha)}$, and $\sqrt{1 - 1.61 f_1 (u, \alpha)}$ have been calculated for various values of u and α, and are plotted on Fig. 13.

Appendix B—Power Factor of the Inverter

The effect of overlapping upon the root mean square values of the anode and primary currents of the inverter may be calculated in the same manner as used in appendix A for the rectifier.

The value of the anode current during the commutating period at the beginning of the anode current wave may be shown to be

$$i_2 = I \left(\frac{\cos (\omega t - \alpha) - \cos \alpha}{\cos (u - \alpha) - \cos \alpha}\right) \tag{29}$$

and during the commutating period at the end of the anode current wave

$$i_1 = I \left(1 - \frac{\cos (\omega t - \alpha) - \cos \alpha}{\cos (u - \alpha) - \cos \alpha}\right) \tag{30}$$

Solving an equation which is similar to that for the rectifier, the effective anode current is found to be

$$I_{eff} = \frac{I}{\sqrt{p}} \sqrt{1 - p\, f_2 (u, \alpha)}$$

where function f_2 is given by

$$f_2 (u, \alpha) = \frac{1}{2\pi}\left[\frac{\sin u (2 + \cos (u - 2\alpha)) - u (1 + 2 \cos \alpha \cos (u - \alpha))}{(\cos (u - \alpha) - \cos \alpha)^2}\right] \tag{31}$$

The equations for the inverter power factor may be derived in the same way as those for the rectifier. The power factor of a 6-phase inverter is

$$\text{Power factor} = \frac{3}{\pi} \frac{\left[\dfrac{\cos \alpha}{2} + \dfrac{\cos (u - \alpha)}{2}\right]}{\sqrt{1 - 3 f_2 (u, \alpha)}}$$

and for a 12-phase inverter

$$\text{Power factor} = \frac{6\sqrt{2}}{\pi(\sqrt{3} + 1)} \frac{\left[\dfrac{\cos \alpha}{2} + \dfrac{\cos (u - \alpha)}{2}\right]}{\sqrt{1 - 1.61 f_2 (u, \alpha)}}$$

The values of $f_2 (u, \alpha)$, $\sqrt{1 - 3 f_2 (u, \alpha)}$, and $\sqrt{1 - 1.61 f_2 (u, \alpha)}$ for various values of u and α are plotted on Fig. 14.

References

1. Principles of Mercury Arc Rectifiers and Their Circuits (a book), D. C. Prince and F. B. Vogdes. p. 112.
2. Mercury Arc Power Rectifiers (a book), O. K. Marti and H. Winograd. p. 60.
3. Mercury Arc Power Rectifiers (a book), O. K. Marti and H. Winograd. p. 57.
4. The Grid Controlled Rectifier, Muller-Lubeck and Uhlman, *Archiv. f. Electrotech.*, v. 27, 1933, p. 364.
5. Current and Voltage Wave Shapes of Mercury Arc Rectifiers, H. D. Brown and J. J. Smith. A.I.E.E. Trans., v. 52, 1933, p. 973–84.
6. Mercury Arc Power Rectifiers (a book), O. K. Marti and H. Winograd. p. 171.
7. Losses in Transformer for Use With Mercury Arc Rectifiers, E. V. DeBlieux. A.I.E.E. Trans., v. 50, 1931, p. 999–1,005.
8. Grid Controlled Mercury Arc Rectifiers, H. D. Brown. Congress International D'Electricite, Paris, v. 5, 1932, p. 783.
9. The Grid Controlled Rectifier, Muller-Lubeck and Uhlman. *Archiv. f. Electrotech.*, v. 27, 1933, p. 368.
10. Mercury Arc Power Rectifiers (a book), O. K. Marti and H. Winograd. p. 57–8.

Selection and Performance of Suspension Insulators

By PHILIP SPORN
FELLOW A.I.E.E.

V. A. MULFORD
ASSOCIATE A.I.E.E.

E. L. PETERSON
MEMBER A.I.E.E.

American Gas and Elec. Co.,
New York, N. Y.

Some of the methods used in selecting and checking suspension insulators during the past 15 years on a large electric power transmission system comprising some 3,000 miles of steel tower lines, most of which operate at 132,000 volts, are outlined in this paper. The results obtained through various tests, the use of these results as a guide for insulator selection, and actual performance and expected life of insulators are discussed. A large amount of laboratory and field test data is included, on the basis of which a life expectancy of 50 years for suspension insulators is believed possible.

THE importance of the suspension insulator as a link in the chain of transmission of electric power sometimes has been minimized, if not overlooked, particularly during the past decade or so. Certainly as far as the engineering literature on the subject is concerned, it frequently would appear that the last and final word on the subject had been said; yet it is a fact that frequently a section of transmission involving millions of dollars of expenditure can be put out of commission for anywhere from a minute to possibly several days by the failure of a single disk insulator among the many tens of thousands.

Considering the complex structure of the suspension insulator, it is surprising that a study of the many elements entering into its composition and the assembly of those elements into a single structure has not been pursued with the same thoroughness as has been applied to many structures of a much simpler nature. Admittedly there has been vast improvement in the design and manufacturing processes of insulators in recent years, but it does not follow that a uniformity of the product has been reached that will assure satisfactory operating reliability. Nearly all manufacturers of suspension insulators periodically change details of the design and methods of assembly of their units. This does not always involve a change in catalog numbers, nor is the purchaser always advised that changes have been made. It may be assumed generally that these changes result in an improvement of the product, but occasionally some slight modification will adversely affect the performance of the insulator. This may be apparent from an exhaustive laboratory test, but not always, and it may take several years of field experience to show up the defect. This means that the selection of insulators to give the best results from a complete engineering standpoint, involving cost, performance, and deterioration, is a difficult problem if one attempts to do it with any degree of precision. It is necessary to know not only that the design of the insulator is correct, but also that a uniformity of the product is obtained. For example, insulators manufactured according to the same design, but during different years, may vary in their performance due to some slight change in materials used or in the care taken in the manufacturing processes.

The authors having been connected for the past 15 years with the construction of some 3,000 miles of steel tower transmission lines, most of which operate at 132 kv, in which the selection and installation of some million insulators was involved, and having had the opportunity later to follow the performance of these lines, believe that some of the methods they have used in the selection and checking of insulators may be of interest. In this paper they will outline some of these methods, indicate the results obtained through the various tests, the use made of these results as a guide for insulator selection, and finally discuss the actual performance of the insulators and point out what light on general deterioration and expected life of insulators is thrown by such performance.

On the basis of the data presented the authors have reached the following conclusions:

1. The present A.I.E.E. standard tests for suspension insulators, which are mainly factory acceptance tests, are not in themselves sufficient to furnish a basis for detecting all insulators of inferior design and manufacture, or for comparing competitive makes of insulators.

2. Based on results obtained by tests conducted by the American Gas and Electric Company, laboratory tests can be devised that will furnish a basis for proper selection of insulators and permit the weeding out of insulators of inferior design and manufacture.

3. Field testing of insulators is essential, and when carried on over a sufficiently long period, can serve as a reliable index of the condition, rate of deterioration, and life expectancy of insulators.

4. If proper selection tests are made in advance, the results of such field testing and the life performance and deterioration of insulators can be predicted with a fair degree of accuracy.

5. Modern suspension insulators of proper design and manufacture, properly selected and correctly applied can be expected to give satisfactory performance over a long period of time, possibly to the extent of 50 years.

Normal Routine Factory Tests

Practically all high voltage insulators are put through various factory routine tests in order to

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 13, 1934; released for publication April 25, 1934. *Not published in pamphlet form.*

eliminate any units that would be unsatisfactory for service. Tests included in this routine inspection vary among the manufacturers, but usually include a 60-cycle flashover of the unassembled bodies, and both 60-cycle and high frequency flashover of the assembled units, although sometimes the latter test is omitted. Porosity tests generally are made on samples selected from each firing batch of porcelain, and many companies run temperature change tests on samples of the assembled units from time to time. Some manufacturers include a mechanical test on their suspension insulators at a certain percentage of their rated strength as a regular routine test on all units. Routine factory tests usually follow the standards adopted by the A.I.E.E. and American Standards Association, which were developed for use as standard factory acceptance tests.

Although these factory routine tests are of great assistance to the manufacturers in keeping their products uniform, and the acceptance tests important to the purchaser, it is questionable whether, taken alone, they give complete indication of the life that may be expected of the insulators. It is believed, however, that supplementary tests can be performed that will give an indication of the life performance and relative merits of the various insulators under consideration. In confirmation of this, it has been the authors' experience that insulators that have performed best in the laboratory tests also have performed best in service.

Selection Test Followed by American Gas and Electric Company

Although the American Gas and Electric Company and its subsidiaries had conducted laboratory tests on insulators previously, they devised in 1922 a series of tests which were made on various makes of suspension insulators; these tests, with some changes and additions, have been repeated more or less periodically up to the present time. The object of these tests was specifically to determine, from the various makes of commercial insulators available in the United States, the insulator best adapted for transmission line service involving moderate loadings in an area where both high summer and low winter temperatures were encountered, keeping in mind that what it was hoped to obtain was an insulator that not only would show up well in the laboratory, but also would stand up over an extended period of time in service.

These tests were occasioned by the fact that a major construction program was being planned at that time for tying together various properties with 132-kv transmission lines. The mechanical test devised for the insulators consisted merely of subjecting them, while carrying normal line voltage, to the maximum loads for which these lines were being designed. This maximum design load, amounting to 6,000 lb, occurred on single suspension strings when the conductors were loaded with excessive ice. It was assumed that this condition might last for a period not exceeding 3 days. The 72-hr time-load test thus devised was followed by a further electrical test to detect any cracks that might have developed. This electrical test consisted of flashing over each unit individually by applying a damped-wave high-frequency voltage for 30 sec.

Some of the units passing the time load and electrical tests then were subjected to a thermal change test consisting of immersing the units first in boiling water for 10 minutes and then immediately transferring them to ice water for 10 minutes with a short high frequency test as previously described following the ice water immersion. Five complete cycles of this test were made. Porosity tests consisting of immersing broken porcelain samples of insulators in a water solution of eosin dye at a pressure of 260 lb per square inch for 14 hours completed the original test procedure.

In all subsequent tests on suspension insulators, there was included an ultimate electrical and mechanical test on all units passing the time-load, high frequency, and thermal change tests. In this test each insulator, while subjected to an electric potential of 60 kv, was pulled to destruction. Starting with a mechanical load of 6,000 lb, this was increased in 500-lb steps every 30 sec until electrical failure, at which time the electrical potential was

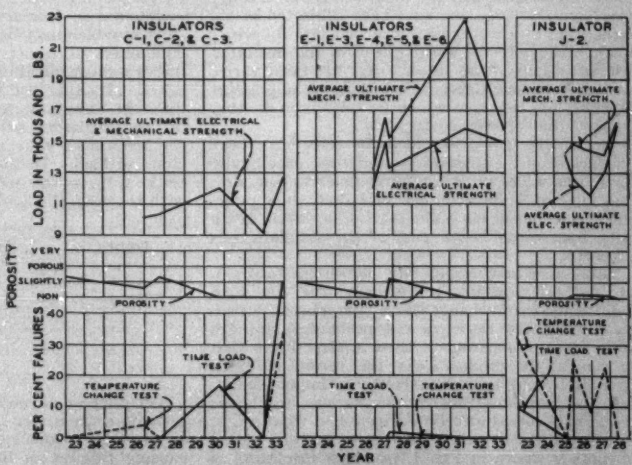


Fig. 1. Results of laboratory tests on 3 different makes of suspension insulators. Note that improvements in one characteristic sometimes have an adverse effect on others

TABLE I. LABORATORY TESTS ON SUSPENSION INSULATORS BY AMERICAN GAS AND ELECTRIC COMPANY

Insulator	72 Hr. Time - Load Tests - % Failures																																				Temperature Change Tests - % Failures											
	Dec. 1922		Aug. 1923		Jan. 1924		Dec. 1924		Aug. 1927		Oct. 1927		June 1928		Oct. 1930		Nov. 1931		Feb. 1932		Dec. 1932		Dec. 1933																							
	Mechanical Failure	Electrical Failure	Mechanical Failure	Electrical Failure	Mechanical Failure	Electrical Failure	Mechanical Failure	Electrical Failure	Mechanical Failure	Electrical Failure	Mechanical Failure	Electrical Failure	Mechanical Failure	Electrical Failure	Mechanical Failure	Electrical Failure	Mechanical Failure	Electrical Failure	Mechanical Failure	Electrical Failure	Mechanical Failure	Electrical Failure	Mechanical Failure	Electrical Failure	Dec. 1922	Aug. 1925	Jan. 1926	Dec. 1926	Aug. 1927	Oct. 1927	June 1928	Oct. 1929	Nov. 1931	Feb. 1932	Dec. 1932	Dec. 1933
A-1									100		0	17																0	65							
B-1							0	8	0	8																		7	7							
C-1	0	0					0	0			0	0													0			4		0						
C-4															0	17																0				
C-3																					0	0	0	20											0	33
C-2																							0	81												67
C-5							0	0																				70								
D-1	0	0					0	0																	0			4								
D-2											0	0																	17							
D-3	0	0																							100											
E-1	0	0																							0											
E-2	0	0																							0											
E-3							0	0			0	12																0		0						
E-4							0	0	0	0	0	0																0	0	0						
E-5											0	0																		0						
E-6											0	0					0	0			0	0								0		0				0
E-7																	0	0												0		0				
F-1	10	40																							100											
F-2	0	0					0	0																	100			0								
F-3							14	0																				0								
F-4	0	0					11	0																	0			12								
F-5																			0	0														0		
G-1	100	-							0	33															67				0							
G-4									0	17																			0							
G-3									0	0	0	0																	0	0						
H-1															0	0																17				
H-2																							0	0												17
I-1	0	0					17	0			0	0													0			0		0						
I-2	0	50																							0											
J-1			0+	0+																						0+										
J-2	0	10	0+	0+	0	0	0	0			0	0	0+	0+											33	0+	25	8		28	0+					

+Tests conducted at manufacturer's plant. Electrical failures were on high frequency following time-load test.

removed and the test continued to mechanical failure. In addition, the thermal change test was revised to include a test on all units passing the time-load test and to consist of 10 cycles from boiling to freezing with high frequency flashovers following the fifth and tenth cycles only. In the more recent tests, half the units being put through the thermal change test have been subjected at the same time to a mechanical load of 3,000 lb, which is approximately the working load of the insulator. The procedure in the porosity test has been varied radically, the most recent test being at a pressure of 10,000 lb per square inch for 6 hours in an alcoholic solution of fuchsine dye.

During the period in which the tests have been conducted on the suspension insulators, checks also have been made at certain intervals as to wet, dry, and impulse flashover of the units and their puncture values under oil. These tests, however, never have been considered a part of the standard test procedure.

Laboratory test results are shown in Tables I, II, and III, covering, respectively, the time-load and temperature change tests, the porosity test, and the ultimate electrical and mechanical strength tests. An examination of these tables shows that in general the product over the period of years covered by the tests has shown an improvement, but also indicates that of the various insulators tested only comparatively few have had what might be called a perfect record. A comparison of 3 makes of units is shown in Fig. 1, in which insulators of one manufacturer, where they are substantially the same or where they are simply revisions of older units, have been grouped together. A further examination of the curves will indicate the difficulties experienced by some manufacturers in raising the ultimate strengths of their insulators without adversely affecting the results of the temperature change and time-load tests.

Attention is called to the temperature change test conducted in January and December 1933, the results of which may be found in Table I. In the test conducted in January 1933, all units were tested under a mechanical load of 3,000 lb, no failure being noted. In the test of December 1933, somewhat different results were obtained. In this test part of the insulators were tested with no load, while the remainder were tested under the 3,000-lb mechanical load. In the tabulation below, the results of the tests on the unloaded insulators are compared with those on the loaded insulators.

Insulator	Loading, Pounds	Per Cent Failures
C-3	0	0
	3,000	100
C-4	0	50
	3,000	100
E-4	0	0
	3,000	0
H-2	0	0
	3,000	50

The purpose of conducting the temperature change tests on units under load was to duplicate as nearly as possible conditions that had arisen in the field causing failures of insulators, duplicates of which previously had passed the usual temperature change tests.

TABLE II. LABORATORY TESTS ON SUSPENSION INSULATORS

POROSITY TEST

Insulator	Dec. 1922 Percentage					Aug. 1925 Percentage					Jan. 1926 Percentage					Aug. 1927 Percentage					Oct. 1927 Percentage					June 1928 Percentage					Oct. 1929 Percentage					Nov. 1931 Percentage					Feb. 1932 Percentage					Dec. 1932 Percentage					Dec. 1933 Percentage				
	Non-porous	Slightly porous	Porous	Very porous	Sum	Non-porous	Slightly porous	Porous	Very porous	Sum	Non-porous	Slightly porous	Porous	Very porous	Sum	Non-porous	Slightly porous	Porous	Very porous	Sum	Non-porous	Slightly porous	Porous	Very porous	Sum	Non-porous	Slightly porous	Porous	Very porous	Sum	Non-porous	Slightly porous	Porous	Very porous	Sum	Non-porous	Slightly porous	Porous	Very porous	Sum	Non-porous	Slightly porous	Porous	Very porous	Sum	Non-porous	Slightly porous	Porous	Very porous	Sum	Non-porous	Slightly porous	Porous	Very porous	Sum
A-1																					33	67																																		
E-1											35	65				50	50																																						
E-2											39	61				50	50					4																																		
C-2			67	33																			67	33																																
C-3																																	100																							
C-4											57	43																																												
C-5											88	12																																												
E-1																																	56	44																						
E-2																																																									
E-3																																																									
E-4																																																									
E-5																																																									
E-6																																																									
C-1																																	12	88																						
C-2																																	12	88																						
C-3																																	12	88																						
C-4																																	12	88																						
C-5																																	12	88																						
E-1																																																									
E-2																																																									
E-3																																																									
E-4																																																									
E-5																																																									
E-6																																																									
C-1																																																									
C-2																																																									
C-3																																																									
C-4																																																									
C-5																																		

them to be performing in an excellent fashion. Of 367,963 suspension insulators tested to date only 2,664 have been found defective, or about 0.724 per cent. The summation of the tests of the different makes of insulators is as follows:

Make of Insulator	Total Tested	Total Failures	Per Cent Failures
C	11,608	60	0.516
J	63,681	2,040	3.205
E	97,848	31	0.032
F	188,618	300	0.159
J	6,208	233	3.755
Total	367,963	2,664	0.724

A résumé of the results of the field tests conducted to date is given in Table IV. It may be seen that the service record of some of the makes of units is exceptionally good while that on other makes show a much higher percentage of failures.

In but 4 instances have groups of insulators been tested for a second time. It might be expected that in such tests, successive tests would show an increasing number of failures per year; but in the repeat tests conducted to date this is not definitely shown, the results being anything but uniform. They are given in the following tabulation:

Insulator	Installed	First Test	Second Test
C-1	1922	After 9 yr 3,990 tested 1 bad.	After 10 yr 3,953 tested 0 bad.
E-3	1925	After 4 yr 16,052 tested 1 bad.	After 7 yr 2,370 tested 0 bad.
			After 8 yr 2,929 tested 3 bad.
F-4	1917	After 5 yr 46,472 tested 27 bad.	After 12 yr 46,472 tested 8 bad.
J-1	1922	After 9 yr 5,182 tested 66 bad.	After 10 yr 5,167 tested 54 bad.

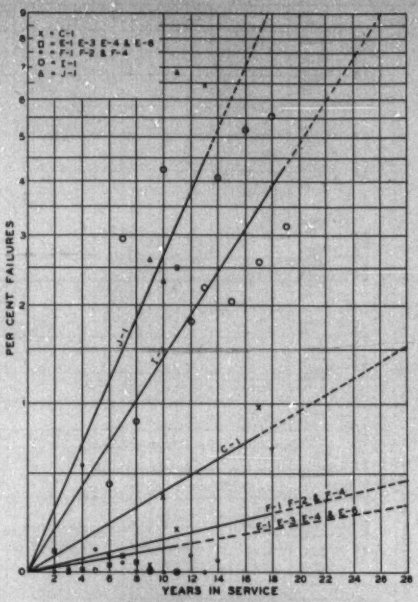


Fig. 2. Deterioration of insulators as revealed by field test data given in Table IV

TABLE III. LABORATORY TESTS ON SUSPENSION INSULATORS BY AMERICAN GAS AND ELECTRIC COMPANY

Ultimate Electrical and Mechanical Test - (Load in Thousands of Pounds)

Insulator	August, 1925						January, 1926						December, 1926						August, 1927						October, 1927						June, 1928					
	Electrical			Mechanical			Electrical			Mechanical			Electrical			Mechanical			Electrical			Mechanical			Electrical			Mechanical			Electrical			Mechanical		
	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.
A-1																			7.1	4.35	1.2	7.8	7.1	6.8	7.5	8.5	7.5	9.5	8.55	8.0						
B-1													12.5	10.8	7.5	20.0	16.5	12.5	14.3	11.5	11.0	21.6	21.6	19.0												
C-1													11.0	10.1	9.0	11.0	10.1	9.0							11.5	10.1	9.0	11.5	10.1	9.0						
C-2													11.5	8.1	6.0	20.0	20.0	19.0																		
E-1													15.0	12.5	8.5	15.0	12.5	8.5																		
E-2																																				
E-3																									18.0	15.2	13.5	18.0	15.2	13.5						
E-4													15.5	11.4	9.0	16.0	12.0	9.5							14.0	13.5	13.0	16.0	14.7	13.5						
E-5													15.5	13.0	10.0	19.0	15.8	13.5	16.0	15.0	11.7	19.6	16.6	14.1	16.5	15.5	14.5	17.0	15.8	13.5						
E-6																									16.0	15.0	11.0	16.5	15.7	15.0						
E-7																									17.0	15.6	8.0	19.5	15.0	13.5						
F-1													16.5	13.5	6.5	16.5	14.5	10.0																		
F-2													11.5	8.8	6.0	11.5	9.0	6.5																		
F-3													12.0	8.9	6.0	12.0	8.9	6.0																		
F-4																			11.0	10.4	8.5	11.0	10.5	9.0												
I-1																			10.5	9.5	8.0	12.5	12.5	10.5												
I-2																			20.0	17.5	15.5	20.0	18.4	16.5	12.5	11.1	9.5	12.5	12.0	10.5						
J-1													8.5	6.6	5.0	8.5	6.6	5.0							14.0	11.1	9.5	16.0	11.4	10.0						
J-2	14.8	14.2	13.8	14.8	14.3	14.0	14.0	12.7	11.5	17.5	14.9	13.0	15.0	11.6	8.0	16.0	14.5	12.0							16.0	13.1	6.0	16.0	14.2	12.0	18.5	16.1	10.5	18.5	16.1	12.5

TABLE III (Cont'd.)

Insulator	October, 1930						November, 1931						February, 1932						December, 1932						December, 1933					
	Electrical			Mechanical			Electrical			Mechanical			Electrical			Mechanical			Electrical			Mechanical			Electrical			Mechanical		
	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.
C-1	12.8	12.0	11.0	12.8	12.0	11.0																								
E-1																			9.7	9.15	8.3	9.7	9.15	8.3	13.1	12.5	12.0	13.1	12.5	12.0
E-3																									9.1	9.1	9.1	10.2	10.2	10.2
E-4							17.5	15.9	14.1	22.0	22.0	20.1													18.2	15.0	12.1	18.2	15.8	14.2
E-6							17.8	14.8	12.8	20.2	17.3	17.3																		
F-1													13.8	12.9	10.8	13.8	12.9	10.8												
F-2	12.1	10.7	10.3	12.1	10.7	10.3																								
F-3																									10.8	9.9	9.1	22.8	19.3	15.8

*Not previously tested at 6000 lb for 72 hr.

TABLE IV. FIELD TESTS ON SUSPENSION INSULATORS

Insulator	Date Installed	1929 Test			1931 Test			1932 Test			1933 Test			Total		
		No. Tested	No. Failures	%	No. Tested	No. Failures	%	No. Tested	No. Failures	%	No. Tested	No. Failures	%	No. Tested	No. Failures	%
C-1	1916															
	1919							219	14	6.39				219	14	6.39
	1921				2890	25	0.87	2353	2	0.08				5243	27	0.52
	1922				3990	1	0.03	3955	0	0	725	4	0.55	8715	5	0.01 *
B-1	1920				240	6	2.5							240	6	2.5
E-3	1925	16052	1	0.006	7738	1	0.013	2778	6	0.216	3658	3	0.08	24927	11	0.036 *
	1926				1501	0	0	510	0	0	1206	0	0	1866	0	0
	1927										203	6	2.95	203	6	2.95
	1930							480	0	0				480	0	0
E-4	1924				3274	0	0	3305	0	0				6579	0	0
	1925				52	0	0							52	0	0
	1926	956	0	0	13947	0	0	9542	0	0	1039	0	0	25484	0	0
	1929										19	0	0	19	0	0
	1931										382	0	0	382	0	0
E-6	1927							6090	3	0.05	219	0	0	6289	3	0.05
	1928							2824	1	0.035	13006	0	0	15830	1	0.006
	1929							840	0	0	924	1	0.108	1764	1	0.056
	1930							2172	3	0.14	3228	0	0	5400	3	0.055
F-1	1924							440	0	0				440	0	0
	1926	22937	2	0.009				100	0	0	3	0	0	23040	2	0.009
	1927										287	0	0	287	0	0
	1929										13	0	0	13	0	
F-2	1921							1091	0	0				1091	0	0
	1922							3175	0	0	830	0	0	3995	0	0
	1923							2729	0	0	378	0	0	3103	0	0
	1924				2280	0	0	5746	0	0	22285	1	0.005	30711	1	0.003
	1925				4018	8	0.20	861	0	0				4879	8	0.164
	1926	4000	0	0	4411	23	0.52	1842	0	0	10032	5	0.05	20285	28	0.14
	1927							351	0	0	4565	0	0	4916	0	0
	1928							2527	20	0.79	570	0	0	3097	20	0.65
	1929				264	0	0				1575	3	0.11	1839	3	0.16
	1930										2401	3	0.11	2401	3	0.11
	1931										56	0	0	56	0	0
F-4	1914							5754	137	2.38				5754	137	2.38
	1915							1845	5	0.27	22732	53	0.23	24577	58	0.24
	1917	46472	27	0.06	46472	8	0.017							46472	35	0.076 *
	1918							10157	5	0.05				10157	5	0.05
	1920										1323	0	0	1323	0	0
I-1	1914				439	17	3.86	4511	179	3.93	19043	616	3.23	23993	812	3.38
	1915				4851	254	5.62				9101	577	6.40	13952	831	5.96
	1916				2033	2	0.097	40	0	0	614	10	1.63	2647	12	0.46
	1917							130	15	11.54				130	15	11.54
	1918				1204	26	2.26	1930	78	4.08	2136	71	3.32	5250	175	3.33
	1919				103	1	0.97	46	2	4.35	60	1	1.68	209	4	1.92
	1920				75	0	0	60	0	0				135	0	0
	1921				118	5	4.25	60	0	0	279	7	2.51	457	12	2.63
	1922										2209	0	0	2209	0	0
	1923							847	0	0				847	0	0
	1924				3454	123	3.56	5639	47	0.83				9093	170	1.87
	1925				1376	6	0.04	751	0	0	75	2	2.67	2202	8	0.04
I-2	1914										430	0	0	430	0	0
	1915				30	0	0				250	0	0	280	0	0
	1916										105	0	0	105	0	0
	1918							657	0	0	214	0	0	871	0	0
	1920				45	0	0				190	0	0	235	0	0
	1921							55	0	0	120	0	0	175	0	0
	1925				348	0	0							348	0	0
	1927							74	0	0				74	0	0
J-1	1922				5182	66	1.29	5169	54	1.05	408	28	6.85	5590	148	2.65 *
	1923							618	85	13.75				618	85	13.75

*All or portion of insulators tested twice.

In order to compare the field performance of insulators with the results obtained in laboratory tests Table V has been prepared. All makes of insulators that were installed in the field during the same period in which they were tested in the laboratory have been included in this table. They have been rated according to the results of both laboratory and field tests. The importance of laboratory tests is attested by the fact that the ratings in the 2 columns correspond and are practically identical.

The graphical comparison of the results obtained in the field and laboratory tests on the type *E* insulators is shown in Fig. 3. Here again results indicate that insulators that test well in the laboratory also perform well in the field.

Deterioration of Insulators

The question of life expectancy of any piece of engineering equipment is one that should be raised every time that its design, manufacture, or purchase is considered, if the problem is to be handled on a rational and engineering basis. It is obvious, for example, that the rate of depreciation to be allowed on a piece of equipment depends on life expectancy, although frequently obsolescence plays the major part in that question. In the case of steel transmission towers, it is the general opinion among engineers that where no unusual climatic conditions exist that would accelerate rusting, the life of such a structure can be taken as a rather long period, possibly of the order of 50 years or more. The logical question is, therefore, if the structure and conductor are good for a 50-yr life, can the insulator be expected to last the same length of time?

It is apparent that the insulators on a given line taken by themselves may not have outlived their usefulness where the rate of deterioration is, say, in the order of only 10 per cent; yet when such a condition is reached the insulation of the line as a whole may have become totally unreliable. Thus, if the criterion of usefulness of a line is its ability to

TABLE V. COMPARISON OF LABORATORY AND FIELD TESTS ON SUSPENSION INSULATORS

Insulator	Laboratory Tests					Field Tests			
	Date Tested	Time Load % Bad	Temp. Change % Bad	Porosity * %	Test Rating	Date Installed	No. Tested	% Bad	Test Rating
I-1	Dec. 1922	0	0	33	1	1922-23	3056	0	1
F-2	"	0	0	44	2	"	7098	.0	1
C-1	"	0	0	44	2	1922	8670	.075	3
J-1	"	10	33	0	4	1922-23	6208	3.75	4
E-3	Dec. 1926	0	0	5	1	1926	1866	0	1
E-4	"	0	0	7	2	"	25484	0	1
F-1	"	16	0	3	3	"	23040	.0087	3
F-2	"	17	12	6	4	"	20285	.138	4
E-6	Oct. 1927	0	0	44	1	1927	6289	.047	1
E-3	"	12	0	29	2	"	203	2.95	2

*Very porous is taken as 100%; porous, 67-2/3%; slightly porous, 33-1/3%; nonporous, 0%.

carry power continuously except for such causes as are extraneous to the line itself, or, in other words, if a situation is reached where the majority of interruptions to the service are caused by insulator failures, then the end of the useful life of the insulation on that line has been substantially reached.

The percentage of failures of insulators determining the end of the usefulness of the insulation of a transmission line cannot be stated generally. It must be determined for each line individually according to the importance of uninterrupted service to that line. The limit possibly may have been reached when the total failures to date are between 5 and 15 per cent of the total insulators on the line.

To show what the experience of the American Gas and Electric Company has been along these lines, Fig. 2 has been prepared from the data on the field tests given in Table IV; years of service for the different insulators have been plotted against the summation of the percentages of insulator failures found to date. In these curves where a manufacturer has several different insulators that are substantially of the same design, they are grouped together. The curves as shown are necessarily approximate due to the scattered position of the points, but seem to indicate that a life expectancy of 50 years for suspension insulators is not beyond realization.

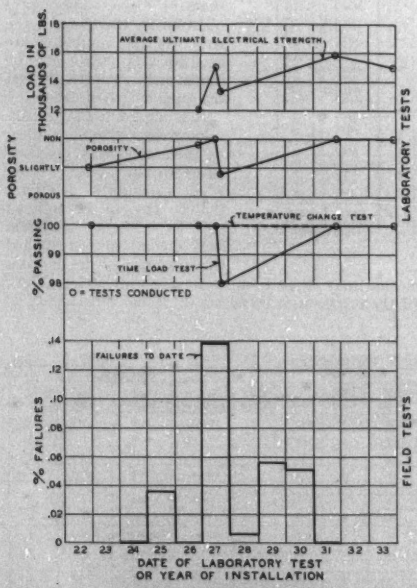


Fig. 3. Comparison of field and laboratory tests on type E insulators

Calibration of the Sphere Gap

A series of sparkover voltage calibration tests on sphere gaps using spheres of various sizes up to 200 cm in diameter are reported in this paper. Tests were made with gap spacings ordinarily used in practice, and with 60-cycle and both positive and negative impulse voltages. Since these tests as well as those of other investigators show that some of the A.I.E.E. standard sphere gap calibration curves are in error, it is recommended that those standards be revised. Recommendations are made for the adoption of separate calibration curves for positive and negative impulses and for correcting the 60-cycle calibration curves of large spheres.

By
J. R. MEADOR
ASSOCIATE A.I.E.E.

General Elec. Co.
Pittsfield, Mass.

FROM THE TIME that electric potentials exceeding a few thousand volts have been in use, it has been standard practice to measure voltages with a spark gap. Needle point gaps were used extensively until 1913 or 1914. The disadvantages of using needles were chiefly that: (1) the points fused necessitating renewal after each sparkover; (2) sparkover voltages were inconsistent under a given condition; (3) the voltages were greatly affected by atmospheric conditions, particularly humidity, but also by temperature and barometric pressure; and (4) a needle gap has a large time-lag. Consequently, the use of the needle gap was limited to sustained low frequency measurements.

In the search for a more accurate measuring spark gap, it was found that the sphere gap offered several advantages over the needle gap. For example, it is not appreciably damaged when sparked over. It is relatively unaffected by humidity changes in the air, although it is affected by changes in air density; and, it appeared to have no time-lag or polarity effect, making it suitable for measuring both low frequency and high frequency voltages of both oscil-

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 23, 1934; released for publication April 30, 1934. *Not published in pamphlet form.*

1. For all numbered references see bibliography at end of paper.

latory and impulse types of either positive or negative polarity. Unlike the needle gap, the sphere gap sparkover potentials are very consistent.

The use of the grounded sphere gap for measuring purposes was first proposed to the A.I.E.E. in 1913 by Chubb and Fortescue[1] and Peek.[2] Their tests were made on small sphere gaps not exceeding diameters of 25 cm (37.5-cm and 50-cm spheres were tested at relatively small spacings).

Peek's measurements of voltage were made chiefly with a voltmeter coil and a step-down transformer. Chubb and Fortescue rectified the capacitance current taken by an air capacitor and measured the average value of the rectified current with a d'Arsonval galvanometer. Based on his own measurements, Peek derived an empirical formula[2] for calculating the flashover voltages for spheres of different diameters and spacings. While no complete sparkover curves were taken on spheres larger than 25 cm in diameter, it naturally was assumed that the formula would apply for all sizes of spheres.

In 1914 the A.I.E.E. adopted calibration curves for sphere gaps having spheres 6.25, 12.5, 25, and 50 cm in diameter, respectively. The calibration of the 50-cm sphere gap did not cover the entire range from zero to diameter spacing. The highest calibration point was for 27.6-cm spacing. These adopted curves were based on the tests by Chubb and Fortescue and Peek. In 1928 the 50-cm sphere gap curve was extended and a 75-cm sphere gap calibration was added to the standards. It is believed that these additions were not based on actual test data. A calibration also was added for 2.0-cm sphere gaps.

When these original calibrations were incorporated in the A.I.E.E. Standards, sphere gaps were believed to be completely free from polarity and time-lag effects. The only known factors affecting the sparkover voltages were temperature and barometric pressure.

In the early stages of impulse testing the demand for extreme accuracy was not as great as it is today; consequently, sphere gaps were very acceptable standards. In fact, it would have been quite difficult to carry on the early impulse testing without the use of sphere gaps. However, with the advent of impulse generators producing potentials up to several million volts, even larger measuring spheres became necessary. These spheres of 100, 150, and 200 cm in diameter were not calibrated at that time on 60 cycles throughout their entire range. Calculated sparkover curves were used in the absence of test curves. Inasmuch as many small sphere gaps had been found to check the calculated curves with good accuracy, it was reasonable to have confidence in the calculated sparkover curves of the larger spheres.

Sphere Gap Inaccuracies

When the importance of standardized coördination of insulation became apparent, greater accuracy in voltage measurement was needed, and various investigators noticed inaccuracies in the sphere gap standard. It was found[3,4] that gaps with different sizes of spheres could not be checked accurately against each other, that there was a marked polarity effect[5,6] at certain spacings, and that when subjected to very steep impulse waves there was an appreciable impulse ratio.[7] It would seem that enough evidence has accumulated in the past few years to justify a general revision and extension of the A.I.E.E. sphere gap calibrations.

Method of Test—60 Cycles

For the 60-cycle data presented in this paper, a testing transformer with a voltmeter coil was used. Sparkover curves were taken on spheres 6.25, 12.5, 25, 50, 75, 100, and 200 cm in diameter. All of the tests were made on sphere gaps having one sphere grounded. A crest voltmeter reading, using the voltmeter coil, gave the voltage measurement.

In order to determine the accuracy of this method of measurement, several tests were made. Using an identical testing transformer as a step-down transformer, the voltmeter coil readings of the 2 units were checked against each other under various conditions of loading and over the complete voltage range of the transformers. This test showed that the voltage from the voltmeter coil was a definite constant proportion of the high side voltage. The wave shape of the high side voltage was measured on a cathode ray oscillograph using a large sphere gap as a capacitance voltage divider. This was found to be in close agreement with the wave shape of the voltmeter coil voltage.

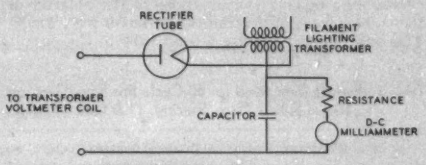


Fig. 1 (above). Schematic diagram of crest voltmeter

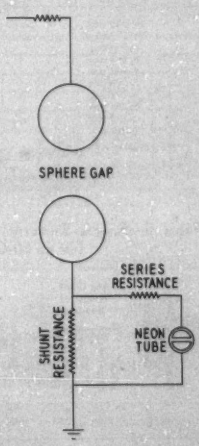


Fig. 2 (right). Neon tube polarity indicator used on 60-cycle tests

The crest voltmeter connected to the voltmeter coil consisted of a rectifier tube, a capacitor, a high resistance, and a d-c milliammeter as shown schematically in Fig. 1. It was calibrated with a 60-cycle voltage of known wave form. The calibration curve was practically a straight line when plotted between milliamperes and crest volts. This crest voltmeter was found to have a high degree of accuracy and the voltage readings were very consistent.

A resistance of 600,000 ohms was used in series with the sphere gaps on all 60-cycle tests. This resistance was placed as close to the sphere gap as possible without introducing the resistors into the field of the gap. Errors are likely to result if the line from the resistors to the sphere gap is too long. Corona on the line wire requires an appreciable amount of corona current to flow through the resistance. Under such conditions the voltage drop between the transformer and the sphere gap becomes excessive. The voltage drop due to the charging current to the spheres is negligible for all practical conditions.

All of the sphere gaps tested except the 75- and 200-cm spheres were mounted vertically in wooden frames that conform to A.I.E.E. specifications. In the 75- and 200- cm sizes the line potential sphere was suspended from the ceiling. The height of the grounded sphere above the floor was maintained at from 3 to 5 diameters. The clearances to nearby line and ground potential surfaces recommended by the A.I.E.E. were used.

At the same time that the 60-cycle sparkover curves were taken, determinations of the polarity of the voltage wave at the time of sparkover were made. This was done by placing a neon tube in the circuit of the grounded sphere as shown in Fig. 2. At the instant of sparkover, the capacitance of the transformer discharges and an impulse is impressed across the neon tube. This impulse is of the same polarity as the voltage wave at the time of sparkover. The polarity of the impulse is indicated by a glow surrounding one of the electrodes in the neon tube. The neon tube circuit must be well shielded from stray fields as it is very sensitive.

Table I—Sample Data Sheet for 60-Cycle Sparkover Test on 50-Cm Sphere Gap; Spacing, 11.0 Cm

Milliammeter Readings and Polarity of Sparkover	
0.295 neg.	0.292 neg.
0.292 neg.	0.292 neg.
0.290 neg.	0.285 pos.
0.293 neg.	0.288 pos.
0.292 pos.	0.290 neg.
0.290 neg.	0.285 neg.
0.292 neg.	0.292 neg.
0.288 pos.	0.290 neg.
0.282 neg.	0.292 pos.
0.292 neg.	0.288 neg.

Average milliamperes—0.290
5 positive polarity sparkovers
15 negative polarity sparkovers

Table II—Sample Summary Sheet for 60-Cycle Sparkover Test on 50-Cm Sphere Gap

Sphere Gap Spacing in Centimeters	Avg Crest Voltmeter Reading: Milliamperes	Avg Crest Voltmeter Reading: Crest Volts	Transformer Ratio	Transformer Kv Crest	Air Density Correction	Corrected Kv, Crest	% Positive Polarity Sparkovers
11.0	0.290	275	1000 : 1	275	0.998	276	25

Test Results—60 Cycles

Test points for 60 cycles were determined by taking from 10 to 20 consecutive sparkovers at each gap spacing. On each sparkover a crest voltmeter reading and a polarity indication were recorded. Table I shows a sample data sheet with the original data in the form in which it was taken. The milliammeter readings then were averaged and the voltage value determined as shown in Table II. The sparkover voltages for all sphere gaps tested are plotted on Figs. 3 to 9, inclusive. The voltages plotted are the averages of from 1 to 5 separate tests.

In order to study these test sparkover curves, a calculated curve is included on each figure for comparison. These curves are calculated using the Peek formula. The reason for including these calculated curves is that they furnish a common basis for reference. There are slight variations between the calculated curves and the A.I.E.E. curves, and furthermore there are no A.I.E.E. curves for the 100-cm and 200-cm spheres that could be used for comparison.

The family of curves shown on Fig. 10 was plotted to compare the test data with the calculated curves. The percentage error based on the test results is plotted against the percentage of diameter spacing of the spheres. It may be noted that these curves have a general similarity of shape. The dotted portion of the curve for 200-cm spheres is extrapolated. It is believed that this limited amount of extrapolation is accurate to within 1 or 2 per cent. Using this dotted percentage error curve and the calculated curve, the test calibration of the 200-cm spheres can be extended to 25 per cent of diameter spacing. This portion of the curve is shown dotted on Fig. 9.

The reason for the necessity of extrapolating the calibration curve is that the testing transformer used is limited in voltage to 800 kv crest. When 2 transformers are connected in series, the voltmeter coil of the grounded unit does not give an accurate reproduction of the high side voltage either in wave shape or voltage magnitude. However, the 2 transformers in series can be used to determine the polarity characteristics of the sphere gaps at voltages above 800 kv crest.

Variation of the polarity of the voltage wave at the time of sparkover with spacing has been termed the polarity characteristic. The polarity characteristic for each size of sphere gap is plotted with the test data on Figs. 3 to 9, inclusive. From these curves it can be seen that practically all of the sphere gap sparkover voltages are affected by polarity. In the range of spacings where both positive and

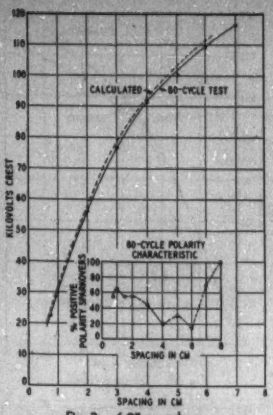


Fig. 3. 6.25-cm spheres

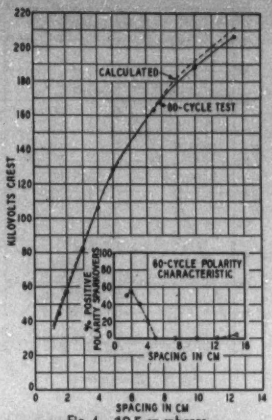


Fig. 4. 12.5-cm spheres

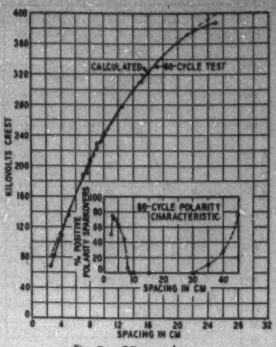


Fig. 5. 25-cm spheres

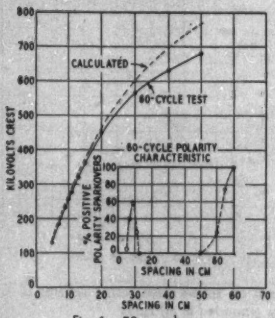


Fig. 6. 50-cm spheres

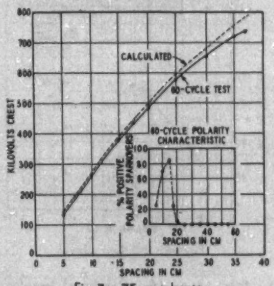


Fig. 7. 75-cm spheres

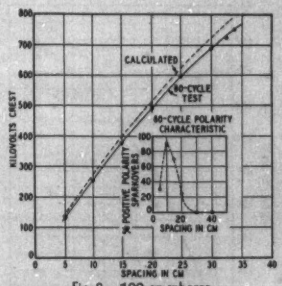


Fig. 8. 100-cm spheres

Figs. 3 to 9. Results of 60-cycle tests on sphere gaps, using various sizes of spheres; one sphere grounded in all cases

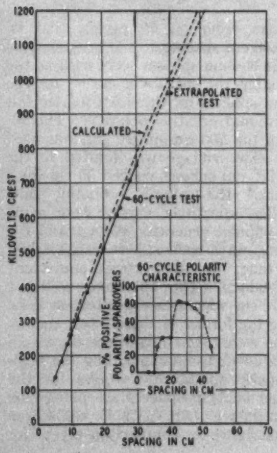


Fig. 9 (left). 200-cm spheres

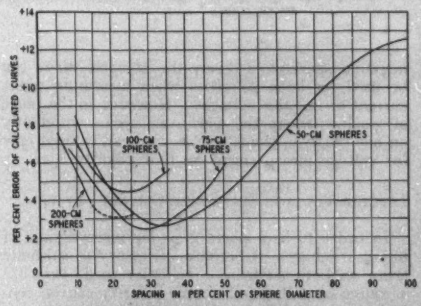


Fig. 10. Percentage error of calculated sphere gap curves based on 60-cycle tests

Plus error indicates that calculated curves are too high

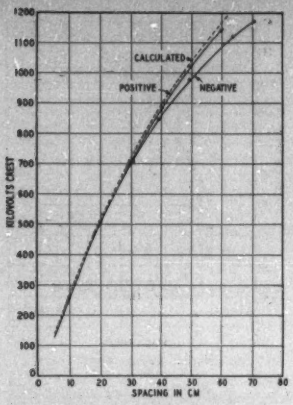


Fig. 11. 100-cm spheres

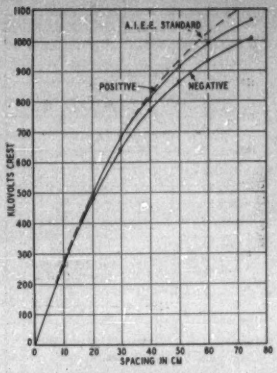


Fig. 12. 75-cm spheres

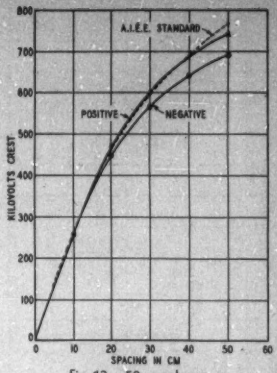


Fig. 13. 50-cm spheres

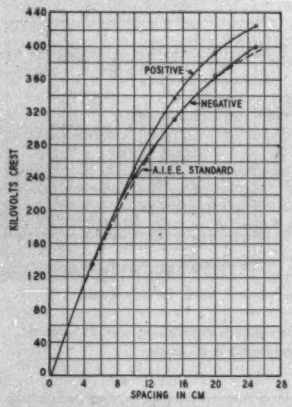


Fig. 14 (left). 25-cm spheres

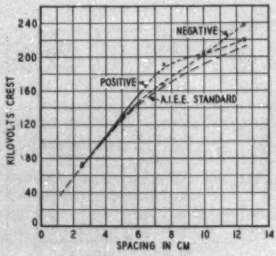


Fig. 15. 12.5-cm spheres

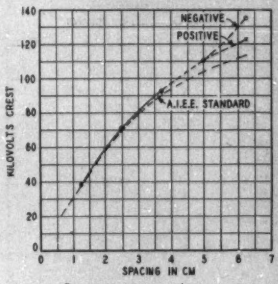


Fig. 16. 6.25-cm spheres

Figs. 11 to 16. Results of impulse tests on sphere gaps, using spheres of various sizes; one sphere grounded in all cases

negative sparkovers occur, the 60-cycle curve can be used for both polarities when measuring direct current or impulse voltages. However, in the range of spacings where the sparkovers occur consistently on one polarity, the 60-cycle curve can be used only for voltage measurement on that polarity.

Impulse Voltage Sparkover Curves

In order to use sphere gaps for measurement of impulse voltages, it becomes necessary to calibrate them on both polarities. In order to do this, (1) a source of voltage where the polarity can be controlled is essential, and (2) the measuring instrument must be free of polarity effect. The first requirement is satisfied by using full wave impulse voltages. The second requirement is satisfied by using 200-cm spheres in the range where both positive and negative sparkovers occur on 60 cycles, that is, with from 10- to 50-cm spacing.

Accordingly, the 200-cm spheres were used as the reference in obtaining the sparkover curves for the 100-cm and 75-cm spheres on the 1.5×40-μsec full wave, both positive and negative polarity. The 60-cycle test curve of the 200-cm sphere gap was used as the standard. The voltage was limited to the sparkover of the 200-cm spheres spaced 50 cm since beyond this spacing the spheres probably show polarity effect. The sparkover curves were made by adjusting the impulse generator voltage and the sphere gap spacings until each sphere gap sparked over part of the time. In other words, equivalent spacings were obtained. The sparkover voltages of the 100- and 75-cm spheres are plotted on Figs. 11 and 12. Using the former of these 2 test curves, the 100-cm spheres were used to calibrate the 50-cm spheres and so on down to and including the 6.25-cm spheres. Impulse sparkover voltages for the 50-, 25-, 12.5-, and 6.25-cm spheres are plotted on Figs. 13 to 16, inclusive. An A.I.E.E. calibration is included on each figure for comparison except for

Tables III to IX—Recommended Values for Sphere Gap Sparkover Calibrations for 60-Cycle Voltages and for Impulse Voltages of Both Positive and Negative Polarity. One Sphere Grounded in all Cases; All Voltages Are Crest Values

Table III—200-Cm Spheres

Spacing in Cm	Calculated Values, Kv (Peek)	Recommended Calibration, Kv: 60 Cycle and Negative Impulse	Recommended Calibration, Kv: Positive Impulse
10	278	259.5	259.5
20	540	509	509
30	781	755	755
40	1,000	979	979
50	1,220	1,181	1,181
60	1,417	*1,350*	*1,360*
80	1,752	*1,640*	*1,660*
100	2,038	*1,870*	*1,900*
120	2,280	*2,050*	*2,085*
140	2,485	*2,200*	*2,250*
160	2,655	*2,330*	*2,400*
180	2,800	*2,440*	*2,520*
200	2,915	*2,520*	*2,620*

Values in *italic* type are extrapolated.

Table IV—100-Cm Spheres

Spacing in Cm	Calculated Values, Kv (Peek)	Recommended Calibration, Kv: 60 Cycle and Negative Impulse	Recommended Calibration, Kv: Positive Impulse
10	275	259	259
20	516	505	505
30	721	703	710
40	896	860	880
50	1,041	988	1,025
60	1,166	1,088	1,130
70	1,268	1,167	*1,210*
80	1,355	*1,235*	*1,280*
90	1,435	*1,295*	*1,340*
100	1,500	*1,335*	*1,390*

Values in *italic* type are extrapolated.

Table V—75-Cm Spheres

Spacing in Cm	A.I.E.E. Standard, Kv	Recommended Calibration, Kv: 60 Cycle and Negative Impulse	Recommended Calibration, Kv: Positive Impulse
7.5	208.5	200	200
15	390	378	378
22.5	546	525	546
30	680	644	685
37.5	790	743	785
45	884	822	867
52.5	962	884	937
60	1,028	935	992
67.5	1,087	978	1,035
75	1,133	1,010	1,070

the 100-cm spheres for which none is available. The calculated curve based on the Peek formula is used for comparison for this size of sphere.

Comparison of 60-Cycle and Impulse Sparkover Curves

The 60-cycle polarity indicator shows that in general from very small spacings to approximately 25 per cent of diameter spacing, the positive and negative polarity sparkover curves should be practically the same. From approximately 25 per cent of diameter spacing to a spacing of one diameter it

Table VI—50-Cm Spheres

Spacing in Cm	A.I.E.E. Standard, Kv	Recommended Calibration, Kv: 60 Cycle and Negative Impulse	Recommended Calibration, Kv: Positive Impulse
5	137.8	130	130
10	262.5	259	259
15	372	362	372
20	460	448	472
25	533	515	544
30	594	566	600
35	646	604	648
40	694	635	688
45		660	718
50		685	743

Table VII—25-Cm Spheres

Spacing in Cm	A.I.E.E. Standard, Kv	Recommended Calibration, Kv: 60 Cycle and Negative Impulse	Recommended Calibration, Kv: Positive Impulse
2.5	73	72	72
5	133.8	136	136
7.5	187.3	194	196
10	234	242	252
12.5	275.5	279	300
15	310.5	310.5	338
17.5	340	339	369
20	361	363	394
22.5	380	378	412
25	394	390	426

Table VIII—12.5-Cm Spheres

Spacing in Cm	A.I.E.E. Standard, Kv	Recommended Calibration, Kv.: 60 Cycle and Negative Impulse	Recommended Calibration, Kv.: Positive Impulse
1.25	38.05	38.0	38.0
2.50	70.1	71.0	71.0
3.75	100.0	102.0	102.0
5.00	125.8	128.0	132.5
6.25	147.0	148.0	161.0
		60 Cycle Only	
7.50	164.3	163.5	
8.75	178.7	176.5	
10.00	191.0	188.0	
11.25	201.5	197.5	
12.50	211.5	206.0	

Table IX—6.25-Cm Spheres

Spacing in Cm	A.I.E.E. Standard, Kv	Recommended Calibration, Kv: 60 Cycle and Negative Impulse	Recommended Calibration, Kv: Positive Impulse
0.625	20.8	19.0	19.0
1.250	38.5	37.5	37.5
1.875	54.6	54.0	54.0
2.500	69.75	68.5	68.5
3.125	81.6	80.0	80.0
		60 Cycle Only	
3.750	90.3	88.5	
4.375	97.5	95.5	
5.000	103.5	101.0	
5.625	109.1	106.2	
6.250	113.3	111.0	

indicates that the negative polarity sparkover curve should be lower than the positive. Accordingly, for full wave impulse testing the negative impulse sparkover voltages should be in good agreement with the 60-cycle sparkover voltages throughout the range of spacings normally used.

An inspection of the test data shows that the negative and positive polarity impulse sparkover voltages are essentially the same at the lower spacings for all of the sphere gaps. Also, the negative polarity sparkover voltages are in good agreement with the 60-cycle sparkover voltages throughout most of the tested range of spacings except for the 6.25- and 12.5-cm spheres. In comparing the 60-cycle and impulse sparkover curves, it is believed that variations of 2 to 3 per cent are within the limits of accuracy for this type of measurement.

The 6.25- and 12.5-cm spheres have a higher sparkover voltage at large spacings on the 1.5×40-μsec full wave, negative polarity, than on 60 cycles. This condition is an indication of time-lag. Oscillograms of full wave impulse sparkovers show that these small sphere gaps do have appreciable time-lag at spacings greater than half of one diameter. Furthermore, as the spacing nears one sphere diameter, a very erratic zone of sparkover voltages is encountered. This is illustrated by the peculiar curvature of the impulse calibration curves on Figs. 15 and 16 just below a spacing of one diameter. The upper parts of these calibration curves have been drawn very freely through the test points. Since it was felt that these portions of the curves should not be used for voltage measurement they were not studied in detail. Parts of the curves that are believed to be unreliable for voltage measurement are shown dotted.

All of the sphere gaps tested show slight evidences of time-lag at a spacing of one diameter. It is believed that for very accurate measurements the impulse calibration curves should not be used beyond 80 per cent of diameter spacing. The 6.25- and 12.5-cm spheres should not be used beyond half of diameter spacing for impulse measurements. Measurements at 60 cycles, of course, are not affected by these limitations.

Effect of Polarity

Perhaps the greatest limitation of the present standard sphere gap calibrations is that they do not take into account the effect of polarity on the sparkover voltage of the spheres. The polarity effect is due to the unsymmetrical field between the spheres. The large ground surface near the grounded sphere is the upsetting factor. At spacings below 25 per cent of sphere diameter the polarity effect is negligible. Grounded and isolated sphere gaps have the same sparkover curve in this range.

Recent tests on shielded sphere gaps indicate that the effect of polarity can be eliminated with properly placed shields. The sparkover curve of the shielded sphere gap having one sphere grounded appears to agree very well with the sparkover curve for isolated spheres. The use of shields is not practical, however, in most laboratories due to space limitations.

Suggested Revision of A.I.E.E. Standards

A comparison of the test data presented in this paper with the present sphere gap calibration curves in general use suggests the following conclusions:

1. The sphere gap calibrations that originally were made on 60 cyles are fairly accurate for 60-cycle and negative polarity impulse measurements. The average error is of the order of 2 per cent.

2. Sphere gap standard curves that were not based on test data are inaccurate for 60-cycle, negative polarity impulse, and positive polarity impulse measurements throughout most of their calibrated range of spacings. These errors in some cases are as high as 15 per cent.

3. In general, all of the standard sphere gap calibrations are inaccurate for impulse measurements on positive polarity at large spacings.

Since these tests and those of other investigators have shown that some of the A.I.E.E. standard sphere gap calibration curves are in error, it seems evident that the standards should be changed. High voltage testing laboratories that use different sizes of spheres have been unable to agree on sparkover voltages. Using the proposed calibrations given in this paper, different sizes of spheres give the same voltage indication in the overlapping range.

The test data given in this paper have been taken under normal conditions of use of the spheres. No attempt has been made to influence the sparkover voltage by light radiations upon the sparking surfaces. The spheres were kept as clean as possible although excessive polishing was found to be unnecessary.

Recommended values for sphere gap calibrations on impulses of positive and negative polarities and 60-cycles are given in Tables III to IX, inclusive. These values are taken from smooth curves drawn from the data presented in this paper. For accurate impulse measurements, sphere gaps of 25-cm diameter and larger should not be used beyond a spacing of 80 per cent of diameter. Spheres smaller than 25 cm in diameter should be limited in spacing to half of the sphere diameter for all impulse measurements. The values given in *italic* type in the tables represent extrapolations not discussed in this paper, but it is believed that they can be used with confidence as being more accurate than the calculated sparkover voltages now in general use. It is recognized that some of the values given indicate an accuracy beyond that which should be used considering the experimental error.

References

1. Calibration of Sphere Gap Voltmeter, Chubb and Fortescue. A.I.E.E. Trans., 1913, p. 739.

2. Discussion of paper listed in item No. 1, F. W. Peek, Jr. A.I.E.E. Trans., 1913, p. 812.

3. Better Standards Needed for Surge Testing, F. D. Fielder. *Elec. World*, Sept. 30, 1933.

4. Spannungsmessungen mit Kugelfunkenstrecken in Luft, C. Stoerk u. W. Holser. *Z. Techn. Phys.*, v. 10, p. 317.

5. A Study of High Voltage Flashovers, J. T. Lusignan, Jr. A.I.E.E. Trans., 1929, p. 246.

6. The Influence of Polarity on High Voltage Discharges, McMillan and Starr. A.I.E.E. Trans., 1931, p. 23.

7. Coördination of Insulation, V. M. Montsinger, W. L. Lloyd, and J. B. Clem. A.I.E.E. Trans., 1933, p. 417.

Some New Developments in Supervisory Control

By
M. E. REAGAN
MEMBER A.I.E.E.

Westinghouse Elec. and Mfg. Co.,
East Pittsburgh, Pa.

New developments in the direct selection system of supervisory control are described in this paper which also touches upon the systems and use of codes and gives examples of the use and operation of equipment.

THE PAPER in the February 1933 issue of ELECTRICAL ENGINEERING (p. 81–4) on the direct selection system of supervisory control explained the general theory of selection by utilizing a code of polarities. The history of the 2 previous selection systems was given and is here briefly abstracted.

The first or code system, introduced in 1921, operated to take the remote ends of the line conductors and switch them from unit to unit until the desired one was reached. The remote equipment selected then sent the same series of impulses back to the office and switched the near end of the line wires from control switch to control switch until the corresponding one was reached. The unit selected could then be operated at will.

The second or synchronous system, brought out in 1924, shifted both ends of the line wires simultaneously from point to point until the unit to be operated was reached. The unit could then be controlled as desired. This saved considerable time.

The direct selection system (1932) utilized no counting or stepping equipment, but by means of relays responsive to direct acting polarity codes the proper unit only at the remote location could be instantly selected and no other. A similar procedure gave the check back to the initiating station. Thus the change was from sequential operation of relays to direct operation and no time was lost in connecting the line wires to units on which no operation was desired.

This general idea has been kept, but important changes have been made since 1932 that are described in the following text, the object of which is to introduce the latest developments in supervisory control and to discuss the new selection and operating circuits. The progress has been chiefly with the 2-wire systems and, as a result, we are able to accomplish practically every type of operation at such split-second speed that now there are rarely advantages in the use of more than 2 wires, except for use as an emergency circuit.

Full text of a paper recommended for publication by the A.I.E.E. committee on automatic stations, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 20, 1934; released for publication May 2, 1934. *Not published in pamphlet form.*

Before proceeding further, a reminder in the form of explanations of a few of the terms connected with supervisory control may be desirable:

1. A *pulse* or *impulse* is the energizing of the line circuit for a short time and then deenergizing it, or the reverse of this cycle. Pulses vary in time interval and polarity in modern systems.

2. *Points* are units of operation. They may vary in equipment, but the usual point of control and supervision includes the control keys, pushbuttons, red and green indicating lamps, and check and disagreement lamps which permit the opening and closing operations to be performed, as on a circuit breaker, and at the same time supervise the circuit so the dispatcher knows the position of the circuit breaker at all times.

3. A *control key* or *twist key* is a 2-position switch which determines whether the circuit breaker will receive the close or trip pulse.

4. A *check lamp* informs the dispatcher that the selection he intended has actually been made, and no other.

5. The *disagreement lamp* blinks when the position of the twist key disagrees with the position of its corresponding circuit breaker. When a circuit breaker trips automatically, an alarm sounds and the disagreement lamp blinks. This immediately notifies the dispatcher and enables him to locate instantly the particular circuit breaker affected.

6. *Supervision* denotes a signalling arrangement whereby the dispatcher is constantly informed of the condition or position of the remote apparatus.

7. An *escutcheon* is a small shield or panel which has assembled on it all of the control keys, pushbuttons and indicating lamps associated with a point.

8. *Relay pulls* means that the relay coil is energized.

9. *Relay drops* means that the relay coil is deenergized.

10. *Telemetering* or *remote metering* is obtaining from a remote station a meter indication of any variable quantity.

In the 2-wire system previously described, pulsating direct current was utilized in some of the selections, but a simpler arrangement has been

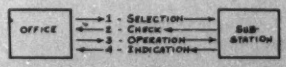


Fig. 1. Line circuits of simplified arrangement of 2-wire system

developed. The line circuit relay equipment is reduced to a pair of receiving relays responsive to the 2 d-c polarities, as shown in Fig. 1.

CODES USED IN OPERATION

It will be recalled that an operation may be divided into 4 distinct steps, namely, selection, check, operation, and indication. When an operator initiates an operation, a selective impulse is sent from the office and received at the substation. The latter immediately sends a verifying impulse back to the office. After the operator has been assured by the verifying impulse that his selection is right

he proceeds to operate the remotely located device. When the remote operation is complete, indication of the change is sent to and recorded on the office board. This is illustrated in Fig. 2.

The characteristics of these impulses may be governed by the polarity of impulse, length of time of

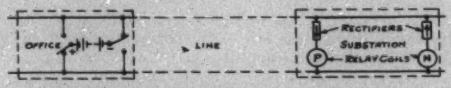


Fig. 2. The 4 steps of a supervisory control operation

impulse, length of time between impulses, number of impulses, or combinations of these. Taking, for instance, the selection of any one of a group of 5 remote units, some of the selecting codes with corresponding checks which might be used are suggested in Fig. 3. A different code is used for checking than for selecting with the exception of code 3. This is done to get the same over-all time for each code, which in this case is approximately $^1/_4$ sec. It will be noted that a short positive pulse is used for selection in code 1 and a long positive pulse is used for the check. Similarly, code 2 uses a long positive pulse for selection and a short positive pulse for the check. Code 3 uses a short positive pulse immediately followed by a short negative pulse for selection while the same combination is utilized for the check. Codes 4 and 5 are identical with codes 1 and 2 except that negative impulses are used instead of positive ones. The complete selection diagram with description is given in the appendix, for those interested in the details of the individual circuits.

Scheme *B* shown in Fig. 4 varies from scheme *A* of Fig. 3 in that it uses 1 and 2 pulses (all short) instead of a combination of short and long pulses. The over-all time of selection and check for scheme *B* is approximately $^1/_3$ sec since arrangements are used to hold long enough after the first pulse to determine if a second pulse is to follow. Timing relays are therefore used as in scheme *A*.

Scheme *C* shown in Fig. 5, uses a series of impulses, both positive and negative, with timing relays partially eliminated. Here again, the over-all time of selection and check is approximately $^1/_3$ sec. Some timing is required because it is necessary to distinguish between a positive pulse followed by a negative one with and without a pause.

Scheme *D* in Fig. 6 uses 3 pulses and has the check pulse immediately following the selection pulse, i. e., select-check-select-check-select-check. With such a scheme, it is possible to shorten the pauses between pulses, and no timing relays are required. The pauses are automatically taken care of by the time required for switching the relays from sending to receiving positions. The over-all timing of scheme *D* is approximately $^1/_3$ sec.

Summing up the advantages of these various schemes, it appears that since speed of operation, simplicity of circuit, number of relays required, etc., must be considered, scheme *A* would be preferred on a small layout of about 5 operations and scheme *D* with 3 or more pulses each way would have definite advantages in the larger stations. For a station where 100 operations are required, the timing for selection and check would be approximately 1 sec for any one of them using scheme *D*.

When considering any form of supervisory control, it must not only take care of the control of 2-position devices such as circuit breakers, or the starting and stopping of machines, etc., but it must also permit the use of the various established auxiliaries such as telemetering, synchronizing, position control, supervision only, and telephony. It is also necessary to design the line circuit so that the lines may be drained of any induced voltages and still not interfere with operation. In the new super-

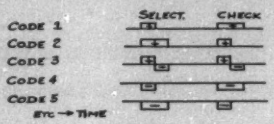


Fig. 3. Scheme A: Short and long pulses

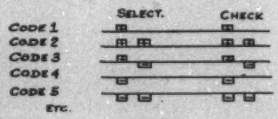


Fig. 4. Scheme B: One and 2 short pulses

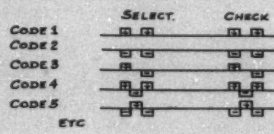


Fig. 5. Scheme C: Short pulses with and without pauses

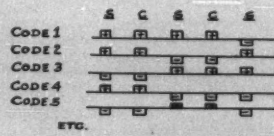


Fig. 6. Scheme D: Three pulses each way; each selection pulse followed with check pulse

Figs. 3 to 6. Four different combinations of impulses for accomplishing supervisory control operations

visory control circuits, all of these features are incorporated. Definite advances have also been made in 2 of the auxiliary operations, remote synchronizing and remote position control, which formerly required 2 points, but now use only one.

Examples of Remote Control

The new remote position control is of particular interest. With it, flexible operation is secured of remotely located transformer tap changers, voltage regulators, motor operated rheostats, gate openings, valve settings, or any other similar multi-position device. The changes of position are indicated to the

dispatcher as they take place, enabling him to stop at any desired point. Furthermore, once it is stopped it may be started and stopped at will in the same or opposite direction without reselection. For example, consider a hydroelectric generator running in a remote automatically controlled station. With the gate opening set at 0.8, it is desired to lower the generator output by closing the gates to 0.6. The gate mechanism has a rheostat connected as a potentiometer across the battery and is so arranged mechanically on the gate or governor mechanism that the moving arm of the rheostat varies its setting with the gate position. The switching is arranged so that the following operations take place:

1. The dispatcher operates the pushbutton (operation 1) to select this particular control function (gate position). With the lighting of the check lamp on the dispatcher's escutcheon showing him he has made the correct selection, the open circuit voltage of the station control battery appears on the meter. This meter has 2 scales, one registering the full scale of the battery voltage expressed in per cent and the other calibrated in gate opening from 0 to 1 in steps of tenths. Thus the dispatcher knows the actual voltage of the battery at the generating station and can use the percentage reading as a multiplier on his gate opening indication.

2. The dispatcher presses the check pushbutton (operation 2). This causes the meter reading to be transferred from the battery to the potentiometer and gives him the gate opening at that instant. He corrects this reading by the percentage multiplier he obtained when he first selected the point.

3. Since he wants to reduce the gate opening, he operates the twist key on his escutcheon to the "lower" position (operation 3) and presses the "master-operate" pushbutton (operation 4). This starts the governor synchronizer motor in the "decreased speed" direction and causes the gates to close. In a hydroelectric station there is usually some lag at this point which would not occur in the control of a tap changer, for instance. Here, the meter reading will not have reached the 0.6 opening due to the inherent lag in the governor and gate mechanism.

4. The dispatcher again presses the check pushbutton (operation 5) and the synchronizing motor on the governor stops but the meter reading remains. Thus he is able to observe the lagged action of the gate position. If, when the meter stops, the travel is not enough, he repeats the action by again pressing the master control followed by the check pushbutton. If he overshoots his 0.6 position, he turns the twist key to the "raise" position and presses the master control. The synchronizing motor now runs in the opposite direction and starts the chain of events that causes the waterwheel gates to open. Pressing the check button again causes this action to stop. Thus he is able to set the gate opening accurately at the 0.6 point. After a little experience, it will not be necessary for the operator to use more than one trial to secure the desired gate opening.

5. The dispatcher releases the set by returning the selection pushbutton to the normal position (operation 6).

It may be seen that he not only has complete control in getting an accurate setting but he knows, by the meter reading, the continuous status of the apparatus.

An equipment has also been developed to meet the requirements of the small installation. This junior equipment has been standardized to a very definite layout. It is limited to the control of 5 units and to 1 station per pair of line conductors. By such a move, it is possible to have the substation equipment housed in a single small relay case which may be added to an existing control board in a similar manner to a protective relay. The dispatcher's equipment is housed in a small cabinet for desk mounting.

The 6 usual types of supervisory control functions are:

1. Combination of control and supervision.
2. Control only.
3. Supervision only.
4. Telemetering.
5. Synchronizing.
6. Position control (with telemetering).

Combination of any 5 of these may be used on the junior equipment.

To see how it may fit into actual service requirements, let us take a few examples. First, a single-unit automatically controlled hydroelectric station is an ideal application.

Point No. 1. Start and stop the generator. Supervision is taken from the generator breaker.

Point No. 2. Telemetering of head. The dispatcher is able here to get an accurate reading of the amount of water available and therefore of the amount of load he can take from the plant.

Point No. 3. Position control of the waterwheel gates. This has been previously described. He is able to adjust the output of the station to any desired amount.

Point No. 4. Supervision of the lockout relay. Since the protection of an unattended station is divided into 2 parts, trouble outside which merely takes the equipment temporarily out of service and trouble inside which operates the lockout relay, the dispatcher knows if it is necessary to send a maintenance man to investigate and repair.

Point No. 5. This is a point of control and supervision which may be used for an outgoing feeder, a station service feeder, or any other one operation.

Fig. 7 (left). Dispatcher's cabinet arranged for desk mounting

Fig. 8 (right). Substation equipment arranged in single relay case for mounting on substation panel

Second, in a single unit railway substation, the 5 points may be used in corresponding ways.

Point No. 1. Start and stop the rectifier, converter, or motor generator set. Supervision may be taken from the d-c line breaker showing when the unit goes on the line.

Point No. 2. Telemetering of load.

Point No. 3. Supervision of the lockout relay.

Points No. 4 and 5. Control and supervision of 2 outgoing d-c feeders.

Third, a small a-c distribution station with an incoming line and 3 low tension feeders could be equipped with this system.

Point No. 1. Control and supervision of the breaker on the incoming line.

Point No. 2. Telemetering of total load.

Points No. 3, 4, and 5. Control and supervision of the 3 low tension feeder breakers.

Similarly, the junior equipment is applicable to the remote control of pumping stations, industrial substations, ventilating fans, and other devices.

Summarizing, the progress in the last year and a half has been the simplification of selection and control circuits and the development of the junior all purpose standardized equipment. In all of this, proved standard relays with their high speed and reliability have been retained.

Appendix—A Simple Selection Circuit

With the set normally at rest, relays 6 and 9 (Fig. 9) at the office normally are energized or "up." The remaining relays are deenergized or "down." At the substation, relay 6 is up. The codes used are:

1. Short positive pulse.
2. Long positive pulse.
3. Short positive pulse, short negative pulse.
4. Short negative pulse.
5. Long negative pulse.

For the 5 points, we have:

Point	Selective Code	Check Code
1	1	2
2	2	1
3	3	3
4	4	5
5	5	4

Operator or dispatcher wishes to select the first point. He therefore depresses $K1$. In time sequence, the operation at both the office and remote substation ends of the line wires are as follows:

Office	Substation
1. $K1$ closed (to send code 1)	
2. Relay 7 pulls (through b contact of relay 3) (puts positive battery on line) (Relay 9 holds, being slow-releasing)	
3. Relay 1 pulls. (Relay 6 also holds)	Relay 1 pulls (Relay 6 holds)
4. Relays 3 and 5 pull in series (Relay 3 locks in)	Relays 3 and 5 pull (Relay 3 locks in)
5. Relay 7 drops (Relay 9 locks in)	
6. Relay 1 drops. (Relay 5 holds in, slow) (Relay 6 locks)	Relay 1 drops (Relay 5 holds) (Relay 6 locks)
7. Relay $B1$ pulls. (Relay $B1$ locks in)	Relay $F1$ pulls (Relay $F1$ locks)
8. Relay 5 drops	Relay 5 drops
9. Relay 3 drops	Relay 3 drops

Thus when $K1$ is pressed, $B1$ at the office and $F1$ at the substation are energized.

The check back to the office is accomplished in exactly the same way, since the sending and receiving relay equipment is duplicated at each end. The proper selection is thus assured before any equipment in the remote station may be operated.

The operator then may set the twist key to the desired position (trip or close) and press the master control pushbutton. The trip or close code is sent to the substation in the same way previously described for the selection, which results in operating the remote unit. As the remote unit changes its position, a contact is made to send the supervision code to the office. Thus the lamps are changed on the dispatching board to correspond with the new position of the remote device.

When $K2$ is operated, relay 7 is not dropped when relay 3 pulls, because the circuit of $K2$ does not go through the b contact of relay 3, so relay 7 remains energized until relay 9 drops. Meanwhile, relay 6, which releases faster than relay 9, has dropped. As relay 7 drops, relay 1 is deenergized and $B2$ pulls since relay 6 is down. Then relay 5 drops, releasing relay 3. Relays 6 and 9 pull again and restore the circuit to its normal condition.

$K3$, when operated, functions the same as $K1$, except that relay 8 is pulled by relay 3. As soon as relay 7 drops, relay 8 puts the negative impulse on the line, pulling relays 2 and 4 at each end. Relay 4 opens the circuit of relay 8, which drops and stops the negative pulse. Relay 2 drops selecting relay $B3$. Relay 5 drops and releases relays 3 and 4.

Pushbuttons $K4$ and $K5$ operate like $K1$ and $K2$ except that relays 8, 2, and 4 pull instead of relays 7, 1, and 3. Thus, relays $B4$ and $B5$ are selected.

The junior equipment uses scheme A (Fig. 3) for the 4 steps of operation (selection, check, operation, supervision). On applications where the junior equipment cannot be applied, such as those requiring more than 5 points, scheme D (Fig. 6) usually is used.

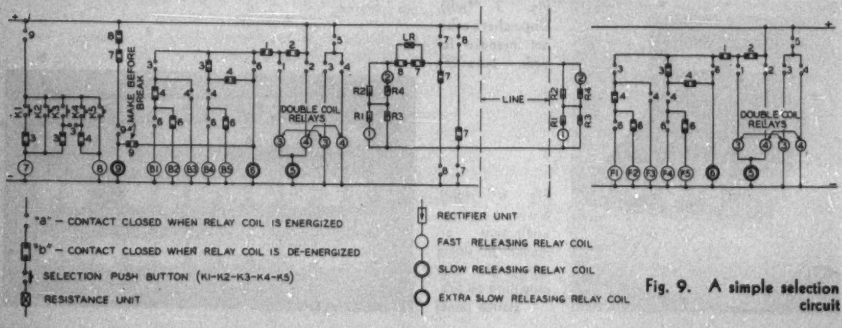


Fig. 9. A simple selection circuit

Selsyn Instruments for Position Systems

By
T. M. LINVILLE
ASSOCIATE A.I.E.E.

J. S. WOODWARD
ASSOCIATE A.I.E.E.

General Elec. Co.,
Schenectady, N. Y

Selsyn instruments are miniature salient pole synchronous machines excited by alternating current. They are used to transmit electrically, to one or several of the instruments acting as the receivers, the rotation given to another of the instruments acting as a transmitter. This paper presents a study of the behavior and accuracy of these instruments at standstill and under synchronous rotation giving results equally applicable to large Selsyn power motors and generators. The data presented are useful in connection with the problems of remote control, synchronous coupling of power drives, the transmission of indicating signals, or remote metering.

STRUCTURALLY a Selsyn device may have several variations of form but the instrument type, in particular, is simply a small salient pole synchronous machine. The transmitter-receiver system consists of one or more miniature synchronous motors (receivers) whose 3-phase armatures are connected to a second synchronous machine operating as a generator or transmitter. The transmitter may be of identical size or larger if several receivers are connected. The field windings are excited in parallel with alternating current, instead of direct current as for synchronous machines, to provide a synchronizing torque when both the receiver and the transmitter are at standstill. This characteristic distinguishes the Selsyn motor from the synchronous motor.

The manner in which the instruments are connected in a simple system consisting of one transmitter and one receiver is shown in Fig. 1. The secondary winding is a 3-phase winding generally connected in wye. The primary winding is usually a coil winding on salient poles. However, a uniform, smooth air gap may be used with the primary winding either a single-phase distributed winding or a 3-phase winding. Still other variations of form have been suggested and used but these are special instruments of no general interest.

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Paper submitted March 23, 1934; released for publication May 3, 1934. *Not published in pamphlet form.*

The 2 instruments of a Selsyn system as shown in Fig. 1 will maintain duplicate positions, when either one or the other is moved, due to an action which can be explained as follows. When the rotating members are in corresponding positions the voltage induced in the secondary winding of one instrument balances that induced in the secondary of the other. Therefore, no secondary current flows. If either instrument is turned out of the position of correspondence the sum of the voltages is no longer zero and a current flows in the secondary windings. This produces a torque causing the other instrument to turn and restore the balance of the voltages. Thus duplicate positions are maintained. Of course, if the secondary voltages of the 2 instruments are inherently not equal a secondary current will always flow. But when the instruments are in duplicate positions none of this secondary current is in the cross axis with respect to either rotor and, therefore, there is no torque. However, when one instrument is turned out of the duplicate position, a component of the secondary current creates a cross field in each instrument. A torque results which turns the instruments to duplicate positions.

Noteworthy applications of Selsyn instruments, in large numbers, have been for remote control purposes. In the field of theater lighting they have made possible smooth variation of effects and simultaneous or independent operation of lighting units. Greater flexibility and easier control have been gained. The Chicago Civic Opera House is an outstanding example. On board ships they are used for signaling from the bridge to engine room

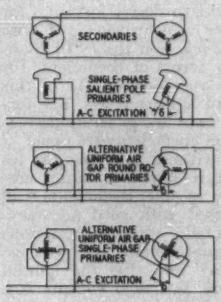


Fig. 1. Diagram of windings and connections for Selsyn system

and for the control of searchlights and other apparatus. In the industry they are used to indicate or control the position of valves, etc., and for signaling between operating stations. In the power generation field they have been used for remote metering, measuring of water levels at different points, measuring of the contents of storage tanks, as remote tachometers, and for many miscellaneous purposes. For public works their noteworthy usefulness is for the control of lift bridges or drawbridges where the 2 ends or halves must be synchronized. As specific meters, indicators, or recorders their uses have been extensive.

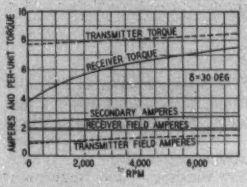


Fig. 2. Speed-torque curves of Selsyn instruments developing 0.3 hp at 7,000 rpm

Because the success of the instruments depends upon the accuracy of the receiver in duplicating the motion of the transmitter it is important that the torque-angle characteristic be known. Moreover in order to build highly accurate and sensitive devices it is necessary to know the influence of the different features of the construction. And, furthermore, the prospective user must be aware of any latent behavior such as oscillation or asynchronous torque. In the following analyses formulas are developed for the various forms of Selsyn instruments determining the standstill torque, current, and power input as a function of the displacement angle between the positions of the rotors. Then the speed term is introduced to derive formulas for the same functions under synchronous rotation. They are derived by the 2-reaction theory of Blondel[1] and are expressed in terms of coefficients for which expressions are given in Section III of this paper, covering the case of salient poles. The formulas for the round rotor case are given as derivatives in which the 2-reaction coefficients are equal.

Saturation is neglected without affecting the results appreciably. Where it must be taken into account judicious shading of the coefficients will allow the method to be used with good accuracy. Core loss is likewise neglected. Other assumptions are that the armature magnetomotive force is sinusoidally distributed in space and that the mutual inductance of the armature and field circuits is a first harmonic only with respect to the electrical space angle.

Results

The magnitude of the torque tending to maintain duplicate positions is, of course, most important. The strength of this torque when salient poles are used compared with that when the air gap is uniform is an important question. It is also valuable to know the strength of the torque when single-phase excitation is used compared to that when the primary windings are 3 phase. The foremost results are the expressions which make it possible to calculate accurately the torque under these various conditions. Space does not permit illustration of all the features of the performance of the instruments but several important conclusions and illustrations of the calculations may be made.

The synchronizing torque of the salient pole instrument exceeds that of the uniform air gap type* under normal conditions even when there is a short circuited winding in the quadrature axis. It is true that such a winding reduces the quadrature reactance and increases the torque as is indicated by eq 24 where, for practical purposes, $Z_q = x_q$. Actually, however, the leakage reactance and the resistance of the winding prevents as large an increase in torque as results when salient poles are used.

At standstill the synchronizing torque of the salient pole type exceeds that of uniform air gap instruments with 3-phase excitation. This is due in part to the addition of a reluctance torque which does not exist in the 3-phase case. This statement, of course, is subject to the details of the design but is true for ideal conditions with equal physical sizes.

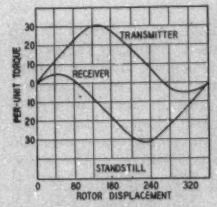
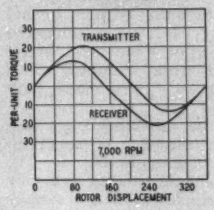
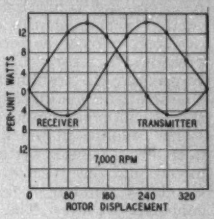


Fig. 3 (left, above and below). Torque-angle performance of Selsyn instruments designed for 0.3 hp at 7,000 rpm

Fig. 4 (below). Power-angle performance showing watts returned to the line by receiver with 3-phase excitation





When rotating, the synchronizing torque of the 3-phase unit increases as the speed of rotation, against the phase rotation, is increased (Fig. 2). The torque of the single-phase unit, either salient pole or uniform air gap, diminishes as the speed is

1. For all references see list at end of paper.

* Analysis of the uniform air gap type is particularly important when standard, wound rotor, induction motors are applied for duplicate position systems of large power.

increased, with equal effect for either direction of rotation. For these reasons position indicating instruments have salient poles while continuously rotating instruments are most satisfactory with uniform air gaps and 3-phase excitation. However, the salient pole type is sometimes more desirable when the rotation must be in either direction. This is true because the torque with 3-phase excitation diminishes more rapidly as the speed increases, when rotation is in the direction of the phase rotation.

In general, the torque angle curves of the transmitter and the receiver will not coincide for either the salient pole or uniform air gap types with either 3-phase or single-phase excitation (Fig. 3). With 3-phase excitation the curves have the maximum difference at standstill and approach similarity as the speed increases. With single-phase excitation the curves are identical at standstill, diverge as the speed of rotation increases, and approach similarity again as the speed is raised above synchronous speed. They do not have so great a divergence as in the 3-phase case. This is another feature making it sometimes desirable to use salient poles for rotating instruments as the average torque of the transmitter and the receiver, and especially the receiver torque, is greater. This is particularly true when the maximum speed is considerably less than the synchronous speed (under about one-half).

Usually both the transmitter and the receiver draw electrical power from the supply lines. However, above certain speeds electrical power is pumped into the lines by the receiver while the transmitter draws power from the lines (Fig. 4). In this case there is a transfer of electrical power through the system. Mechanical and electrical energy are delivered to the transmitter and both forms of energy compose the output of the receiver.

The ability of Selsyn instruments to hold 2 or more remotely located shafts in synchronism as though they were geared, either at standstill or when continuously rotating, opens up a wide field of application. Heretofore, this field has been limited to those applications which could be filled by mechanical devices such as gears, chains, belts, etc.

The following 3 sections of the paper comprise the general analysis of the instruments and give the formulas for calculating their performance. The results have been substantiated by comparison of calculated and tested performance of the instruments.

Part I—Standstill Torque-Angle Characteristics

Single-Phase Salient Poles

Approximate equations for current and torque may be established directly from synchronous machine theory. However, the following analyses are built up from fundamental laws in order to establish a theory especially adapted to Selsyn instruments, including the important effect of the resistance of the windings.

The method used is to write the vector equations for the primary and secondary circuits according to Kirchoff's laws using the applied voltage as the axis of reference. These equations determine the

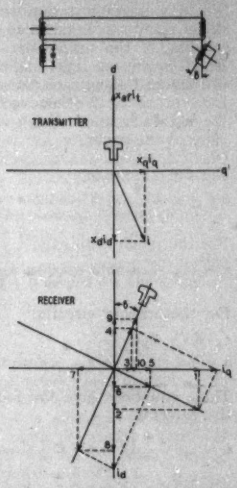


Fig. 5. Equivalent circuit and space diagram of flux linkages for salient pole instruments at standstill

1 = $x_q i_q \cos^2 \delta$
2 = $x_q i_q \sin \delta \cos \delta$
3 = $x_d i_q \sin^2 \delta$
4 = $x_d i_q \sin \delta \cos \delta$
5 = $x_q i_d \sin \delta \cos \delta$
6 = $x_q i_d \sin^2 \delta$
7 = $x_d i_d \sin \delta \cos \delta$
8 = $x_d i_d \cos^2 \delta$
9 = $x_d i_r \cos \delta$
10 = $x_d i_r \sin \delta$

currents in terms of which the torque is expressed. The magnetomotive forces and flux waves are sinusoidal in space and, therefore, can be split into components along space axes using the sine and cosine as multipliers. Time relations are expressed by complex quantities related to the exciting voltage. Space relations are expressed by simple quantities along 2 axes in space quadrature.

Selsyn instruments of any type, either with 3-phase or single-phase excitation and with salient poles or uniform air gaps, are represented by the circuits of Fig. 1. This is the basic system of one indicating or receiving instrument connected to one transmitting unit. The excited or primary members, in the case of single-phase excitation, may have a short-circuited winding in quadrature with the exciting winding. This may be in the form of a bar winding (amortisseur bars in the pole face) or a winding wound in slots, or a winding formed by short circuiting 2 terminals of a 3-phase wye or delta-connected winding. In the latter case single-phase excitation is applied from one terminal to the other 2 connected together. These forms of quadrature windings are included in Fig. 1. They reduce the quadrature impedance of the secondary winding but this effect may be accounted for in the calculation of the quadrature impedance of Section III. The presence of such windings does not alter the analysis.

The reactance voltage present in the secondary circuits may be expressed by the components illus-

trated in Fig. 5. This figure is a space diagram showing the resolution of the secondary current into components in the axes of symmetry of the 2 machines. When these components are multiplied by the reactance coefficients in the respective axes the reactance voltages in each axis are determined. These voltages are shown in the diagram. The direct space axis is taken as the axis of the primary winding of the transmitter. The quadrature axis is, of course, at right angles to it. The voltages are summed along each axis separately and equated to zero, giving 2 (time vector) equations. All of the nomenclature is listed in the appendix at the close of the paper.

For the direct axis:

$$0 = j(x_d i_d + x_d i_d \sin^2\delta + x_d i_d \cos^2\delta + x_d i_q \sin\delta\cos\delta - x_q i_q \sin\delta\cos\delta + i_r x_{af}\cos\delta + i_s x_{af}) + 2r_a i_d \quad (1)$$

For the quadrature axis:

$$0 = j(x_q i_q + x_d i_q \sin^2\delta + x_q i_q \cos^2\delta + x_d i_d \sin\delta\cos\delta - x_q i_q \sin\delta\cos\delta + i_r x_{af}\sin\delta) + 2r_a i_q \quad (2)$$

For the primary circuits:

$$e = Z_f i_s + jx_{af} i_d \quad (3)$$

$$0 = Z_f i_r + jx_{af} i_d \cos\delta + jx_{af} i_q \sin\delta + e \quad (4)$$

These equations give the following expressions for the currents:

$$i_d = \frac{jx_{af} e}{B^2 - AC}(B\sin\delta + C - C\cos\delta) \quad (5)$$

$$i_q = \frac{-jx_{af} e}{B^2 - AC}(A\sin\delta + B - B\cos\delta) \quad (6)$$

$$i_s = \frac{1}{Z_f}(e - jx_{af} i_d) \quad (7)$$

$$i_r = -\frac{1}{Z_f}(e + jx_{af} i_d\cos\delta + jx_{af} i_q \sin\delta) \quad (8)$$

where:

$$A = jZ_f(x_d + x_q\sin^2\delta + x_d\cos^2\delta) + x^2_{af}(1 + \cos^2\delta) + 2r_a Z_f \quad (9)$$

$$B = (jZ_f(x_d - x_q) + x^2_{af})\sin\delta\cos\delta \quad (10)$$

$$C = jZ_f(x_q + x_d\sin^2\delta + x_q\cos^2\delta) + x^2_{af}\sin^2\delta] + 2r_a Z_f \quad (11)$$

In the majority of applications the displacement angle δ is small. Under these conditions:

$$A = 2(Z_f Z_d + x_{af}^2) \quad (12)$$

$$B = (Z_f Z_d - Z_f Z_q + x_{af}^2)\sin\delta \quad (13)$$

$$C = 2Z_f Z_q \quad (14)$$

$$i_q = \frac{jx_{af}\, e\, A\sin\delta}{AC} \quad (15)$$

or

$$i_q = \frac{jx_{af}\, e\sin\delta}{2Z_f Z_q} \quad (16)$$

and $I = e/Z_f$ = exciting current. (17)

These results, apparent from physical reasoning, are useful in determining the torque for small angles.

It is physically evident and has already been established (eq 19 of reference 2) that the torque is given by:

$$T = I_q\Psi_d - I_d\Psi_q \quad (18)$$

where

$$\Psi_d = x_{af} I + x_d I_d \quad (19)$$

$$\Psi_q = x_q I_q \quad (20)$$

The reference equation for Ψ_q has a term representing quadrature, primary, excitation. Although the general case, including that of a short-circuited primary winding in the quadrature axis is under consideration, the formulas for reactance (Section III) give the combined quadrature impedance for the secondary. Therefore, in case of a quadrature, primary circuit, x_q in eq 20 above must be the reactive component of Z_q', eq 73.

From eqs 18, 19, and 20, the torque is the sum of the scalar products:

$$T = x_{af} I \cdot i_q + x_d i_d \cdot i_q - x_q i_q \cdot i_d \quad (21)$$

For small angles i_d is negligible so that the torque is given by:

$$T = x_{af} I \cdot i_q \quad (22)$$

This is the electrical torque due to the primary and secondary currents. The reluctance torque terms are negligible. Substituting eqs 16 and 17:

$$T = \frac{(jx^2_{af}\, e\sin\delta)}{2Z_f Z_q} \cdot e/Z_f \quad (23)$$

Taking the scalar product:

$$T = v^2 x_q \sin\delta/2Z^2_q \quad \text{synchronous watts} \quad (24)$$

where v is the normal secondary voltage ($= jx_{af}e/Z_f$).

The total torque is obtained when line-to-line values for the coefficients of the 3-phase winding are used.

Single-Phase Round Rotor

The formulas are the same as for the salient pole case except that here:

$$Z_a = Z_d = Z_q \quad (25)$$

$$A = 2Z_f Z_a + x^2_{af}(1 + \cos^2\delta) \quad (26)$$

$$B = x^2_{af}\sin\delta\cos\delta \quad (27)$$

$$C = 2Z_f Z_a + x^2_{af}\sin^2\delta \quad (28)$$

Three Phase

For this case there is only the one coefficient, Z_a of secondary impedance to be considered. Currents are considered to be established by excitation of one unit only with the primary of the other unit under 3-phase short circuit. Currents are then superposed for simultaneous excitation of both units. As the short circuit of the primary winding is 3 phase there is no displacement angle to be taken into account until superposition is made. All vectors are time vectors.

Voltages appearing in the secondary circuits are:

$$2Z_a i_a + jx_{af}(i_s + i_r) = 0 \quad (29)$$

Voltages appearing in the primary circuits are:

$$e = Z_f i_s + jx_{af} i_a \quad (30)$$

$$0 = Z_f i_r + jx_{af} i_a \quad (31)$$

Solution of these equations gives:

$$i_t = A/D \tag{32}$$

$$i_r = C/D \tag{33}$$

$$i_a = B/D \tag{34}$$

where

$$A = 2Z_aZ_f + x_{af}^2 \tag{35}$$

$$B = -jx_{af}Z_f \tag{36}$$

$$C = -x_{af}^2 \tag{37}$$

$$D = 2Z_f(Z_fZ_a + x_{af}^2) \tag{38}$$

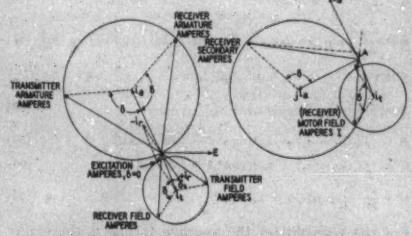


Fig. 6 (left). Time phase vector diagram showing the current loci of 3-phase Selsyn instruments at 7,000 rpm

Fig. 7 (right). Graphical calculation of torque for 3-phase instruments

Torque = (scalar projection of secondary amperes on the field amperes, A) (scalar length of the field amperes) (mutual inductance, x_{af})

With rotation of the transmitter in the direction of the phase rotation the net currents are:

For the transmitting instrument:

$$I_t = A/D - C/D\,(\cos\delta - j\sin\delta) \tag{39}$$

$$I_a = B/D(1 - \cos\delta - j\sin\delta) \tag{40}$$

For the receiving instrument:

$$I_r = A/D - C/D\,(\cos\delta + j\sin\delta) \tag{41}$$

$$I_a = B/D(1 - \cos\delta - j\sin\delta) \tag{42}$$

All of the vectors are referred to the excitation voltage.

Since $i_d = i_a$ and $i_q = ji_a$ the torque from eq 21 is:

$$T_t = jx_{af}i_a \cdot I_t \qquad \text{synchronous watts} \tag{43}$$

The receiver torque is:

$$T_r = jx_{af}I_a \cdot I_r \qquad \text{synchronous watts} \tag{44}$$

If the coefficients and exciting voltage are line-to-line values the total torques in inch-ounces are obtained when the results of eqs 43 and 44 in synchronous watts, are multiplied by K where:

$$K = (8{,}500\sqrt{3})/2\pi n_s \tag{45}$$

where n_s is the synchronous revolutions per minute. The term, $\sqrt{3}$, becomes 3 if the coefficients and the exciting voltage are line-to-neutral values.

The formulas neglect the core loss but otherwise are the same as would be obtained from the usual induction motor circuit (see reference 3).

The calculations may be made graphically, if desired, by use of the circle diagrams shown in Fig. 6. It is obvious from eqs 39 to 42 that the current loci are circles. In the torque calculation, Fig. 7, the secondary current circle is rotated 90 deg in the direction of the phase rotation. The circumference of each circle is divided into as many divisions as steps of δ are to be taken and the vectors are drawn for each step. For any value of δ, either the primary or secondary vector is scaled as is the perpendicular projection of the other upon it. The product of the 2 measurements is then taken and multiplied by x_{af} giving the torque in synchronous watts. The method is subject to inaccuracy due to the fact that the scalar product is taken at nearly a 90-deg angle for some values of δ. However, it is an excellent method for calculating torque-angle curves since points which are out of line are readily detectable.

N-Unit Systems

When receiving instruments are connected in parallel to a larger transmitter there are a number of variations to be considered.

First there is the case of all receivers being disconnected except one, when the coefficients of the transmitter and receiver will not be alike. In this case there are the coefficients Z_{at}, Z_{qt}, Z_{ar}, Z_{qr}, Z_{ft}, Z_{fr}, x_{aft}, x_{afr} to be considered in the single-phase case and Z_{at}, Z_{qt}, Z_{ft}, Z_{fr}, x_{aft}, x_{afr} in the 3-phase case. The subscripts t and r indicate the transmitter and receiver respectively. The solution is obtained identifying the coefficients of eqs 1, 2, 3,4, 29, 30, and 31 by this nomenclature, and proceeding as before.

Secondly, there is the case of similar receivers operating simultaneously with one transmitter. In this case the general nomenclature just given is to be used and all coefficients for the receivers are to be divided by the number of parallel units, n. With these coefficients the current and torque of the transmitter is obtained. The total current for all of the receivers, primary or secondary is n times the current for any one. The torque is likewise n^2 times the torque of any one.

Finally there is the case of unlike receivers in parallel, operating with one transmitter. There is little need for the solution of this case although it is easy to obtain when the coefficients of the transmitter are small compared to those for any receiver. In this case the voltage of the secondary system is taken to be fixed assuming the transmitter to have negligible (zero) impedance. The coefficients for the transmitter drop out of the equations and the equation for the primary circuit of the transmitter vanishes. The remaining equations are solved as before and the results substituted in the expression for torque.

Other variations have been suggested but as yet they have little value and are beyond the scope of this paper.

Part II—Torque-Angle Characteristics With Synchronous Rotation

Single Phase, Salient Poles

When the primary or secondary rotates, relative to the other, with a constant speed of n rpm, the armature current is composed of 2 balanced phase currents rotating with positive and negative phase sequence when n is less than the synchronous revolutions per minute. One moves at the speed $(s + 1)$ and the other at $(s - 1)$ where s is $np/120f$; f is the excitation frequency; and the speed is expressed as a fraction of the synchronous speed $120f/p$.

The balanced 3-phase magnetomotive forces rotating over the poles are resolved into components pulsating with respect to the poles in the 2 axes of symmetry. For example, a secondary current i_f, rotating at speed $(1 + s)$ with the rotor moving at speed s is represented by a pulsating component i_f in the direct axis and by ji_f in the quadrature axis, each component pulsating at normal frequency. Likewise a current i_b, rotating at $(s - 1)$, is represented by components, pulsating at normal frequency, i_b in the direct axis and $-ji_b$ in the quadrature axis. In Fig. 8 these components are shown for both the transmitter and receiver. Since the direct and quadrature space axes are taken as those of the transmitter, the components must be resolved onto the symmetrical axes of the receiver, giving 8 pulsating magnetomotive forces or currents in the axes of the receiver whereas there are only 4 for the transmitter. Each of the components is multiplied by the reactance coefficient of its respective axis, giving components proportional to flux at normal frequency. These components in the receiver are then resolved back into the space axes q and d of Fig. 8 and summed up for each axis. The final components are given in the figure. The summation for the direct axis is:

$$\begin{aligned}\Psi_d = {} & i_b(x_d + x_d\cos^2\delta + x_q\sin^2\delta) - ji_b(x_d - x_q)\sin\delta\cos\delta \\ & + i_f(x_d + x_d\cos^2\delta + x_q\sin^2\delta) + ji_f(x_d - x_q)\sin\delta\cos\delta + x_{af}i_i + x_{af}i_r\cos\delta \end{aligned} \tag{46}$$

and for the quadrature axis:

$$\begin{aligned}\Psi_q = {} & -ji_b(x_q + x_d\sin^2\delta + x_q\cos^2\delta) + i_b(x_d - x_q)\sin\delta\cos\delta + ji_f(x_q + x_d\sin^2\delta + x_q\cos^2\delta) + i_f(x_d - x_q)\sin\delta\cos\delta + x_{af}i_r\sin\delta \end{aligned} \tag{47}$$

These are pulsating flux linkages in each axis. They are converted to the rotating components,

$$\Psi_f = (\Psi_d - j\Psi_q)/2 \tag{48}$$

$$\Psi_b = (\Psi_d + j\Psi_q)/2 \tag{49}$$

and are multiplied, respectively, by $j(1 + s)$ and $-j(s - 1)$ to obtain the voltage produced in the secondary at the 2 frequencies. To each is added the (ir) voltage and the sums equated to zero. Two equations result for the secondary circuit:

$$0 = \{4r_a/(1 + s)\}i_f + j\Psi_f \tag{50}$$

$$0 = \{4r_a/(s - 1)\}i_b - j\Psi_b \tag{51}$$

The field or primary equations are,

$$e = Z_f i_r + jx_{af}(i_f + i_b) \tag{52}$$

$$0 = Z_f i_r + jx_{af}(\cos\delta + j\sin\delta)i_f + jx_{af}(\cos\delta - j\sin\delta)i_b + e \tag{53}$$

Simultaneous solution of these equations gives:

$$i_f = \frac{jx_{af}\,e}{2(BC - AD)} \times \Big[D(1 - \cos\delta + j\sin\delta) - B(1 - \cos\delta - j\sin\delta)\Big] \tag{54}$$

$$i_b = \frac{jx_{af}\,e}{2(BC - AD)} \times \Big[A(1 - \cos\delta - j\sin\delta) - C(1 - \cos\delta + j\sin\delta)\Big] \tag{55}$$

$$i_i = \frac{e}{Z_f} - \frac{jx_{af}}{Z_f}(i_f + i_b) \tag{56}$$

$$i_r = \frac{-1}{Z_f}\Big\{e + jx_{af}(\cos\delta + j\sin\delta)i_f + jx_{af}(\cos\delta - j\sin\delta)i_b\Big\} \tag{57}$$

where

$$A = \frac{2r_aZ_f}{1 + s} + jZ_f(x_d + x_q) + x_{af}^2 \tag{58}$$

$$B = \{jZ_f(x_d - x_q) + x_{af}^2\}(\cos^2\delta - j\sin\delta\cos\delta) \tag{59}$$

$$C = \{jZ_f(x_d - x_q) + x_{af}^2\}(\cos^2\delta + j\sin\delta\cos\delta) \tag{60}$$

$$D = \frac{2r_aZ_f}{1 - s} + jZ_f(x_d + x_q) + x_{af}^2 \tag{61}$$

For the transmitter the average torque is the scalar product

$$T_t = jx_{af}(i_f - i_b)\cdot i_i + j(x_d - x_q)(i_b + i_f)\cdot(i_f - i_b) \tag{62}$$

and for the receiver:

$$T_r = \{jx_{af}i_r + j(x_d - x_q)\{i_f(\cos\delta + j\sin\delta) + i_b(\cos\delta - j\sin\delta)\}\cdot\{i_f(\cos\delta + j\sin\delta) - i_b(\cos\delta - j\sin\delta)\}\} \tag{63}$$

The torque expressions are immediately apparent from eq 21 where $i_d = (i_f + i_b)$ and $i_q = j(i_f - i_b)$.

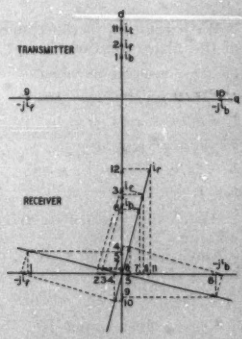


Fig. 8. Space diagram of flux linkages for salient pole instruments under rotation

DIRECT AXIS LINKAGES

1 = i_bx_d
2 = i_fx_d
3 = $i_fx_d\cos^2\delta$
4 = $-ji_bx_d\sin\delta\cos\delta$
5 = $-ji_fx_q\sin\delta\cos\delta$
6 = $i_bx_d\cos^2\delta$
7 = $i_fx_q\sin^2\delta$
8 = $i_bx_q\sin^2\delta$
9 = $ji_bx_q\sin\delta\cos\delta$
10 = $ji_fx_q\sin\delta\cos\delta$
11 = $x_{af}i_r$
12 = $x_{af}i_r\cos\delta$
(Field) = $x_{af}(i_f + i_b)$

QUADRATURE AXIS LINKAGES

1 = $ji_fx_q\cos^2\delta$
2 = $-i_fx_q\sin\delta\cos\delta$
3 = $-i_bx_q\sin\delta\cos\delta$
4 = $ji_fx_d\sin^2\delta$
5 = $-ji_bx_d\sin^2\delta$
6 = $i_fx_d\sin\delta\cos\delta$
7 = $i_bx_d\sin\delta\cos\delta$
8 = $-ji_bx_q\cos^2\delta$
9 = ji_fx_q
10 = $-ji_bx_q$
11 = $x_{af}i_r\sin\delta$
(Field) = $x_{af}i_r(\cos\delta + j\sin\delta) + x_{af}i_b(\cos\delta - j\sin\delta)$

To determine the torque of the receiver from eq 21 the currents i_j and i_k must first be rotated into the symmetrical axes of the receiver using the operators of eq 53.

In the case of a round rotor, $x_d = x_q = x_s$. For a number of receivers in parallel the solution is made the same as indicated for the standstill case.

Three Phase

The formulas are identically the same as those given for the standstill case where,

$$Z_s = \frac{r_s}{1+s} + jx_s \tag{64}$$

in eq 35 and 38. s is the per unit revolutions per minute and is positive when rotation is in the direction of the phase rotation. For negative rotation the sign of the j terms in eqs 39 to 42, inclusive, must be reversed.

Part III—Reactances

The reactances of Selsyn instruments are the same as those of synchronous machines;[4] accordingly they are calculated by methods established already. As a guide, the basic formulas will be given, omitting the elaboration sometimes used for accurate calculations in design. Each formula for 3-phase windings gives the reactance from line to line with wye connection.

Direct Axis, Line to Line, 3-Phase Reactance

$$x_{ad} = \sqrt{3}\,\omega\ \phi_{ad} N_s K_s\, 10^{-8}$$

where

ω = $2\pi f$
f = frequency of excitation supply
N_s = turns/phase
K_s = combined pitch and distribution factor
ϕ_{ad} = flux of armature reactance

$$= \frac{2A\ A_{dB} B_g}{F_g}$$

A = peak of armature reaction ampere turns

$$= \frac{4}{\pi}\sqrt{3}\ N_s K_s$$

A_{dB} = ratio of maximum density of fundamental flux to maximum density of actual flux when armature is excited with a sine wave magnetomotive force (Fig. 13 of reference 5)
B = maximum density of normal field flux with armature circuit open
A_g = area of gap per pole
F_g = normal field, air gap, ampere turns (peak value)

The combined formula is:

$$x_{ad} = \frac{24\omega}{\pi^2}\frac{A_{dB} B A_g N_s^2 K_s^2}{F_g}\, 10^{-8} \text{ ohms} \tag{65}$$

Quadrature Axis, Line to Line, 3-Phase Reactance

$$x_{aq} = x_{ad}\left(\frac{1 + C_s C_d}{2}\right) K_q \tag{66}$$

where K_q is obtained from Fig. 1 and C_s and C_d are respectively slot and duct coefficients from Fig. 2 of reference 5.

Direct Synchronous Reactance

$$x_d = x_{ad} + x_l \tag{67}$$

where x_l is the leakage reactance[6]

Quadrature Synchronous Reactance

$$x_q = x_{aq} + x_l \tag{68}$$

Single-Phase Field Reactance

$$x_f = \omega\phi N_f 10^{-8} = \frac{2\omega}{\pi}\frac{A_{dB} B\ A_g N_f^2 K_\phi}{F_g}(1 + K_l)10^{-8} \text{ ohms} \tag{69}$$

where

N_f = total field turns in series for all poles
K_ϕ = ratio of the area of the actual exciting flux wave to the area of its fundamental (see Fig. 10 of reference 5)
K_l = pole leakage factor (see Fig. 7, Part II of reference 5)

Direct Secondary Impedance

$$Z_d = r_a + jx_d \tag{70}$$

where

r_a = resistance line to line
= 2 times lag resistance

The line resistance may be added to r_a if desired in which case the resistance of one full length line is added.

Quadrature Secondary Impedance

$$Z_q = r_a + jx_q \tag{71}$$

Mutual Reactance Between Primary and Secondary

$$x_{af} = \sqrt{3}\omega\phi K_s N_s\, 10^{-8} = \frac{2\sqrt{3}\omega}{\pi}\frac{A_{dB} A_g B}{F_g} N_f N_s K_s\, 10^{-8} \text{ ohms} \tag{72}$$

Quadrature Secondary Impedance With a Short-Circuited, Quadrature, Primary Winding

$$Z_q' = \frac{(r_a + jx_q)(r' + jx') + (x_{af}')^2}{(r' + jx')} \tag{73}$$

where

r' = resistance of shorted winding

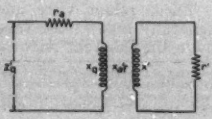


Fig. 9. Circuit for quadrature axis with a short-circuited primary circuit

x' = reactance of shorted winding
x_{sf}' = mutual reactance between secondary and shorted primary windings

To determine these coefficients the formulas already given for 3-phase or single-phase windings are applied with a change of constant if necessary to fit the type of winding

The impedance Z_s' will be recognized as that of the circuit of Fig. 9.

PRIMARY IMPEDANCE

$$Z_f = r_f + jx_f \tag{74}$$

Appendix—List of Symbols

(All coefficients for 3-phase windings are line to line)

e = primary, exciting, voltage
i_a = armature or secondary line current
I_d = i_d = direct axis component of i_a
i_b = balanced 3-phase secondary current of phase sequence frequency $(s - 1)$
i_f = balanced 3-phase secondary current of positive phase sequence at $(1 + s)$
I_q = i_q = quadrature axis component of i_a
i_r = primary or field current of the receiver
i_t = primary or field current of the transmitter
I = net primary current of either receiver or transmitter
n = speed of rotation in revolutions per minute
P = number of poles
r_a = armature or secondary resistance
r_f = field or primary resistance
s = per-unit speed of rotation
v = secondary (armature) voltage
x_a = reactance of armature for uniform air gap instruments
x_{ad} = reactance of armature (secondary) reaction in the direct axis for salient pole instruments
x_{aq} = reactance of armature reaction in quadrature axis
x_{af} = mutual reactance between armature (secondary) and field (primary) windings
x_d = total armature reactance in the direct axis
x_f = reactance of field (primary) winding
x_l = leakage reactance of the armature winding
x_q = total armature reactance in the quadrature axis
Z_a = armature (secondary) impedance with uniform air gap
Z_d = direct axis armature impedance = $r_a + jx_d$
Z_f = field (primary) winding impedance = $r_f + jx_f$
Z_q = quadrature axis armature impedance = $r_a + jx_q$
δ = displacement angle between space positions of the rotors
Ψ_d = direct axis secondary flux linkages
Ψ_q = quadrature axis secondary flux linkages

References

1. SYNCHRONOUS MACHINES—PART 1. AN EXTENSION OF BLONDEL'S TWO-REACTION THEORY, R. E. Doherty and C. A. Nickle. A.I.E.E. TRANS., v. 45, 1926, p. 912–47.

2. TWO-REACTION THEORY OF SYNCHRONOUS MACHINES, R. H. Park. A.I.E.E. TRANS., v. 48, 1929, p. 716–30.

3. INDUCTION MOTORS AS SELSYN DRIVES, L. M. Nowacki. ELEC. ENGG., v. 52, 1933, p. 848–53. (Important references are listed in the bibliography of this paper.)

4. THE REACTANCES OF SYNCHRONOUS MACHINES, R. H. Park and B. L. Robertson. A.I.E.E. TRANS., v. 47, 1928, p. 514–36. (This paper covers more extensive definitions than are necessary for Selsyn instruments. It is cited particularly for the references accompanying it.)

5. GRAPHICAL DETERMINATION OF MAGNETIC FIELDS, R. W. Wieseman. A.I.E.E. TRANS., v. 46, 1927, p. 430–7.

6. THE CALCULATION OF THE ARMATURE REACTION OF SYNCHRONOUS MACHINES, P. L. Alger. A.I.E.E. TRANS., v. 47, 1928, p. 493–513, formula 35.

7. LA JONCTION ELECTRIQUE "SIEMENS" ET SES APPLICATIONS AUX TELECOMMANDES, Albert Sorneis. *Rev. Gen. de L'Electricite*, v. 33, 1933, p. 651–63.

A Compensated Automatic Synchronizer

A relay for automatically synchronizing rotating machines has been developed which uses vacuum tubes to reduce mechanical adjustments, and which gives the closing indication at a constant time in advance of synchronism. This latter quality is shown to be required for rapid synchronizing with acceptable accuracy, in the absence of extremely accurate speed control. The theoretical requirements of such a synchronizer are derived mathematically in this paper, and a description of a relay which fulfills these requirements is given.

By
H. T. SEELEY
ASSOCIATE A.I.E.E.

General Electric Co., Philadelphia, Pa.

THE earliest automatic synchronizing probably was done in attended stations. It was not wholly intentional, for the relays had been installed only as protective devices to prevent bad synchronizing; but the operator's confidence increased to the point where it became natural to "pull the button early and let the relay do it."

These early installations provided experience under operating conditions so that the manufacturers felt ready to furnish the necessary synchronizing relays when (about 1922) some systems chose automatic operation for some of their largest units, where the familiar "pull-in" or "self-synchronizing" method would cause disruption of the system. Although different manufacturers produced different designs, most of these early relays appear to have performed only the following basic functions: (1) Prevent giving the closing indication if the average frequency difference exceeded a certain value; and (2) give the closing indication at a fixed angle in advance of synchronism, if the frequency difference permitted giving it at all. The function of bringing about approximate equality of frequency between the 2 sources was performed by separate devices, not treated in this paper.

These relays were adequate for the conditions generally met at the time of their design, and still have the inherent advantages of simplicity and low

Full text of a paper recommended for publication by the A.I.E.E. committee on automatic stations, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 26, 1934; released for publication April 27, 1934. *Not published in pamphlet form.*

cost which suggest their use on some of the less exacting of present-day installations where the same conditions exist. These conditions are (1) generating units of medium or high reactance, driven by prime movers stable at no load, and (2) tie lines not operating near the stability limit, where synchronizing angles of, say, 30 deg can be tolerated without inconvenience.

However, later experience, particularly with propeller type waterwheels, indicated that it was desirable (1) to vary the closing angle of the relay with the frequency difference so as to compensate for a constant breaker closing time, (2) to minimize the effect of voltage magnitudes on the closing angle and frequency difference setting of the relay, and (3) to increase the accuracy of frequency difference indication by reducing the angular zone in which the average is measured.

Relative Error of Fixed-Angle and Proportional-Angle Synchronizers

The maximum error with the fixed-angle type of relay results when the relative velocity of the 2 vectors is zero at the relay closing angle, but their acceleration a is the maximum possible during the synchronizing period. If the relay closing angle is θ_r and the breaker closing time T seconds, the angular error is

$$\theta_r + \frac{aT^2}{2} \tag{2}$$

(See appendixes for meaning of symbols and for derivation of equations.)

Feature (1) in the second paragraph preceding requires that the closing indication be given only when the angle θ is decreasing and has the value

$$\theta = sT \tag{3}$$

where s is frequency difference (hereinafter called "slip" for brevity) in degrees per second, and T is closing time in seconds of breaker plus control relay. This assumes constant closing time, and constant slip during this time; the rate of change of slip at the instant of giving the closing indication might be taken into account, but differences in closing time of the same breaker are difficult to estimate in advance. Variable closing time and variable slip during closure result in angular displacement at the instant the breaker contacts close. Simple means are available to prevent closing if this displacement is excessive and these same means make it unnecessary to take account of rate of change of slip.

Equation 3 shows that the relay closing angle should be advanced proportionally to the slip—a fact familiar to every operator with a little experience in synchronizing. The maximum error with a synchronizer having this characteristic is

$$\pm \frac{aT^2}{2} \tag{4}$$

It will be seen that this error is less than that of a constant angle synchronizer, by the amount of the constant angle θ_r of the latter. θ_r can be reduced to any reasonable value by suitable refinements, but to do so causes a proportional reduction in the maximum slip at which synchronizing can be accomplished. With erratic prime movers or slow breakers, this decreases the chances of synchronizing almost to zero.

An important fact brought out by these equations is that the difficulty of synchronizing (as measured by the angular errors encountered) increases in proportion to the square of the breaker closing time T. It appears, therefore, that a given percentage decrease in breaker closing time will improve synchronizing conditions more than an equal percentage decrease in acceleration obtained by improved governor adjustment or hydraulic conditions.

Operating Principle

The synchronizer described in this article was designed to meet the 3 requirements stated at the end of the introduction. Its operating principle is described in detail in the following pages, but may be summarized briefly as follows:

1. Phase angle is measured indirectly by measuring the vector difference between machine and bus voltages. (Fig. 1.)
2. The vector difference voltage is rectified to obtain a beat voltage of slip frequency instead of power frequency.
3. The rate of change of this slip-frequency beat voltage is measured by means of a transformer. (Fig. 2, Fig. 12.)
4. This rate-of-change voltage is subtracted from the beat voltage so that the resultant (after filtering out the ripple voltage) will cause a relay operation (through a compensated amplifier) at an angle of advance proportional to slip. (Fig. 12).
5. A circuit is included (Fig. 9) which compensates for differences in voltage magnitudes so that the beat voltage goes through zero (thus permitting synchronizing even at small slips) even if one voltage is above normal and the other below normal.
6. Cut-off (maximum permissible slip for synchronizing) is controlled by a simple instantaneous relay operated from beat voltage, together with an adjustable time auxiliary relay. (Fig. 12.) By this means the error in measurement of cut-off frequency can be reduced to a small value.

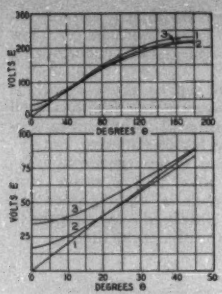
Compensation for Breaker Closing Time

The definite time interval required to allow for breaker closure could be provided by the following combination:

(a) An effect proportional to phase difference and source voltage magnitude.
(b) An effect proportional to slip (or rate of change of phase difference) and source voltage magnitude.

The desired advance time T may be obtained by adjustment of the proportionality factor of one or both, and by opposition of the effects to give a closing indication when (b) overcomes (a).

The first requirement is, then, to find some quantity proportional to phase difference; probably the oldest method of measuring phase difference is the vector difference method, using the "dark lamp" connection. In Fig. 1 is shown the relation between vector difference and phase angle. The condition of minimum bus voltage 0.85 times normal is commonly assumed in the design and application of control apparatus for industrial service, and we might further assume the generator voltage regulated to normal. However, the requirements for unattended installations are more severe, and operating limits of 0.8 to 1.1 times normal have usually been as-



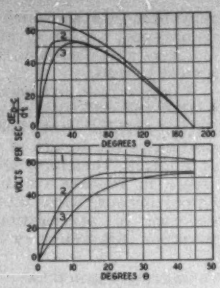


Fig. 1 (left). Vector difference versus phase angle

See eq 5 of appendix for definiton of E

Curve	Machine Voltage	Bus Voltage
1	Normal	Normal
2	Normal	0.85 Normal
3	1.1 Normal	0.8 Normal

Fig. 2 (right). Rate of voltage change versus phase angle. (slip = 36 deg per sec)

See eq 7 of appendix for definition of volts per second
See subcaption of Fig. 1 for meaning of curves 1, 2, and 3

sumed in this service. Figure 1 therefore shows the relation for each of these assumptions.

The next step is to produce a voltage proportional to slip, or to the rate of change of phase angle, which is simpler because we already have a quantity (vector difference) roughly proportional to phase angle and we need only measure its rate of change. However, the vector difference voltage is not of slip frequency, but of power frequency and is, therefore, not directly useful for our purpose. This difficulty can be overcome by rectifying and filtering the vector difference voltage, after which its rate of change is nearly proportional to the rate of change of phase angle (neglecting the ratio error of the rectifier, and the phase shift of the filter at slip frequency).

Assuming sinusoidal voltages, the form factor is 1.11, so the rectified but unfiltered vector difference voltage E_{d-c} at any angle (average value over a period of one cycle at power frequency) is 0.9 of the corresponding value shown in Fig. 1. The filter used in this application begins with a resistance much larger than that of the rectifier load, so the effect of the filter on the average value of voltage may be neglected. In Fig. 2 is shown the rate of change of this average at a slip of 36 deg per sec or 0.1 cycle per sec.

We may assume that this rate of change is measured in some manner which introduces a constant k such that with equal a-c voltages on the 2 sources being synchronized, the rate of change voltage $\frac{k\,dE_{d-c}}{dt}$ equals the d-c phase difference voltage itself at the maximum desired closing angle θ. If this equality is adjusted at 45 deg when operating at a slip

$$s = \frac{\theta}{T} = \frac{45}{T} \text{ (see eq 3)}$$

$$\text{then } k_{45\,\text{deg}} = 1.05\,T \tag{8}$$

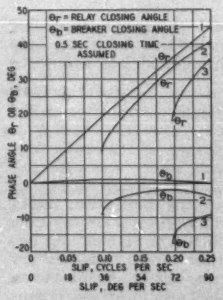
k is calculated for 45 deg because this is judged to be the largest angle of advance that will be required in any ordinary application. A breaker time of 0.5 sec is chosen as being slightly greater than average. These 2 values together determine 0.25 cycles per sec as the maximum permissible slip for synchronizing. However, these values are chosen only for illustration and will change from one installation to another.

In Fig. 3 are shown the relay closing angles θ_r and breaker closing angles θ_b calculated on the basis of a breaker closing time of 0.5 sec, for which $k = 0.5 \times 1.05 = 0.525$. The breaker closing angles are derived from the relay closing angles by the relation $\theta_b = \theta_r - sT$, assuming constant slip during breaker closure.

It will be noted that if the voltages are unequal there is a zone around zero slip, within which synchronizing cannot occur. The limits of this zone are at positive and negative slips

$$s = \frac{M^2 - B^2}{MB\,\pi K} \tag{10}$$

and are at the left ends of the curves for conditions 2 and 3 in Fig. 3.



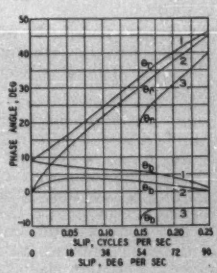


Fig. 3 (left). Theoretical characteristics of uncompensated vector difference synchronizer

See eq 9 of appendix for meaning of sin θ
See subcaption of Fig. 1 for meaning of curves 1, 2, and 3

Fig. 4 (right). Theoretical characteristics of vector difference synchronizer, compensated by constant bias for voltage inequality of 0.15 normal

See subcaption of Fig. 1 for meaning of curves 1, 2, and 3

If synchronizing must be performed down to practically zero slip with a voltage difference $M - B = C$ then a constant bias $0.9C$ may be subtracted from E_{d-c} so that the resultant will pass through zero at

zero degrees for this particular value of difference in magnitudes; this requires a readjustment of k.

The results of a graphic determination of characteristics under these conditions are given in Figs. 4 and 5, for the same assumed voltages and closing time as Fig. 3. (See Fig. 19 in appendix, for method.)

Compensation for Voltage Difference

A more flexible means of compensating for various differences in voltage magnitudes is to subtract from the rectified vector difference a d-c voltage which equals this rectified vector difference at zero degrees. The necessary d-c voltage may be obtained economically (see Fig. 6) by rectifying each of the voltages, opposing them against each other, and filtering them to remove the effect of phase angle. In order to make use of the difference between the voltages, it is necessary to shunt each rectifier by a resistor to pass the reverse current.

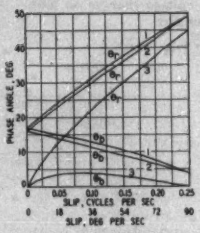


Fig. 5. Theoretical characteristics of vector difference synchronizer compensated by constant bias for voltage inequality of 0.3 normal

See Figs. 1 and 3 for meaning of curves and symbols

The polarity of this resultant still depends upon which source voltage is higher, so the desired effect is obtained only for a difference in one direction, and the opposite effect results from a difference in the other direction. It is therefore necessary to rectify the resultant, as indicated in Fig. 6, thus obtaining a d-c voltage of fixed polarity and of magnitude proportional to the arithmetical difference between the voltages.

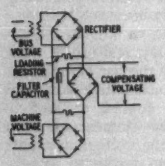


Fig. 6. Circuit for automatic compensation for voltage inequality

Subtracting this inequality voltage from the vector difference voltage, the resultant is always zero at zero degrees, no matter whether the voltage inequality is zero or a larger value.

The possible inoperative zone near zero slip (defined by eqs 10 and 11) is thus eliminated. The characteristics calculated graphically for this connection with the same assumed voltage and closing time are given in Fig. 7.

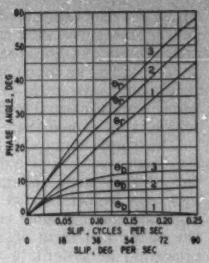


Fig. 7. Theoretical characteristics of vector difference synchronizer automatically compensated for voltage inequality

See Figs 1 and 3 for meaning of curves and symbols

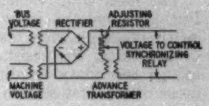


Fig. 8. Circuit for constant advance time (proportional advance angle)

Adjustment of Advance

Having found a system of connections which gives satisfactory theoretical advance characteristics, it is necessary to find a practical means of measuring the rate of change of E_{s-r}. This may be done by means of an "advance transformer" as shown in Fig. 8. The primary reactance at the frequencies to be transmitted is made small in comparison with the resistance of the primary circuit, so the primary current varies at a rate practically in proportion to the rate of change of E_{s-r}. The magnetic circuit of the transformer has a fixed series air gap to minimize the effects of permeability changes and hysteresis. Therefore, the flux varies at a rate practically in proportion to the rate of change of primary current and thus approximately in proportion to the rate of change of E_{s-r}. The induced secondary voltage then indicates the rate of change of E_{s-r}.

Factor k determines the advance time and should be adjustable to conform with different circuit breaker closing times. However, an equivalent effect may be obtained, and the use of high resistances avoided, by connecting a potentiometer resistor across E_{s-r}. Moving the tap on this resistor changes the proportionality factor $\left(\frac{1}{k}\right)$ of E_{s-r} and thus increases or decreases the advance time. The resistor may be calibrated with permanent markings corresponding to various values of advance time, to facilitate field adjustment.

Filter System

The voltage appearing across the output terminals of the advance network may be considered to include 2 parts—one (desired) component of slip frequency with the associated direct current and harmonics;

and the other (undesired) ripple component of twice power frequency with its harmonics. The advance transformer amplifies the ripple frequency component several times as much as it does the slip frequency component, the ratio of the 2 amplifications being approximately equal to the ratio of the 2 frequencies, which is never less than 200:1 in the operating zone.

The ripple component is then several times the slip frequency component at the output terminals of the advance network, and this ripple frequency voltage must be attenuated to a negligible value before applying the combined voltages to a relay; otherwise the relay will buzz at ripple frequency instead of operating at a definite point in the slip frequency cycle.

The basic filter element is of the form shown in Fig. 9, where the series impedance shown may be either predominantly resistive or inductive. In the present case, the resistance of the advance transformer secondary winding serves as the series element of the first section of the filter. The ratio of output to input for one stage is $A = \frac{X_c}{(X_R - X_C)^2 + R^2}$, and for N stages it is A^N. The phase shift for one stage at the transmitted frequency is

$$\theta = \tan^{-1} \frac{R}{X_c - X_R}$$

and for N stages it is

$$\theta = N \tan^{-1} \frac{R}{X_C - X_R} \qquad (12)$$

The phase shift is the only source of error introduced by the filter, since the relay operation is to occur at zero voltage and this is not changed by a decrease in amplitude.

Equation 12 shows that the phase shift for the transmitted frequency would be zero if the resistance

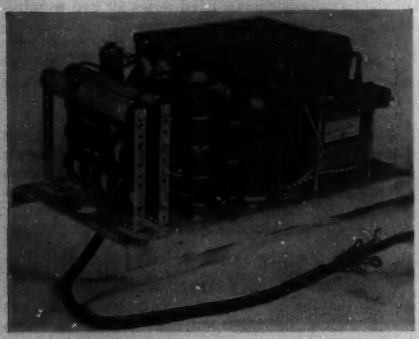


Fig. 10. Auxiliary box, cover removed

of the circuit were zero, but a reactor of the necessary high reactance would be expensive to construct with small enough resistance to reduce the phase shift to an acceptable value. However, the attenuation increases exponentially with the number of stages, while the phase shift increases only in proportion to the number of stages, so by using a multistage filter, it is possible to get the necessary attenuation at ripple frequency by means of an inexpensive resistance-capacitance filter and yet keep the phase shift of the slip frequency down to a small value.

The auxiliary assembly with cover removed is shown in Fig. 10. This includes the insulating transformers, rectifiers, loading and adjusting resistors, advance transformer, and filter.

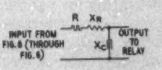


Fig. 9. Filter element

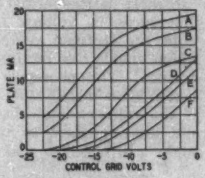


Fig. 11. Effect of source voltage changes on tube characteristics

Plate load = 6,000 ohms

Curve	Tube	Filament Volts	Plate Volts	Screen Volts
A	233	2.2	137.5	137.5
B	233	2	125	125
C	233	1.6	100	100
D	112A	5.5	137.5	
E	112A	5	125	
F	112A	4	100	

Compensated Amplifier

In order that the advance transformer may be of reasonable size and cost, and may require only a small amount of energy from the network generating the slip frequency voltage, it is necessary to use a very large number of turns of fine wire in the secondary; this gives a high secondary resistance. The cost of the filter is decreased by the use of small capacitances, but this also necessitates a high resistance per stage of filter.

The total resistance of these elements is such that they cannot transmit (at the voltage available at the operating point) sufficient power to actuate with the necessary accuracy any purely electromechanical relay. A tube amplifier may be interposed but it must be compensated for variations in filament and plate voltage, and protected so that its failure will not cause undesired operations.

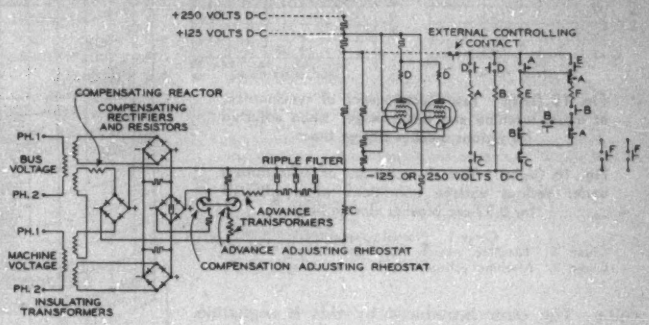
In Fig. 11 is shown the change in tube characteristics, caused by changes in plate and filament source voltage from 0.8 to 1.1 normal. Normal plate voltage is assumed to be 125 volts because that is the value usually available for operation of the circuit breaker.

These curves show that changes of the assumed magnitude in plate and filament voltages will cause as great a change in plate current as would a large change of voltage on the control grid. The changes

in plate current are not in direct proportion to the source voltage, so the most accurate method of compensation seems to be the use of 2 similar tubes in a balanced arrangement, both supplied from the same source. The tubes may be made to actuate a "plate difference" relay (D in Fig. 12) responsive to the difference in plate current.

Fig. 12. Connection diagram of automatic synchronizer

A. Auxiliary cut-off relay
B. Auxiliary relay for D
C. Cut-off relay
D. Differential relay
E. Set-up relay
F. Final auxiliary relay

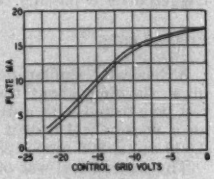


The characteristics, under similar conditions, of 2 tubes of similar rating purchased at different times and not purposely matched, are shown in Fig. 13. It will be seen that the difference between plate currents in the normal operating range is equivalent to that caused by a difference of about 0.6 volts on the grids. This difference can be compensated for by means of a slight bias in the adjustment of the differential relay D.

If the control grid of the control tube is allowed to become positive it acts as a plate and since its current must flow through a high resistance, its voltage no longer corresponds to the open circuit voltage of the source. In order to prevent this, it is necessary to apply a bias to the grid so that up to and somewhat beyond the operating point the grid will be negative and the grid current will be negligible. Bias batteries are objectionable because their internal resistance increases gradually so that operation becomes unstable and periodic replacement is necessary. This bias therefore is obtained by means of the voltage drop due to the filament currents flowing through a resistor to negative.

Fig. 13. Difference in characteristics of 2 type 233 tubes chosen at random

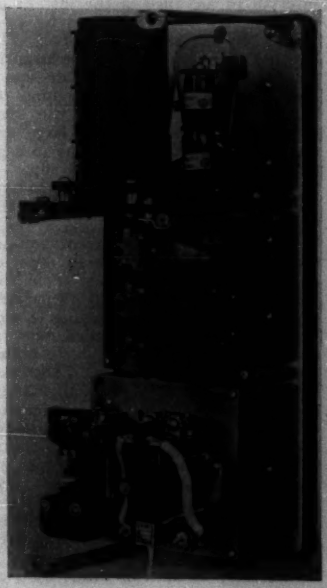
Filament voltage = 2 volts
Plate voltage = 125 volts
Screen voltage = 125 volts
Plate load = 6,000 ohms

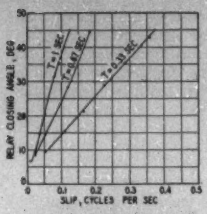


The filaments are connected in series so that if either tube has burned out or been withdrawn, relay D will not be actuated and no synchronizing will take place. This series connection places the filaments at different potentials, tending to unbalance the plate currents, but this is compensated for and balance is restored by connecting the grid of the tube with more positive filament to a tap on the bias resistor.

This compensation is so complete that the grid voltage at which relay D operates is the same within 0.4 volt for d-c control voltages from 100 to 140

Fig. 14. Synchronizing relay, cover removed





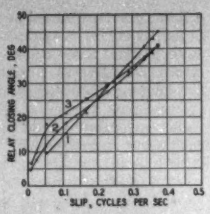


Fig. 15 (left). Test characteristics of synchronizer at equal machine and bus voltages when adjusted for various breaker closing times

Fig. 16 (right). Test characteristics of synchronizer under various voltage conditions when adjusted for 0.33-sec breaker closing time

Curve 1. Normal voltages (N)
Curve 2. Machine voltage, N; bus voltage, 0.85 N
Curve 3. Machine voltage, 1.1 N; bus voltage, 0.8 N

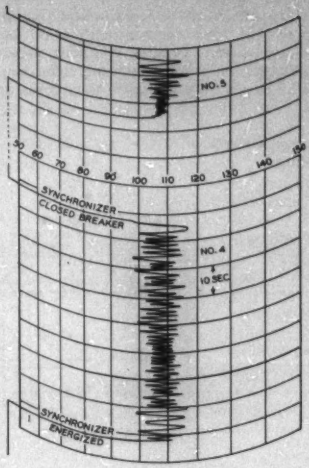
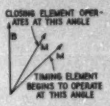


Fig. 17 (left). Synchronizing as recorded by graphic voltmeter across vector difference of machine voltage and 0.1 bus voltage (to keep within scale limits)

Fig. 18 (below). Vector relations in a constant-angle synchronizer



volts. The error introduced by this is negligible, especially in comparison with the effect of changes in breaker closing time due to these same changes in control voltage. However, it would be undesirable to have the relay operate later at low control voltages.

Relay System

Having produced a relay operation at the desired interval in advance of the instant of synchronism, some means is still required for preventing operation when the slip is excessive. This is necessary because (1) even perfect synchronizing at high slip causes large current rushes due to the mechanical inertia of the synchronous machines on the 2 sources; (2) the advance angle of the synchronizer falls below the desired value at large angles and slips; and (3) the angular error due to a given change in breaker time is proportional to slip.

This function may be performed by a simple undervoltage relay (C in Fig. 12) actuated by the rectified vector difference voltage.

Relay B has not sufficient contact capacity for most circuit breaker closing relay coil circuits, so an internal auxiliary relay (F in Fig. 12) is used. This has two electrically separate circuits each capable of closing and carrying 18 amp.

If relay F were controlled only by relays B, C, and A, it would be possible to obtain late closures around the limiting value of slip; because relay B could operate at the desired angle but relays C and A might close possibly 0.15 sec later and F would still close. This is prevented by relay E, which is connected through the checking contacts of relay B, so that it must be picked up by relays C and A before relay B operates, or else it cannot pick up until relay B has reset again.

The assembled synchronizing relay is shown in Fig. 14. The auxiliary box is mounted on the relay mounting studs behind the board, and connected to the relay connection studs by a cable with each lead cut to the proper length. All panel wiring runs to the relay studs, and none to the auxiliary box.

Over-All Characteristics

Characteristics of the assembled relay when adjusted for 3 different breaker closing times are shown in Fig. 15. In Fig. 16 are shown the characteristics when adjusted at normal voltage for one value of breaker closing time, and then subjected to the other voltage conditions previously assumed. These results were obtained with a phase shifter driven by a d-c motor with speed control by adjustment of armature voltage. The advance time was measured by a cycle counter connected to be started by the synchronizing relay and stopped at zero phase angle by a gas or mercury vapor hot cathode electronic tube triggered by a passing contact on the phase shifter.

Field Tests

A basically similar design of automatic synchronizer showing about the same accuracy in factory test was tested with automatic switching equipment on a waterwheel driven generator rated 2,250 kva, 2,300 volts, 505 amp, 138.5 rpm.

The waterwheel was of the propeller type, operating at 20 ft head. Its no load speed was somewhat unsteady, as shown by Fig. 17, in which each point of maximum and minimum voltage corresponds approximately to 180 deg and 0 deg, respectively.

The synchronizer and speed matcher were held out of circuit until the mechanical timer on the (Woodward) governor had released. The unit required about 30 sec to come to synchronous speed, and each test was begun at low speed, probably less than 0.1 normal. The breaker closing time was 0.45 to 0.5 second.

Synchronizing angles were read by close observation of the synchroscope but are probably subject to considerable errors in reading. Current read was the maximum swing indicated on a switchboard ammeter (800-amp scale). Since this was easier to read, and since the machine and bus voltages were well balanced at the time of the test, these currents are a more accurate indication of performance.

The poorest shot (45 deg late) was caused by the slip increasing to a high value after approaching zero phase angle at a very small value; this could not be prevented by the synchronizer because it occurred after the correct closing indication had been given. Where necessary, however, it might be prevented by an additional relay to take advantage of the trip-free characteristics of the synchronizing breaker.

Summary

In the absence of extremely accurate speed control, rapid synchronizing with acceptable accuracy requires giving the closing indication at a constant time (rather than a constant angle) in advance of synchronism. System conditions may cause a difference in magnitude of the voltages of the 2 sources, and synchronizing should still take place under these conditions.

A relay has been developed which meets the above requirements and which does not require numerous or delicate field adjustments. Mechanical adjustments have been reduced to a minimum by the use of vacuum tubes, which have been applied in such a way that if a tube has failed no operation can occur. The arrangement compensates automatically for the effects of both source and control voltage variations, on the relay.

Table I—Field Tests on Automatic Synchronizer

Test No.	Time Seconds	Angle Degrees	Early, Late or Backing	Fast or Slow Direction	Amp
1	35	5	E	S	10
2	45	10	L	F	180
3	35	0		S	0
4	120	0		F	20
5	40	30	B	S	450
6	45	5	L	S	110
7	45	0		S	75
8	40	5	E	F	10
9	45	20	B	S	350
10	40	10	L	F	150
11	30	0		F	0
12	30	0		F	0
13	40	5	L	F	90
14	90	10	E	F	100
15	55	5	E	S	110
16	50	0		F	0
17	50	0		F	20
18	40	10	L	S	150
19	50	10	E	S	110
20	55	0		F	80
21	55	15	E	S	150
22	50	45	L	F	650
23	45	15	E	S	140
24	45	15	B	S	160
Avg	49	10			125

The 3 backing shots apparently resulted from the slip reversing its sign after entering the synchronizing zone at a value above cut-off and before zero phase angle was reached; these unexpected conditions do not cause false operation with the design covered by this paper.

Appendix A—Symbols

a = relative acceleration of the 2 voltage vectors, in degrees per degree per second
B = bus voltage
E = vector difference between machine and bus voltages
E_1 = machine and bus voltage, when of equal magnitude
E_{d-c} = rectified vector difference voltage
k = advance transformer secondary voltage divided by $\frac{dE_{d-c}}{dt}$
K = 0.00555 k
M = machine voltage
s = frequency difference (slip) in degrees per second (= 360 times frequency difference in cycles per second)
s_m = maximum permissible (constant) slip for synchronizing
s_r = slip at θ_r
t = time setting of timing relay of a constant angle synchronizer, seconds (timing element must close ahead of θ_r to permit synchronizing)
T = closing time of control relay and breaker, seconds
θ = phase angle between machine and bus voltages
θ_r = θ at the instant when the synchronizing relay starts to close the breaker
θ_t = θ at the instant when the timing element of a constant-angle synchronizer begins to operate

Appendix B—Derivation of Equations

Error of Constant Angle Synchronizer

The relay elements are assumed to be adjusted so that the breaker contacts close at zero phase angle when operating at a constant slip equal to s_m, so

$\theta_r = s_m T$ (See Fig. 18)

Also, for this condition $\theta_t - \theta_r = s_m t$

since the timing element must close at or before θ_r in order to permit synchronizing

Therefore $(\theta_t - \theta_r)/t = s_m$

and $(\theta_t - \theta_r)T/t = \theta_r$

One limiting condition is where the slip at θ_r is the maximum value permitted by the settings of θ_r, θ_t, and t, and where a is at its maximum value (s increasing) and remains so. For this condition, the slip at θ_t is

$s_r - at$,

the average slip between θ_t and θ_r is

$$\frac{s_r + (s_r - at)}{2} = s_r - (at/2)$$

and $\theta_t - \theta_r = [s_r - (at/2)]\, t = s_r t - at^2/2$

so $s_r = [(\theta_t - \theta_r)/t] + (at/2)$

Average slip during time T is

$s_r + (aT/2) = ((\theta_t - \theta_r)/t) + (at/2) + (aT/2)$

and the angle during time T is

$[(\theta_t - \theta_r)\, T/t] + (atT/2) + (aT^2/2)$

Since $(\theta_t - \theta_r)\, T/t = \theta_r$, and the closing indication is given at θ_r, the error in degrees late at the instant of breaker contact closure is

$[(\theta_t - \theta_r)\, T/t] + (atT/2) + (aT^2/2) - [(\theta_t - \theta_r)\, T/t]$,

which is $(atT/2) + (aT^2/2)$ (1)

The term $(aT^2/2)$ is due to the acceleration while the breaker is closing, and cannot be decreased by adjustment of the relay. The term $(atT/2)$ is due to part of the acceleration while the slip is being measured and is practically always smaller than the other term, but is difficult to reduce below a small value wh ch depends on the operating principle and construction of the timing element.

The other limiting condition is where the slip at θ_r is zero but the acceleration is at its maximum and of such sign as to cause the phase angle to increase instead of decreasing from this point. The angle traversed during time T is then $\frac{aT^2}{2}$ and the error is

$$+\frac{aT^2}{2} \qquad (2)$$

The errors resulting from the 2 limiting conditions are equal when $(atT/2) + (aT^2/2) = \theta_r + (aT^2/2)$ or $atT/2 = \theta_r$

Assuming reasonable values such as

$\theta_r = 30$ deg, $t = 0.2$, $T = 0.5$, then

$a = 600$ deg per sec per sec, so it is obvious that the largest errors with a fixed angle synchronizer will be experienced with the backing shots covered by the second case.

Maximum Probable Error of Proportional Angle Synchronizer

Closing angle of relay $\theta_r = sT$ (3)

Average slip during time $T = s \doteq \frac{aT}{2}$

Angle traversed during time $T = sT \doteq \frac{aT^2}{2}$

Error in degrees $= sT \doteq \frac{aT^2}{2} - sT$

$$= \doteq \frac{aT^2}{2} \quad (4)$$

Vector Difference Voltage

From trigonometry

$$E = \sqrt{M^2 + B^2 - 2MB\cos\theta} \quad (5)$$

Average Value of Rectified Voltage

Average value of a-c voltage =

$$\frac{1}{1.11}\sqrt{M^2 + B^2 - 2MB\cos\theta} = 0.9\sqrt{M^2 + B^2 - 2MB\cos\theta} \quad (6)$$

(where 1.11 = form factor for a sine wave)

Rate of Change of Rectified Voltage

$$\frac{d}{d\theta}E_{d-c} = \frac{d}{d\theta}0.9\sqrt{M^2 + B^2 - 2MB\cos\theta}$$

$$= \frac{0.9\,MB\sin\theta}{\sqrt{M^2 + B^2 - 2MB\cos\theta}} \text{ in volts per radian}$$

Since one radian $= \frac{360 \text{ deg}}{2\pi}$

$$\frac{d\,E_{d-c}}{d\theta} = \frac{1.8\pi}{360}\frac{MB\sin\theta}{\sqrt{M^2 + B^2 - 2MB\cos\theta}} \text{ in volts per degree}$$

$\frac{d\theta}{dt} = s$ in degrees per second

$$\frac{dE_{d-c}}{dt} = \frac{dE_{d-c}}{d\theta}\frac{d\theta}{dt}$$

$$= \frac{0.005\,\pi\,sMB\sin\theta}{\sqrt{M^2 + B^2 - 2MB\cos\theta}} \quad (7)$$

Derivation of k_{adeg}

$$\frac{0.005\,k\,\pi sMB\sin\theta}{\sqrt{M^2 + B^2 - 2MB\cos\theta}} = 0.9\sqrt{M^2 + B^2 - 2MB\cos\theta}$$

at the operating point of the relay.

$0.005\,k\,\pi s\,MB\sin\theta = 0.9\,(M^2 + B^2 - 2MB\cos\theta)$

$0.005\,k\,\pi\,\theta\,MB\sin\theta = 0.9\,T\,(M^2 + B^2 - 2MB\cos\theta)$

$$k = \frac{180T\,(M^2 + B^2 - 2MB\cos\theta)}{\pi\,\theta MB\sin\theta}$$

Assuming $M = B = E$

$$k = \frac{180T\,(2E^2 - 2E^2\cos\theta)}{\pi\,\theta E^2\sin\theta}$$

$$= \frac{360T}{\pi\,\theta}\,\frac{1 - \cos\theta}{\sin\theta}$$

At 45 deg,

$$k = \frac{360T}{45\pi}\,\frac{0.2929}{0.7071}$$

$$= 1.05T \quad (8)$$

Equation for Closing Angle

$$\frac{0.005\,k\pi sMB\sin\theta}{\sqrt{M^2 + B^2 - 2MB\cos\theta}} = 0.9\sqrt{M^2 + B^2 - 2MB\cos\theta}$$

at the operating point of the relay.

$0.00555\,k\pi sMB\sin\theta = M^2 + B^2 - 2MB\cos\theta$

Let $0.00555\,k = K$

$(M^2 + B^2) - \pi KsMB\sin\theta = 2MB\cos\theta$

Squaring, substituting $(1 - \sin^2\theta)$ for $\cos^2\theta$, and simplifying,

$(M^2 - B^2)^2 - 2(M^2 + B^2)\,\pi KsMB\sin\theta + (\pi^2K^2s^2 + 4)M^2B^2\sin^2\theta = 0$

Solving the quadratic,

$$\sin\theta = \frac{(M^2+B^2)\pi Ks \pm \sqrt{(M^2+B^2)^2\pi^2K^2s^2 - (M^2-B^2)^2(\pi^2K^2s^2+4)}}{(\pi^2K^2s^2 + 4)\,MB} \quad (9)$$

If $M = B = E_1$

$$\sin\theta = \frac{2E_1^2\pi Ks \pm \sqrt{4E_1^4\pi^2K^2s^2 - 0}}{(\pi^2K^2s^2 + 4)E_1^2}$$

$$= \frac{2\pi Ks \pm 2\sqrt{\pi^2K^2s^2}}{\pi^2K^2s^2 + 4}$$

$$= \frac{4\pi Ks}{\pi^2K^2s^2 + 4}$$

Limits of Slip Defining Inoperative Zone

Synchronizing will not occur if the term under the radical in eq 9 is negative, so the minimum slip for synchronizing may be found by setting the term equal to zero

$(M^2 + B^2)^2\,\pi^2K^2s^2 - (M^2 - B^2)^2\,(\pi^2K^2s^2 + 4) = 0$

$(M^4 + 2M^2B^2 + B^4)\,\pi^2K^2s^2 - (M^4 - 2M^2B^2 + B^4)\,(\pi^2K^2s^2 + 4) = 0$

$4M^2B^2\pi^2K^2s^2 - 4(M^2 - B^2)^2 = 0$

$$s = \frac{M^2 - B^2}{MB\pi K} \quad (10)$$

Angular Limits of Inoperative Zone

Since the term under the radical in eq 9 is zero for this condition,

$$\sin\theta = \frac{(M^2 + B^2)\,\pi Ks}{MB\,(\pi^2K^2s^2 + 4)} \quad (11)$$

Graphic Determination of Operating Points

Using Fig. 4 as an example,

$M = 115$ volts

$B = 97.7$ volts

$C = M - B = 17.3$ volts

Constant bias $= 0.9C = 15.5$ volts

In Fig. 19 is shown curve 2 of Fig. 1 multiplied by 0.9 and replotted 15.5 volts lower.

Determination of K

E_{d-c} at 45 deg $= 0.9 \times 83.5 = 75$ (from Fig. 1, curve 2)

E_{d-c} compensated $= 75 - 15.5 = 59.5$

$\frac{d\,E_{d-c}}{dt}$ (at $\theta = 45$ deg and $S = 0.1$) $= 53.7$ (from Fig. 2, curve 2)

$\frac{d\,E_{d-c}}{dt}$ (at $\theta = 45$ deg and $S = 0.25$) $= \frac{0.25}{0.1}\,53.7 = 134$

$$k = \frac{E_{d-c} - C}{\frac{dE_{d-c}}{dt}} = \frac{59.5}{134} = 0.444$$

In Fig. 19 is shown curve 2 of Fig. 2 multiplied by Sk for 5 values of S. The intersections of these 5 curves with the main curve of $(E_{d-c} - 0.9C)$ are the desired operating points at this value of slip.

The other 2 curves in Fig. 4 are obtained in a similar manner using the same values of C and k.

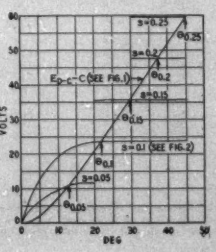


Fig. 19. Graphic determination of operating points θ

Curves marked s are $k\frac{dE_{d-c}}{dt}$

High Voltage Insulators

In this description of the manufacturing processes for suspension insulators, from design and research to finished product, is given a comprehensive list of the laboratory equipment required for adequate testing. Methods of testing for defects and the manner of assembly are sketched, and the need for further standardization is mentioned.

By
W. A. SMITH
ASSOCIATE A.I.E.E.

J. T. LUSIGNAN, JR.
MEMBER A.I.E.E.

Both of the
Ohio Brass Co.,
Barberton, Ohio

THE FUNCTION of an insulator is to support an energized conductor at a certain operating voltage without complete internal or external failure for a certain minimum or indefinite period. In doing so it must not involve any localized corona or surface discharges which would create radio interference in nearby receivers. In order that the insulator may be capable of the above, it must pass through an orderly procedure of research, design, and manufacturing.

Research

This stage may be either for the purpose of developing an entirely new type of insulator or to bring about certain desirable revisions in an existing type. Research may be divided into 3 classes:

1. Review of service records, experiences, and troubles in the field.
2. Study of publications on tests, experiments, and research.
3. Investigations by laboratory and field studies.

From the first class we secure much valuable information, coming mostly from the operating sources. The information thus obtained is thoroughly reliable, and much time and money has been spent to obtain and classify it. It is necessary, however, to recognize that the value of this may be limited for one or more of the following reasons: investigation only incidental to operation or regular work; lack of time and equipment; influence of commercial aspect; difficulty in securing all facts; or little opportunity to make comparisons with similar data. The correction of these undesirable conditions, and the closer coöperation of operators and manufacturers in the collection and analysis of field data, will serve greatly in perfecting insulator designs for operating service.

In the second class, involving a study of publications and private records, there is a very helpful fund of information, a study of which gives the investigator a running start and suggests many ideas, some quite opposed to others.

The third class, namely investigations by laboratory and field studies, is the generally accepted idea of research. In this the proper personnel and equipment is necessary to obtain dependable results and minimize erroneous conclusions.

In insulator research not only are electrical engineers necessary, but also mechanical and ceramic engineers, metallurgists and chemists, whose responsibilities consist of making investigations of all materials and combinations of materials entering into insulator manufacture. As an example, an oil-filled bushing may have as many as 15 or 20 different materials in its assembly. At some time all of these must have been investigated and analyzed. In order to do this properly, facilities which should be a part of the factory require the principal items of equipment given here.

Ceramic Laboratory

1. For the testing and investigation of raw materials: ovens, furnaces, standard screens, and other apparatus for physical tests.
2. For ceramic trials: ball mills, blungers, lawns, pumps, filter presses, pug mills, forming equipment, drying ovens, and an experimental kiln capable of firing ware at high temperatures of the order of cone 18, about 2,700 deg F.
3. For clay and glaze making control: equipment for specific gravity, viscosity and moisture measurements, water analysis, and pressure and temperature recording.

Fig. 1. Tension and compression testing machine for suspension type insulators

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 3, 1934; released for publication April 25, 1934. *Not published in pamphlet form.*

Chemical Laboratory

1. For analysis of material: chemicals and apparatus suitable for water, non-metallic and metallic minerals, metals, oils, fats, waxes, resins and gums; and ovens and balances for checks of moisture in raw materials and material in process.

2. For testing: particle size testing machine for control of body clay and glaze ingredients, cement, plaster, sand, etc.; microscopes, low and high power, with photographic facilities; and machines for rapid preparation of samples of metals, porcelain, cement, etc.; machines for tension, compression and hardness tests of metals, cement, porcelain and organic dielectrics; viscosimeter to determine flow of oils and insulating compounds; centrifuge for physical analysis of clay; oxygen bomb for accelerated aging of materials; micrometer gage for measuring minute volume changes of cement, plaster, etc.; and equipment for corrosion and other aging tests.

Mechanical Laboratory

Equipment here should be:

1. Tension and compression testing machine of about 100,000 lb capacity. If this machine is not equipped for cantilever and true torsion testing, there should be additional equipment capable of testing individual units in cantilever up to 20,000 lb, and in stacks as high as 10 or 12 ft, and in torsion up to 150,000 in. lb. All of these should be equipped with recording apparatus. A typical tension and compression machine is illustrated in Fig. 1 and a suitable cantilever and torsion machine in Fig. 2.

2. Porosity testing machine, with pressure capacity of 5,000 lb per sq in.

3. Hot and cold water tanks for thermal tests, preferably steam heated and refrigerator cooled, and capable of covering standard specification ranges. In Fig. 3 is shown one efficient form which facilitates easy and rapid handling of the insulators being tested.

4. Combined tension and thermal testing apparatus.

5. Outdoor time loading test racks. A set of outdoor racks with capacities for numerous experimental units is illustrated by Fig. 4.

Electrical Laboratory

1. Impulse generating, measuring, and recording apparatus: voltage range from 20 to 3,000 kv; high current surge capacity of order of 100,000 amp at from 100 to 150 kv with 40-μsec wave; wave length control from 0.5 μsec to 100 μsec; operating speed of at least one measured and recorded flashover per minute; high voltage potentiometers and sphere gaps capable of measuring accurately all wave crests in the voltage range.

2. Normal frequency generating, measuring, and recording apparatus: voltage range to 1,500 kv to ground; high voltage wave shape sufficiently close to sinusoidal to allow accurate calibration; high voltage potentiometers and sphere gaps capable of measuring accurately high voltage values in the range.

3. High frequency testing apparatus: oscillator equipment with voltage range to 750 kv for special insulation studies; sustained high frequency equipment for radio insulation studies.

4. Corona testing apparatus: dark room facilities, with voltage sources to 500 kv.

5. Radio interference testing apparatus: radio-interference-proof room with voltage sources to 500 kv; radio interference measuring equipment capable of making studies according to present generally accepted practices.

6. Atmospheric contamination study apparatus: suitable chamber or room for duplicating fog, dust, smoke, and other special atmospheric conditions encountered in service, with voltage sources to 300 kv; facilities for observing discharges, and measuring and recording currents and voltages associated with such discharges occurring under conditions obtained.

7. High current testing apparatus: current generating capacity up to 10,000 amp at 25 and 60 cycles, and facilities for measuring and recording same.

8. Phase angle, power factor, and similar testing apparatus: suitable instruments for measuring accurately phase angles, transformation ratios, power factors, dielectric constants, etc., in connection with low voltage circuits of bushings, constants of insulating materials, assembled units, etc.

Illustrative of a research program using the ceramic, chemical, electrical, and mechanical laboratory facilities outlined is the following example:

On one line of suspension insulators the research program extended over a period of several years at a cost of well over $30,000. In this program the insulators were assembled in small batches of 5 or 10 units and careful attention was given to note and record the various characteristics.

During this time 171 design variations were made and tests to destruction of 2,700 units were carefully analyzed and recorded. Of these, 1,600 were special units requiring new manufacturing equipment. By the process of elimination, a few types were selected as possessing the most desirable characteristics, and these were subject to further study and tests. In the final assemblies, great care was exercised to insure that one, and only one, feature was changed at a time, and every batch of special units was paralleled by a batch of control units of a type which shows consistent performance. The final designs were subjected to all available tests. Some batches of these units loaded to 80 per cent of their average mechanical and electrical strength values, as determined by A.I.E.E. specifications, have stood the outdoor time-load test for about 2 years without a single failure. Parallel research work to secure precise measurements of the performance of the individual parts of assembled units under different loading and temperature conditions is being continued.

In selecting designs for intensive development, the determining factor was not high combined mechanical and electrical strength. In fact, 2 designs having higher strength and requiring less manufacturing expense were discarded because the construction used in them seemed hazardous. The final choice was influenced to a very great degree by the records of previous designs which have shown successful performance in service for many years.

As an example of a similar research program on another form of insulation, the development of one group of a new type of oil-filled bushing was recently completed at a cost of well over $25,000.

Fig. 2. Cantilever and torsion testing machine for pillar and pin type insulators

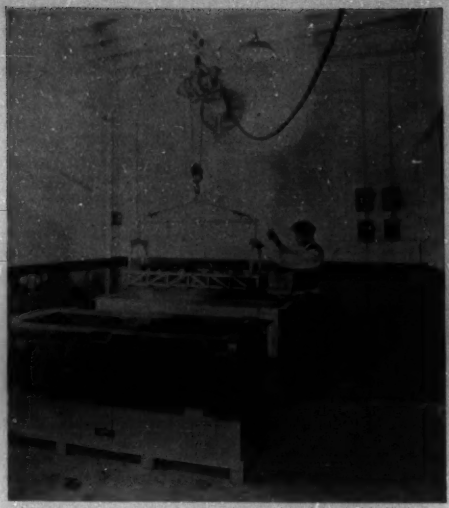


Fig. 3. Hot and cold tanks for thermal tests on insulators

Design

The basic requirements of a design are marketability for the manufacturer and economy for the user. These facts must be borne in mind by the designer. In general, designs are compromises and this is especially true with respect to insulators. Here we have 2 major requirement classifications, electrical and mechanical. As a rule these are of similar importance but, unfortunately, they dictate methods of treatment that are quite opposed to each other. Also, a design usually requires several different materials each with its own characteristics, making the derivation of formulas quite difficult or impossible. True, many phases of the design can be solved by standard or special formulas, but some of the most important features require the formulas to be modified to secure better agreement with experience. Some valuable empirical formulas are derived from both electrical and mechanical tests.

In the designing of insulators at the present time, it is probable that in most cases the general shape and type are dictated by past experience and service. Most forms derived from calculations must be modified to make them practical for manufacturing. All new designs are subjected to rigorous mechanical and electrical tests to determine their characteristics.

The relative diameters of porcelain and hardware, in so far as they effect mechanical properties, can be largely determined by formulas, and the effect of the porcelain outer diameter on flashover value can be calculated with sufficient accuracy. The relationship which holds here is that the flashover for 60 cycle or long impulse waves occurs over the shortest striking distance. For short wave or short time lag, flashover holds well to the porcelain surfaces and closely follows the leakage paths. In other words, for the first class of breakdown, insulators may be compared on the basis of their tight string or striking distances, while for the second class, which is a cascading breakdown, they may be compared by their relative total leakage distances.

The proper spacings to be used for pillar and suspension insulators from a mechanical consideration can be calculated with a fair degree of accuracy. From an electrical standpoint, insulator spacing values enter in so far as they affect the total striking and leakage distances, as noted in the previous paragraph. As a rule the diameter-spacing relationship is so arranged as to minimize the danger of cascading under average flashover conditions. Cantilever values on pillar insulators may also be satisfactorily calculated for either base or cap mounted positions, assuming that calculations or tests have previously been made to determine the strength and point of failure of a single unit.

The leakage distances and surface resistances are affected entirely by the shapes of the porcelain members. Leakage distance largely governs the flashover voltage of a unit, principally that of a cascading type such as occurs with short-time impulses. It has some bearing on the wet flashover voltages and breakdown under fog contamination conditions. Leakage distances can be raised by increasing diameters and lengths of the porcelain bodies, by adding petticoats, grooves, ribs, etc., and are comparatively easy to measure. The surface resistance of an insulator largely affects the flashover voltage and leakage current under conditions of fog, dew, surface contamination from atmospheric impurities, etc. Any increase of the total porcelain surface of an insulator from line to ground obviously raises the surface resistance to an extent depending upon the shape and location of the added surface. For example, the addition of concentric petticoats of small diameter effects much greater resistance increase than does that of larger diameters. The reason for this is that the smaller diameter petticoats add to the length of the total leakage path without contributing as great widths. A standard 10-in. diam insulator with properly arranged underneath petticoats should have a surface resistance well over twice that of a smooth disk unit with no petticoats. The theoretical surface resistance may be calculated or measured with a fair degree of accuracy, although the task is a tedious one. While this theoretical value may be some indication of the ability of the insulator to check fog flashovers, heavy leakage currents, etc., it is not an absolute criterion. This is because a calculated value assumes a uniform surface coating of moisture, dirt, carbon, etc., whereas in service this coating may vary, dependent upon the amount of protection and the degree of rain washing which the particular porcelain shape allows. Very careful study and design judgment is essential in choosing the proper porcelain shapes where leakage resistance is an important factor.

Corona on an insulator is important in so far as it

Fig. 4. Typical outdoor insulator racks for time loading tests

involves radio interference, precipitation of foreign particles on the dielectric surfaces, and possible attacks on metal parts from nitric acid formation. It may be minimized by controlling the design of both metal and porcelain members to avoid any overstress of the air at the maximum voltage at which the insulator may have to operate. Sharp metallic edges, pockets of air under metal caps or between assembled porcelain shells, etc., are typical corona origins on insulators and therefore to be avoided in design considerations. The determination of the corona and radio characteristics of an insulator must depend largely upon tests as reliable calculations are practically impossible. In addition, tests themselves are not entirely satisfactory as far as obtaining absolute design values are concerned, as there have been no standardized methods evolved as yet for measuring corona or radio characteristics. In regard to the corona tests, the principal lack is a means of determining definitely the appearance and disappearance points of the local corona discharge, since this depends upon the visual powers and position of the observer. In the case of radio interference tests the principal need is a definition of what constitutes interference in service, and how this is to be measured in the laboratory.

From the standpoint of corona and radio characteristics, however, progress in design can be effected by making comparative tests either simultaneously or successively on trial units, and determining the best from the relative performances found. So far this has served to give very satisfactory results, although the cost of comparative tests is high because of the repetition of readings and test set-ups necessary. This would be unnecessary if quantitative unit values could be obtained on individual specimens which could be depended upon for comparison with test values secured at other times.

Manufacturing

The general methods used in the manufacture of insulators are familiar to most engineers. There are, however, a number of details which will probably be of interest. Visitors to an insulator factory frequently express surprise when they see the amount of high-grade machinery and equipment used in insulator manufacturing. The nature of the materials from which insulators are made precludes the possibility of great accuracy in manufacturing. These same materials are subject to troubles which are seldom, if ever, found except in those of a fragile nature. To minimize these troubles, it is necessary to be constantly on guard and to keep machinery and equipment properly adjusted.

In the forming processes many gauges are necessary for setting forming tools and checking diameters, head thicknesses and other dimensions on green, dry and fired ware. Inspectors must be located at several positions along the manufacturing line and be provided with the necessary equipment for checking the product and detecting faults at the earliest possible moment. For control of the manufacturing process, the ceramic department should have equipment for clay conditioning and workability tests, and temperature and humidity controllers and recorders. New lots of clays, spars, and other materials should be tested, and texture and water content of the porcelain body must be watched. For kiln control it is essential to have pyrometric cones, shrinkage disks, optical pyrometers, thermocouples with recorders, draft gauges, CO_2 meters, flow meters, pressure gauges, and regulators for gas or oil firing, or fuel analysis equipment for coal firing.

In addition to the laboratories and testing equipment already mentioned, the inspection department should have proper facilities for checking quality of clay body, glaze and sand, drying, firing, assembly and curing, and for electrical and mechanical tests. Exceedingly close tolerances must be maintained wherever possible to balance up the processes which are not subject to close control. A variation in the water content of the clay body of 0.5 per cent or even less, or a slight variation in the density of the glaze, may cause much porcelain to be scrapped. A difference of 1 cone (approximately 15 deg C) in the firing range may cause rejection of over-fired ware or necessitate refiring under-fired ware. When it is realized that it is impossible to have all sections of a kiln or parts of a car at the same temperature, one

understands the importance of having adequate control methods and checks.

After the porcelain has passed through the kilns or firing process and during its progress in the assembling line, suitable equipment should be available to make the following tests and inspections: visual inspection, 60-cycle flashover and high frequency flashover part tests, and mechanical and high frequency flashover tests on assembled units. In some factories the insulators range all the way from small 1-piece telephone types to bushings composed of many parts and weighing over 5,000 lb. It is obvious that the methods of manufacturing cannot be the same in all cases, but, as an example, let us follow the suspension insulator through the assembling stage. Without going into minute details, the procedure is about as follows: A visual inspection in well lighted areas, and made by experienced men, picks out most of the defective porcelain ware. A vigorous 60-cycle flashover test will eliminate most of the remaining defective parts. The high-frequency flashover test will reveal any pieces which have defects deeply located and of such a nature that the 60-cycle test will pass them.

From the high frequency "kick test" the porcelain disks pass to the assembling area. Here the tops of the heads are dipped in paraffin to prevent any contact with cement or metal parts. The sanded surfaces or grip sections of the heads are then sprayed with a compound to give a certain amount of relief which allows for distribution of load and relief from thermal stresses. Gaskets having a low absorption factor are placed over the head. These prevent the metal caps from coming into contact with the porcelain and the lower edge of the cap from exerting a downward stress on the porcelain flange. A carefully measured amount of high-grade neat cement is placed in the cap which is then worked into position against the paper gasket.

The insulators are then placed on cars and run into the curing tanks which are heated to a predetermined temperature by live steam which deposits moisture throughout the curing process. In Fig. 5 is shown a typical battery of such curing tanks. The temperature and steam flow are controlled by thermostats, and recorded by recording thermometers. After 24 hr in the tanks the cars are removed, one at a time, for pin assembly. The first operation is to remove the paper gaskets and clean all cement out from between the lower edges of the caps and the porcelain disks. The sanded surface in the pin hole is then sprayed with a compound, after which a paper disk is forced to the bottom of the pin hole. This disk is for the purpose of providing a cushion between the head of the pin and the porcelain. A compound-coated pin is then cemented in the pin hole with a neat cement which has been carefully mixed in a small batch using definite proportions of cement and water. The pins are locked in place by stiff paper gaskets. The insulators are then returned to the curing tanks where they remain under controlled conditions of temperature and moisture for about 5 days, after which they are drawn from the tanks, cleaned and tension tested to 40 per cent of their rated load. Following the mechanical test they are subjected to a final electrical test to insure that there are no defects. The cement surfaces around the pins are then coated with wax and the insulators are crated for shipment.

Usually designs can be made to meet all specifications without working a hardship on the manufacturer. There are, however, some instances where it is very difficult to meet all of the conditions, of which one of the most notable is that of threaded porcelain pin holes. The only existing national standard covering this important feature of pin type insulators permits a greater tolerance in the manufacture of test gauges than is allowed the insulator manufacturer in the commercial production of insulators. Undoubtedly such conditions will be corrected when brought to the attention of the proper standardization committee. Both user and manufacturer have evidenced a need and desire for further general standardization, which includes defining existing design dimensions and acceptance specifications. The authors urge an early consideration of this highly desirable work, as it will be most helpful in future development.

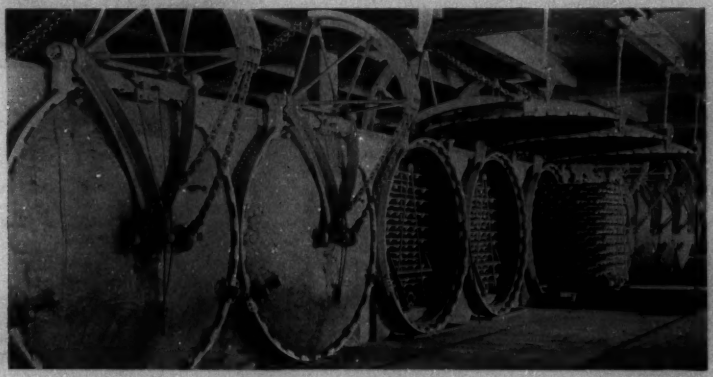


Fig. 5. Battery of insulator curing tanks

A Telemeter With Pilot Coil Transmitter

The feature of the current-type telemeter described in this paper is the pilot coil which acts as a detector of load changes.

By
L. J. LUNAS
ASSOCIATE A.I.E.E.

H. L. BERNARDE
ASSOCIATE A.I.E.E.

Westinghouse Elec. & Mfg. Co., Newark, N. J.

THE current-type telemeter, in which a small direct current proportional to the quantity being measured is transmitted to distant receivers, was one of the earliest and most reliable forms. It has enjoyed wide acceptance and has survived the test of successful operation. Some of the main advantages of the current system are as follows:

1. The readings are continuous.
2. The receiving instruments are simple, rugged, d-c milliammeters of either the indicating or recording type.
3. Only 2 wires are required between the transmitter and receiver.
4. The transmitted current is the same in all parts of the telemeter circuit, obviating errors present in potential schemes which are subject to leakage.
5. Telephone cable circuits are suitable for use as telemeter circuits. The telemeter current causes no interference with other circuits in the cable and the leakage resistance of the cable pair is so high as to have negligible effects on the readings.
6. Totalization of various circuits is accomplished with a high degree of accuracy by paralleling output currents.

Early forms of the current-type telemeter had the disadvantage of slow response due to designs having high inertia.[1] The continued interconnection and growth of superpower systems with the attendant interchange and sale of large blocks of power has made it necessary to telemeter quantities with high accuracy and quick response. Where 5, 10, or even 15 sec for the telemeter to travel from zero to full scale was acceptable before, conditions today require that this time be reduced to approximately 1 sec, or equal to that of corresponding indicating instruments. Furthermore, the accuracy of the telemeter must not be affected by variations in control voltage or frequency, variations in line resistance or of aging, or variation in any of the components of the apparatus.

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted November 20, 1933; released for publication May 4, 1934. *Not published in pamphlet form.*

1. For numbered references see list at end of paper.

Description of Mechanism

The new current-balance telemeter is a simple, rugged device combining the usual instrument mechanisms with conventional vacuum tube circuits and giving an accurate, quick response. The transmitter consists of 2 principal units as shown in Fig. 3. The transmitter mechanisms are mounted with their shafts in the same vertical centerline and having their moving elements mechanically coupled. The lower unit is the primary element which may be an ammeter, voltmeter, wattmeter, or any electrical or mechanical mechanism of the deflection type. The upper unit of the transmitter is a permanent-magnet moving-coil milliammeter mechanism connected to oppose the torque of the primary element. These 2 units are conventional switchboard type instrument mechanisms without pointers and with torque springs replaced by conducting strips. A small "pilot coil,"[2] which moves in an a-c electromagnetic field, is connected to the moving element system to detect any divergence of the primary element from the balance position and to adjust the current in the balancing milliammeter through an amplifier of the transformer-coupled, rectified-output type. The pilot coil acts as a detector of changes in load, obviating the use of contacts which characterized earlier forms of current telemeters. It is movable in the air gap of a stationary electromagnet having an iron core. As it is moved to either side of the null position, a voltage is induced in the coil, the magnitude of which depends upon the amount of deflection and the polarity upon the direction of deflection. The voltage output of this pilot coil is fed to an amplifier, the d-c output of which is connected in series with the balance element, the line and receiving instruments, or, in other words, feeds the telemeter circuit.

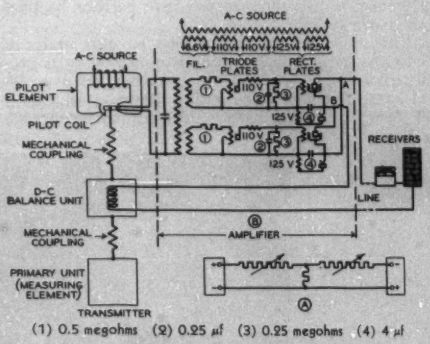


Fig. 1. External wiring of Pilotel telemeter

Since the torques of the balance element and the measuring element must be equal for all conditions of rest, the direct current in the balance element, line, and receivers is proportional to the quantity being metered and is thus a measure of its magnitude. This interaction may be more readily understood by noting that the system will move until the amplified pilot-coil current is just sufficient to balance the moving system.

Operation

This arrangement gives complete freedom from errors which might otherwise arise from the great changes in line resistance, wide variations in control voltage and large changes in amplifier characteristics. Any such change would tend to increase or decrease the telemeter current and thus destroy the condition of balance existing in the moving system. The resulting motion of the system would change the pilot coil output and the balance would be restored. It is apparent that the moving system of the transmitter will have a definite position for any one condition of load, control voltage, line resistance and amplifier constants, but any change in any one or more of these will cause the mechanism to move to a slightly different position to restore the balance. However, the current in the receiver is always proportional to the load except for such negligible effects as bearing friction and line leakage.

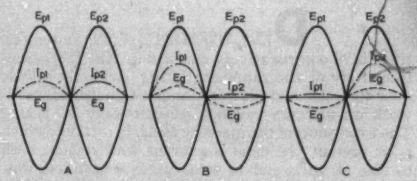


Fig. 2. Action of pilot coil under load changes

A—Pilot element at zero (no load)
B—Pilot element to right of zero
C—Pilot element to left of zero

E_p Plate voltage
I_p Plate current
E_g Grid voltage

Subnumerals 1 and 2 refer respectively to tubes Nos. 1 and 2

Action of Amplifier

The action of the amplifier may be understood by considering it as an equivalent network circuit having two separate sources of voltage. Two of the arms are variable resistances, as schematically represented by rheostats in Fig. 1A. With the separate sources connected to the network with opposite polarities as shown, the direction and magnitude of the current flowing in the fixed resistance depends upon the relative positions of the rheostats. With one rheostat set to higher resistance than the other, current will flow through the fixed resistor in one direction. Conversely, interchanging the rheostat values, the current will flow in the opposite direction.

In the actual apparatus described, the pentode tubes are analogous to the rheostats of the equivalent circuit described above. The plate currents are controlled by the grid potentials applied from the output of the pilot coil. Any change in load changes the pilot coil output and unbalances the network. See Fig. 2. The grid potentials which are controlled by the pilot output are equal for the no-load condition and hence the plate currents are equal as shown in Fig. 2A. For any condition of balance the potential difference is zero between points A and B of the bridge circuit. Any change in load changes the grid voltages. The corresponding plate currents increase and decrease accordingly, which unbalances the bridge circuit causing the potential difference between A and B to set up a proportional flow of current in the telemeter circuit. This action is reversible as will be seen by a study of Figs. 2B and 2C. Since a reversal in torque of the primary unit reverses the current in the telemeter circuit, the action is suitable for zero center scales in cases of reversals in power flow.

Fig. 3. Telemeter transmitter (left) and associated amplifier

Deflection

The amplification factor and the magnitude of the voltage induced in the pilot coil are so chosen that the moving system has a maximum travel of only a few degrees. Since the scale of the wattmeter

measuring element is practically uniform over this small range, totalization of the quantities of a number of circuits is accomplished with a high degree of accuracy. The responsiveness of the transmitter is higher than that of corresponding switchboard-type instruments. This is because the deflection of the moving system is only a small fraction of the deflection of the corresponding indicating instrument. When used with a Pilotel recorder receiver, the time of response of which is about 1.25 sec, the response of the telemeter system is about the same as that of an indicating wattmeter connected directly to the circuit.

Any variation in control voltage affects the output of the amplifier tubes. This tends to change the amplifier output but any such change is immediately followed by a change in the position of the moving system which compensates for such variations. Aging or change in the characteristics of the amplifier tubes is compensated for in the same manner.

Accuracy

The accuracy of the telemeter depends solely upon the calibration of the transmitter and receiver. To state this in definite figures would be to assign a probable accuracy of 1 per cent for the transmitter and for the receiving instruments. Since these units are rugged switchboard-type mechanisms, the problems of permanency of calibration and maintenance are no greater than in conventional switchboard instruments.

Actual tests have shown that sensitivity compares favorably with that of the corresponding indicating type switchboard instruments. The mechanical coupling between elements is the result of considerable development. Necessary flexibility has been obtained with negligible error caused by lag.

The d-c output derived from alternating current is filtered, but ripples or pulsates slightly. This does not affect the accuracy of the indications since the permanent magnet moving coil receiving instruments do not respond to any a-c component and read only direct current.

The use of pentode tubes, which have a high ratio of a-c impedance to d-c resistance eliminates any errors that might result from wide variation in transmission circuit characteristics.

Up to this point only primary elements which exert a torque proportional to the measured quantity have been considered. In the case of non-electrical quantities, such as pressures measured by bourdon tubes or sylphon bulbs, or positions as transmitted by position indicator motors, the measuring unit exerts a torque against the torque of the balance unit, as in the case of electrical quantities. The system described has been in operation chiefly in the laboratory, with limited field experience.

References

1. A Report on Telemetering, Supervisory Control and Associated Communication Circuits, prepared by a joint subcommittee of the A.I.E.E. *Abs., Elec. Engg.*, v. 51, Sept. 1932, p. 613.

2. A New Electronic Recorder, H. L. Bernarde and L. J. Lunas. Elec. Engg., v. 52, March 1933, p. 188.

Voltage Control of Vapor Rectifiers

Some of the changes to be introduced into the mathematical treatment of rectifier circuits when the firing of the anodes of a rectifier is advanced or retarded by control of the arc are described. The points considered and illustrated by theoretical curves include commutation between anodes, regulation, and wave shape of the output voltage for the more usual transformer connections, and resulting variations in functions of the transformer reactance and of the nature of the d-c load.

By
DIDIER JOURNEAUX
ASSOCIATE A.I.E.E.

Allis-Chalmers Mfg. Co., Milwaukee, Wis.

DEVELOPMENT of the vapor rectifier is of comparatively recent date, the first scientific study of the vapor arc dating back only a little over 40 years[1] and the initial stage of Cooper-Hewitt's work on mercury cathode rectifiers only 33 years.[2] The expansion of the mercury cathode rectifier, which is at present the most important with respect both to size of units and to total capacity installed, was, however, very limited in extent until the advent of a steel-clad rectifier capable of successfully meeting the operating requirements of large power converting apparatus.[3] Although Schaefer's rectifier was far from having the degree of perfection now expected of modern units, it provided a starting point for the development of reliable and efficient units of large capacity. This development has resulted in an amazing expansion of the use of rectifiers for electric traction, electrolysis, lighting, communication, and other uses, which bids fair to continue at an increasing rate when the demand for power equipment returns to its normal level.

In most rectifiers now in service, the arc is entirely uncontrolled, the operation of the rectifier resting on the valve action of the anodes, i. e., their property of receiving but of not emitting electrons, and on the characteristics of the circuits associated with it. In general, a rectifier may be considered as a synchronous switch which automatically transmits to

Full text of a paper recommended for publication by the A.I.E.E. electrical machinery committee, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted Feb. 28, 1934; released for publication April 9, 1934 (revised May 1, 1934). *Not published in pamphlet form.*

1. For numbered references see bibliography at end of paper.

the d-c line the voltage of whichever a-c phase has the highest momentary voltage, the different phases of the a-c line being used in rotation. Such an uncontrolled switch is incapable of any regulating action on the voltage of the d-c line, and the voltage is then regulated by tap changing, or by means of induction regulators, d-c boosters, saturated reactors, or the like.

Principle of the Arc Control

The desirability of obtaining voltage regulation or current regulation without the use of additional power equipment was felt as early as 1903 by P. H.

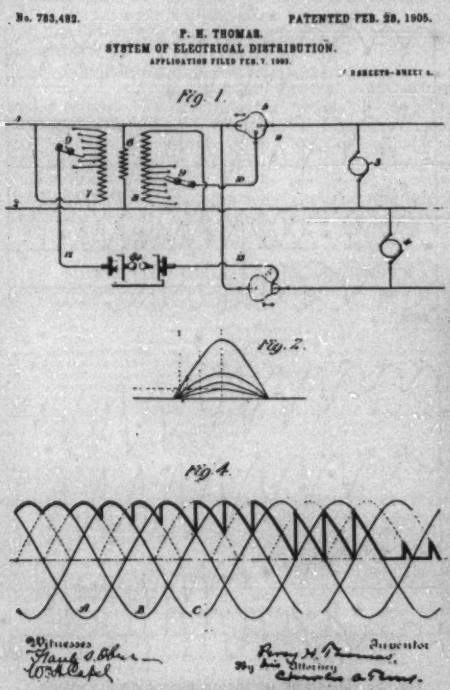


Fig. 1. Early patent for single-phase 3-wire rectifier, with voltage control by starting electrodes, and voltage curve of a similar 6-phase rectifier

Thomas,[4] who realized that the problem could be solved by controlling the arc. A sheet of the Thomas patent is reproduced in Fig. 1, in which the diagram (marked Fig. 1) shows the connections for a single-phase 3-wire system, and the curve (marked Fig. 4) illustrates the regulation obtainable with a 3- to 6-phase system shown in another figure of the patent. The rectifier of Thomas consisted of a group of glass bulbs each having an anode and a cathode, in which the arc had to be reignited once during every cycle. This ignition was obtained by impressing a sufficiently high voltage between the cathode and an auxiliary electrode to break down the space adjacent to the cathode. This electrode may be an internal electrode *11* or an external electrode or starting band *5;* when the latter is used the electrostatic field reaches the space adjacent to the cathode through the glass wall of the bulb. The transfer of the arc from one anode to another is then always dependent upon the production of the ignition impulse and may be retarded at will during the positive half cycle of the anode voltage to impress, on the d-c line, either the peaks of the voltage waves of the successive anodes, or portions of waves of lesser magnitude. This permits regulation of the output voltage from its unregulated value down to zero.

The method of control remains essentially the same when the arc is controlled by means other than those utilized by Thomas, such as starting electrodes immersed in the mercury and electrostatic grids. The latter are now in successful commercial operation in steel-clad rectifiers of the type having several anodes and a continuously excited cathode, but are perhaps better known for their application to the control of glass rectifiers with thermionic cathodes. The grids do not call for material changes in the de-

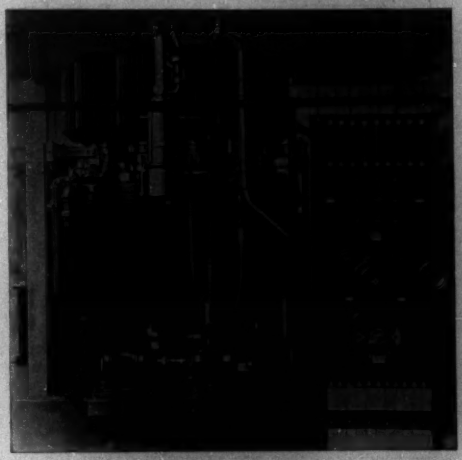


Fig. 2. 5,000-amp 625-volt mercury arc rectifier, with voltage control by grids, supplying a traction load

sign of the rectifiers as may be seen from Fig. 2, which shows a 5,000-amp 625-volt rectifier provided with grid control supplying a traction load. The voltage can be regulated manually or automatically

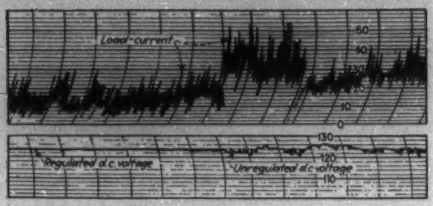


Fig. 3. Voltage and current charts of the rectifier of Fig. 2

to give to the machine a flat or a sloping characteristic. In Fig. 3 are illustrated portions of a voltage graph and of the corresponding current graph of this rectifier, clearly indicating the effectiveness of the grids in spite of constant fluctuations of the load.

The essential characteristics of the grid controlled rectifier will necessarily be deduced from the char-

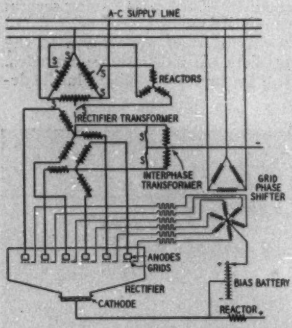


Fig. 4. Typical diagram of connections of grid controlled rectifier with or without interphase transformer

acteristics of the uncontrolled rectifier, which have been extensively considered in the literature.[5]

Connection of the Rectifier and Grids

In the following treatment only operating conditions adapted to comparatively simple computation are considered, and such approximations are made as are consistent with engineering accuracy, or as can be corrected for. Most computations relate to the general case of a p-phase rectifier, and the corresponding curves are generally drawn for the case of a 6-phase rectifier operating in one of 2 different connections obtained as shown in Fig. 4. The switches s in this figure being in the position shown, the rectifier transformer has its 3-phase primary winding connected in delta and its 6-phase secondary winding connected diametrically in star. This connection lends itself to a simple analysis of the operation of the rectifier. When all the switches s are reversed, the secondary winding is divided into

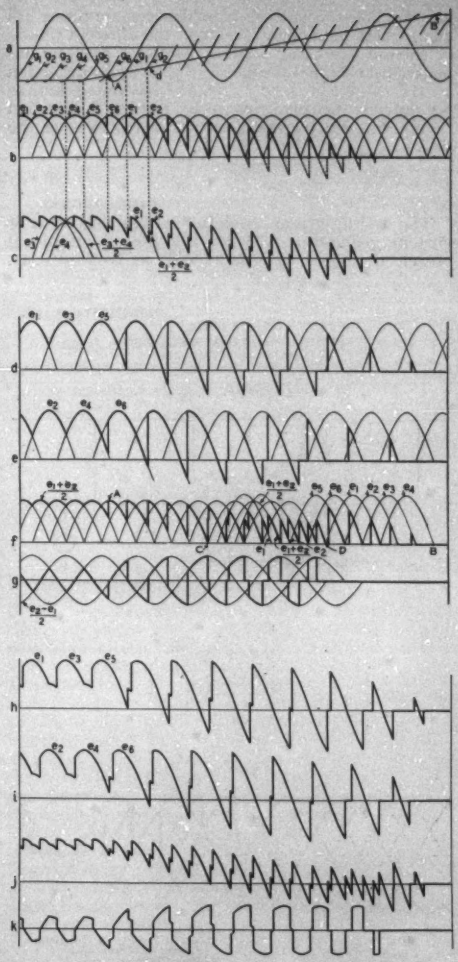


Fig. 5. Diagrams of the rectifier output voltages obtained by varying the grid voltages

a—Grid voltage: g_1 to g_6 = alternating components
d = common continuous component
b—No-load and low-load voltage: diametrical connection, solid line; voltage with resistance load, dotted lines: changes in the voltage curve with inductive load
e_1 to e_6 = anode voltage
c—Voltage on inductive load; diametrical connection; rectifier transformer working reactance 5 per cent
d to g—Diagrams for interphase transformer connection at transition resistance load
h to k—Diagrams for interphase transformer connection; transformer working reactance 12.25 per cent
d and h—Output voltage of anodes 1, 3, and 5
e and i—Output voltage of anodes 2, 4, and 6
f and j—Output voltage of the rectifier
g and k—Voltage of 1 interphase transformer coil

2 3-phase systems connected by an interphase transformer, and the primary winding is connected in star, each phase thereby being given a 30 deg lag. The switches are arranged also to reduce the primary turns by 50 per cent and to insert suitable reactors in each phase, so that changeover raises the secondary voltage in the ratio of 2 to $\sqrt{3}$ and increases the phase reactance in the ratio of 2.45 to 1. The rectifier, at least when operating without grids, then has the same d-c voltage and the same regulation with either connection, and the study of the interphase transformer connection, which is by far the more important of the 2, becomes easier to comprehend by a comparison with the diametrical connection.

Grids may be energized in numerous ways; in Fig. 4 they receive 6-phase alternating voltages from the line through a phase shifter, all grids receiving, in addition, a common positive or negative continuous voltage from a battery connected between the cathode and the secondary neutral point of the phase shifter. To illustrate the action of the grids with the transformer in diametrical connection, the grid voltages are assumed to lag 135 deg behind the corresponding anode voltages, and the continuous grid voltage is varied from a maximum positive value to a maximum negative value for regulating the output voltage from its maximum value to zero; any intermediate degree of regulation may then be obtained by adjusting the grid voltage to an intermediate value.

Table I—Symbols Used in Following Text

e	instantaneous secondary phase voltage
E	rms secondary phase voltage
e'_d	instantaneous regulated continuous voltage
E_{do}	average unregulated no-load continuous voltage
E'_{do}	average regulated no-load continuous voltage
E''_{do}	rms regulated no-load continuous voltage
E_d	average unregulated continuous voltage under load
E'_d	average regulated continuous voltage under load
E_{dt}	average continuous transition voltage
E'_t	rms voltage of interphase transformer coil
d	continuous grid voltage component
g	alternating grid voltage component
i	instantaneous anode current
I	continuous current
I_{dt}	transition load
K	coefficient
L	phase inductance
p	number of secondary phases
R	phase resistance
S	shaded area in Fig. 8
u	angle of overlap
x	ωt
x_0	angle of delay
y	angle of delay x_0 plus angle of overlap u
X	phase reactance
X_w	phase working reactance
A_{pn}	coefficient of sine component, nth harmonic in output voltage of p-phase rectifier
B_{pn}	coefficient of cosine component, nth harmonic in output voltage of p-phase rectifier
H_{pn}	rms value, nth harmonic in output voltage of p-phase rectifier
TIF	telephone interference factor
W_n	weighting factor for the nth harmonic

No-Load Voltage With Diametrical Connection

In Fig. 5a sine curves g_1 to g_6 represent the grid alternating voltages. To release the current through its anode, each grid must be at a voltage more positive than a predetermined or critical voltage which is assumed to be the cathode voltage. This assumption is sufficiently accurate for the usual steel-clad rectifiers in which the grid alternating voltages may range from 100 to 200 volts rms while the critical voltage is within a few volts of the cathode voltage. In the figure the grid continuous voltage is represented with reversed polarity; each grid then becomes positive and releases the anode current when the grid alternating voltage curve passes from the negative to the positive side of the line representing the grid continuous voltage. Up to point A these intersections occur at the times of intersection of the anode voltages, represented by curves e_1 to e_6 in Fig. 5b. The no-load output voltage, drawn in heavy line in Fig. 5b, then consists of the peaks of the anode voltages, as in the absence of grids. The continuous voltage obtained from the anode voltage curves under different operating conditions is what may be called the gross continuous voltage; it includes the net continuous terminal voltage as actually measured at the terminals plus the arc drop in the rectifier, and also, when the rectifier is loaded, the resistance drop in the transformer. The net voltage may then be easily computed from the gross voltage; at the usual operating voltages of 600 or more the curves of the 2 voltages remain closely parallel and need not both be considered.

During interval AB the grid continuous voltage component is gradually reduced and then reversed; the grids release the anode currents at increasingly lagging points of the cycle, and the output voltage of the rectifier gradually decreases to zero.

At no load or at low resistive loads the current can flow only when the anode voltages are positive, so that the firing periods of the anodes are shortened, the flow of current being discontinuous when the firing of the anodes is delayed to a large degree.

Computation of the no-load output voltage will be considered with reference to Fig. 6, in which curves e_1 and e_2 represent the voltages of adjacent anodes of a p-phase rectifier, differing by an angle

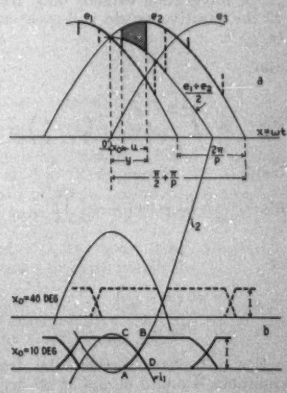


Fig. 6. Commutation of the anode currents, diametrical connection

$2/\pi p$. Taking the intersection of these curves as the origin of abscissas, the equations of the two voltages are:

$$e_1 = E\sqrt{2}\cos[x + (\pi/p)] \tag{1}$$

$$e_2 = E\sqrt{2}\cos[x - (\pi/p)] \tag{2}$$

The period of current flow of each anode extends over an angle $2\pi/p$, the flow of current in anode 2 beginning at the origin of abscissas if the rectifier is not regulated. If all the anode currents are delayed by an angle of delay x_o the firing periods of each anode will remain of normal length, finishing not later than the end of the positive half cycle, if, considering curve e_2, for example,

$$x_o + (2\pi/p) < (\pi/2) + (\pi/p)$$

or $x_o < (\pi/2) - (\pi/p)$

The average gross no-load continuous voltage E'_{do} is equal to the average voltage of anode 2 during its firing period and is then

$$E'_{do} = \frac{1}{\frac{2\pi}{p}}\int_{x_o}^{x_o + \frac{2\pi}{p}} E\sqrt{2}\cos\left(x - \frac{\pi}{p}\right)dx$$

and, by integration,

$$E'_{do} = \frac{E\sqrt{2}\sin\frac{\pi}{p}}{\frac{\pi}{p}}\cos x_o \tag{3}$$

Introducing the no-load voltage E_{do} of the unregulated rectifier of value[6] $E\sqrt{2}\sin(\pi/p)/(\pi/p)$ as the unit of voltages,

$$\frac{E'_{do}}{E_{do}} = \cos x_o \tag{4}$$

showing that the no-load regulated voltage varies with the cosine of the angle of delay regardless of the number of phases of the rectifier. Equation 4 is represented by curve ABC in Fig. 7. When $(\pi/2) - (\pi/p) < x_o < (\pi/2) + (\pi/p)$ the anode firing periods are no longer consecutive and of length $2\pi/p$; integration extends only from x_o to the end of the positive anode half-cycle at angle $(\pi/2) + (\pi/p)$

and

$$E'_{do} = \frac{1}{\frac{2\pi}{p}}\int_{x_o}^{\frac{\pi}{2} + \frac{\pi}{p}} E\sqrt{2}\cos\left(x - \frac{\pi}{p}\right)dx$$

hence

$$E'_{do} = \frac{E\sqrt{2}}{\frac{2\pi}{p}}\left[1 - \sin\left(x_o - \frac{\pi}{p}\right)\right]$$

or

$$\frac{E'_{do}}{E_{do}} = \frac{1 - \sin\left(x_o - \frac{\pi}{p}\right)}{2\sin\frac{\pi}{p}} \tag{5}$$

For a 6-phase rectifier the transition between equations 4 and 5 occurs at 60 deg delay, equation 5 then being represented by curve BD in Fig. 7. Curve ABD in Fig. 7 then illustrates the gradual decrease of the voltage during interval AB in Fig. 5b.

Voltage at Low Inductive Loads

Curve ABD is also valid for pure resistance loads too low to cause an appreciable overlapping of the successive anode currents. In general, however, rectifier d-c circuits are highly inductive. For example, the inductance of ramified 600-volt railway systems averages 1 mh measured at the substation,[7] and in addition, a reactor of from 0.2 to 1 mh is frequently inserted in the d-c line to limit the current in shunt filters used for reducing the output voltage ripple. In a 6-phase rectifier supplied from a 60-cycle line the fundamental frequency of the voltage ripple is 360 cycles, at which frequency a 1-mh reactor constitutes a reactance of 2.26 ohms. In comparison, the load resistance of a 3,600-kv, 600-volt rectifier operating at 10 per cent load, which amounts to 1 ohm, is relatively small. For a first approximation, the load reactance may be considered as so large that the flow of current is sustained during all negative portions of the anode voltages, provided the average voltage remains at all positive. When the average voltage reaches zero to become negative, x_o then being equal to $\pi/2$, the anode currents are no longer consecutive and each anode fires under a voltage of zero average value, the load resistance then being zero. The continuous voltage under this inductive resistance low-load condition differs from the voltage represented by the heavy line in Fig. 5b by the addition of the dotted portions. The average value of the voltage then continues to be represented by formula 4 and follows curve ABC in Fig. 7 to point C, being zero from point C to point D.

If the load inductance is of moderate value the average voltage will follow curve ABC up to some point between B and C, and from this point will rejoin point D. In addition, the physical phenomena

ABD—Average voltage at low resistance load; diametrical connection
ABCD—Average voltage at low inductive load; diametrical connection
HKD—Rms voltage at low resistance load; diametrical connection
HKLD—Rms voltage at low inductive load; diametrical connection
ABEFG—Average voltage at resistance transition load; interphase transformer connection
ABCG—Average voltage at inductive transition load

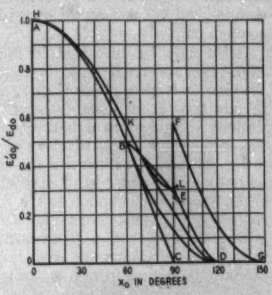


Fig. 7. Variation of the output voltage of 6-phase rectifiers as a function of the angle of delay

of the rectifier being less simple than is assumed here, the experimental values of the voltage may be appreciably lower than those in Fig. 7.[12]

In measuring the average voltage a d'Arsonval voltmeter should be used; a dynamometer voltmeter, however, should be used when the rms value of the voltage is desired. For the load conditions and for the values of x_o at which the average voltage is represented by equation 4, the rms voltage E'_{do} is expressed by

$$E'_{do} = \sqrt{\frac{1}{\frac{2\pi}{p}} \int_{x_o}^{x_o + \frac{2\pi}{p}} \left[E\sqrt{2}\cos\left(x - \frac{\pi}{p}\right)\right]^2 dx}$$

and, by integration,

$$E'_{do} = E\sqrt{1 + \frac{\sin\frac{2\pi}{p}}{\frac{2\pi}{p}}\cos 2x_o} \tag{6}$$

The rms value of the voltage of which equation 5 gives the average value is obtained in a similar manner:

$$E'_{do} = \sqrt{\frac{1}{\frac{2\pi}{p}} \int_{x_o}^{\frac{\pi}{2} + \frac{\pi}{p}} \left[E\sqrt{2}\cos\left(x - \frac{\pi}{p}\right)\right]^2 dx}$$

hence

$$E'_{do} = E\sqrt{\frac{p}{\pi}}\sqrt{\frac{\pi}{4} + \frac{\pi}{2p} - \frac{x_o}{2} - \frac{1}{4}\sin 2\left(x_o - \frac{\pi}{p}\right)} \tag{7}$$

On inductive short circuits, when $x_o > \pi/2$, the average voltage is zero, but the rms voltage has a value

$$E'_{do} = \sqrt{\frac{1}{\frac{2\pi}{p}} \int_{x_o}^{\pi + \frac{2\pi}{p} - x_o} \left[E\sqrt{2}\cos\left(x - \frac{\pi}{p}\right)\right]^2 dx}$$

hence

$$E'_{do} = E\sqrt{\frac{p}{\pi}}\sqrt{\frac{\pi}{2} + \frac{\pi}{p} - x_o - \frac{1}{2}\sin 2\left(x_o - \frac{\pi}{p}\right)} \tag{8}$$

The values of E'_{do} given by formulas 6, 7, and 8, and divided by E_{do}, are plotted as curves *HKL*, *KD*, and *LD*, respectively, corresponding to curves *ABC*, *BD*, and line *CD* of the average voltage. The no load rms voltage then follows curve *HKD*, and the low inductive load voltage curve *HKLD*. Actually, with a load inductance of moderate value, the voltage will rejoin point *D* from a point intermediate between *K* and *L*.

When the rectifier load consists only of a voltmeter of comparatively high resistance and of a comparatively large condenser, the condenser being directly connected across the d-c line or being part of a shunt filter, the condenser is charged at the peak value of the output voltage and remains charged at this value, except that it discharges to some extent through the meter between successive voltage peaks. The voltmeter then reads slightly less than $E\sqrt{2}$ if $x_o < \pi/p$, and reads slightly less than $E\sqrt{2}\cos[x_o - (\pi/p)]$ for greater values of x_o up to $(\pi/2) + (\pi/p)$.

Voltage Under Load

Operation of a p-phase rectifier will next be considered assuming that it carries a d-c load I, and that the load reactance is large enough to effectively suppress the ripple of the load current. Each transformer phase is affected by an inductance L and a resistance R, both referred to the secondary side and including the inductance and resistance of the a-c supply line from the generator to the rectifier. Again, considering the operation of anodes 1 and 2, receiving voltages e_1 and e_2, upon release of the arc at anode 2 the current in anode 1 gradually decays during an interval u while the current in anode 2 rises to its full value I. This transient condition is caused by the phase inductances, phases 1 and 2 momentarily forming a circuit closed by the arc, to which Kirchhoff's second law may be applied:

$$e_1 - Ri_1 - L\,di_1/dt - (e_2 - Ri_2 - L\,di_2/dt) = 0 \tag{9}$$

Solving equations 1, 2, and 9 simultaneously, the formula for i_2 during the commutating period is obtained:

$$i_2 = \frac{E\sqrt{2}\sin\frac{\pi}{p}}{\sqrt{R^2 + X^2}}\left[\sin(x - \varphi) - \epsilon^{\frac{R}{X}(x_o - x)}\sin(x_o - \varphi)\right] + \frac{I}{2}\left(1 - \epsilon^{\frac{R}{X}(x_o - x)}\right) \tag{10}$$

where $\varphi = \tan^{-1}(X/R)$ and $X = \omega L$. Once i_2 is known, i_1 is obtained from the relation

$$i_1 + i_2 = I \tag{11}$$

Formula 10 shows that i_2 consists of a steady state sinusoidal component superimposed on a steady state d-c component and 2 logarithmic transient components. Fortunately, the commutation between anodes occupies only a small part of the cycle, usually less than 30 deg, and the ratio X/R is generally large, of the order of 3, so that no appreciable error is made in neglecting R and in therefore assuming the transient components of i_2 to be constant. Under these assumptions

$$i_2 = \frac{E\sqrt{2}\sin\frac{\pi}{p}}{X}(\cos x_o - \cos x) \tag{12}$$

and hence from equation 11

$$i_1 = I - \frac{E\sqrt{2}\sin\frac{\pi}{p}}{X}(\cos x_o - \cos x) \tag{13}$$

In Fig. 6b are shown in full lines the wave shape of i_1 and i_2 as given by formulas 12 and 13 for an angle of delay of 10 deg. Only portion *AB* of curve i_2 is useful, i_2 being equal to I from point *B* on; i_1 varies from I to zero as shown by portion *CD* of curve i_1.

During interval *AD*, the gross continuous voltage of anodes 1 and 2 firing in parallel is:

$$e'_d = e_2 - L\,di_2/dt$$

This formula, combined with equation 9 in which, in view of equation 11, $di_1 = -di_2$, gives

$$E'_d = \frac{e_1 + e_2}{2} \tag{14}$$

During the periods of overlap, anodes 1 and 2 thus operate at the average of their phase voltages, giving to the continuous voltage curve the aspect indicated by the heavy line in Fig. 6a.

Angle of Overlap

This same figure also shows in dotted lines the current and voltage curves for $x_o = 40$ deg, the axis of the currents being displaced by the proper amount to permit using again the curve of i_2 drawn previously and to illustrate the gradual decrease of the angle of overlap u for increasing values of x_o. It is, however, more convenient to consider, instead of the angle of overlap, the angle $y = x_o + u$, representing the delay in the full voltage operation of the anode, and which may be considered as a generalization of the angle u. Substituting the value y for x in formula 12 gives:

$$\cos x_o - \cos y = \frac{IX}{E\sqrt{2}\sin\frac{\pi}{p}} \tag{15}$$

For computing y it is convenient to utilize a quantity X_w, which will be referred to as "working reactance," which, when referred to the primary side and measured with the d-c line short circuited and carrying the current I, is related to I, X, and E by the formula

$$X_w = 100\,\frac{I_p X_p}{E_p} \tag{16}$$

Therefore X_w is simply the familiar percentage reactance X per cent[8] multiplied by the ratio of the

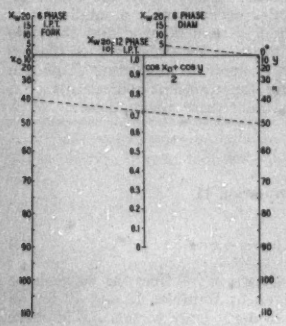


Fig. 8. Chart for computing angle of overlap and average continuous voltage

load I being considered to the full load, and which becomes equal to X per cent at full load. The relation between E_p, I_p, X_p, and E, I, and X differs with the transformer connection; and for any particular connection formula 15 may be written

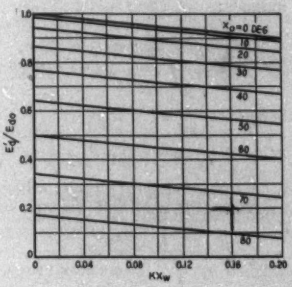
$$\cos x_o - \cos y = KX_w \tag{17}$$

where K is the familiar coefficient of the formula $\cos u = 1 - KX$ relative to uncontrolled rectifiers[8] and corresponding to $x_o = 0$ in formula 17. In general, $E_p = E$ and $X_p = X$, so that

$$K = \frac{I}{I_p}\,\frac{1}{100\sqrt{2}\sin\frac{\pi}{p}} \tag{18}$$

The value of K is 0.0245 for the 6-phase diametrical connection, 0.01 for the 6-phase fork or interphase transformer connection and 0.0516 for the 12-phase interphase transformer connection. Figure 8 is a chart of formula 17. Below the axis of abscissas 2 parallel vertical lines carry linear scales of cos x_o and cos y, respectively, but are graduated in values of x_o and y. Above the axis other vertical lines carry scales of X_w for the 4 transformer connections mentioned above. The scales are so arranged that when a line is drawn between the point marked with the value of X_w considered and a fixed point on the axis all pairs of values of x_o and y are joined by lines parallel to this line. For example, if $X_w = 5$ per cent (diametrical connection)

Fig. 9. Regulation curves for different values of the angle of delay



and $x_o = 40$ deg, y will be 50 deg, and, by difference, $u = 10$ deg.

To obtain the voltage under load in Fig. 5, the values of x_o for each cycle are read on Fig. 5a; y or u is obtained from Fig. 8, and a period of overlap is added in each cycle of Fig. 5b as indicated in Fig. 6, thus obtaining Fig. 5c. This figure is purely illustrative, as it is drawn under the academic assumption of an inductive load drawing a constant current regardless of the voltage. The quantity X_w is taken as 5 per cent, a representative figure for rectifiers operating at full load.

The effect of the phase reactance under load is to decrease the continuous voltage by the shaded area in Fig. 6. The value of this area is

$$S = \int_{x_o}^{y} \frac{e_2 - e_1}{2} = \int_{x_o}^{y} E\sqrt{2}\sin\frac{\pi}{p}\sin x\,dx$$
$$= E\sqrt{2}\sin\frac{\pi}{p}(\cos x_o - \cos y)$$

or, in view of formulas 17 and 18,

$$S = E\,\frac{I}{I_p}\,\frac{X_w}{100} \tag{19}$$

and is, therefore, a constant at constant current. The voltage then becomes

$$E'_d = E'_{do} - \frac{S}{\frac{2\pi}{p}} = E'_{do} - \frac{E\sqrt{2}\sin\frac{\pi}{p}}{\frac{2\pi}{p}}(\cos x_0 - \cos y) \tag{20}$$

Hence, in view of formula 4,

$$E'_d = E_{do}\cos x_o - \frac{E_{do}}{2}(\cos x_1 - \cos y) \tag{21}$$

and

$$\frac{E'_d}{E_{do}} = \frac{\cos x_o + \cos y}{2} \tag{22}$$

This value is read directly on the central vertical line in Fig. 8, and is 0.704 in the example chosen. From formulas 17, 20, and 21 also follows:

$$E'_d = E'_{do} - \frac{KX_w}{2}E_{do} \tag{23}$$

and

$$\frac{E'_d}{E_{do}} = \cos x_o - \frac{KX_w}{2} \tag{24}$$

The above relations obtain up to $x_o = \pi/2$; at greater values of x_o the anode currents are no longer consecutive, and the rectifier operates at zero average continuous voltage on an inductive short circuit. The curves of the average voltage in function of x_o at different loads are all identical to curve ABC in Fig. 7, but are displaced vertically below ABC by the amount $KX_w/2$. The curves of the voltage in function of KX_w are parallel straight lines, shown in Fig. 9. The inherent regulation is the same for any value of x_o, including the value zero obtained in the unregulated rectifier. This figure may also be provided with different scales of abscissas graduated in values of X_w for the values of K corresponding to any desired connection.

Back Emf Load and Output Voltage Harmonics

In general, the load of a rectifier, in addition to being inductive, consists for the most part of a back emf due, for instance, to traction motors or to electrolytic cells. In many instances, also, rectifiers are operated in parallel with synchronous converters or with d-c generators. In either case voltage regulation of the rectifier by grids, which increases the ripple of the rectifier output voltage, may result in the rectifier net voltage being lower than the load back emf or the voltage of the other converters. As long as the average net voltage of the rectifier remains higher than the back emf or generator voltage, and provided that the rectifier d-c feeder has considerable inductance, the anode currents remain consecutive and the rectifier output current remains continuous at the voltage obtained above for the inductive load condition. When these conditions are no longer fulfilled, however, the current consists of a succession of non-consecutive impulses, and when the rectifier peak output voltage is less than the back emf or generator voltage, the rectifier ceases operating.

The value e'_d of the regulated output voltage of a p-phase rectifier may be represented by a Fourier series similar to the series representing the unregulated voltage,[3] but in which the constant term has the new value E'_d. Thus

$$e'_d = E'_d + \Sigma A_{pn}\sin npx + \Sigma B_{pn}\cos npx \tag{25}$$

coefficients A and B being obtained by integration over a complete ripple of the output voltage:

$$A_{pn} = \frac{p}{\pi}\int_{x_o}^{x_o+\frac{2\pi}{p}} e'_d \sin npx\, dx$$

$$B_{pn} = \frac{p}{\pi}\int_{x_o}^{x_o+\frac{2\pi}{p}} e'_d \cos npx\, dx$$

For this integration e'_d may be separated into an overlap portion and a full anode voltage portion:

$$e'_d = \left[\frac{e_1+e_2}{2}\right]_{x_o}^{y} + \left[e_3\right]_{y}^{x_o+\frac{2\pi}{p}}$$

$$= \left[E\sqrt{2}\cos\frac{\pi}{p}\cos x\right]_{x_o}^{y} + \left[E\sqrt{2}\cos\left(x-\frac{\pi}{p}\right)\right]_{y}^{x_o+\frac{2\pi}{p}}$$

Hence,

$$A_{pn} = \frac{pE\sqrt{2}}{\pi}\left[\int_{x_o}^{y}\cos\frac{\pi}{p}\cos x\sin npx\, dx + \int_{y}^{x_o+\frac{2\pi}{p}}\cos\left(x-\frac{\pi}{p}\right)\sin npx\, dx\right]$$

and, by integration, and dividing by E_{do},

$$\frac{A_{pn}}{E_{do}} = \frac{1}{2}\left[\frac{\sin(np+1)y}{np+1} - \frac{\sin(np-1)y}{np-1} + \frac{\sin(np+1)x_o}{np+1} - \frac{\sin(np-1)x_o}{np-1}\right] \tag{26}$$

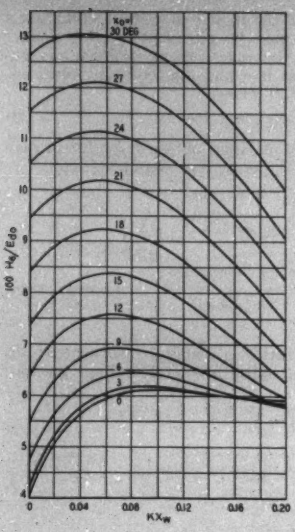
B_{pn} is obtained in a similar manner:

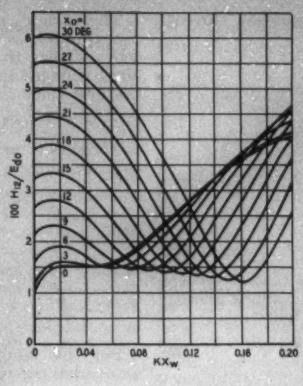
$$\frac{B_{pn}}{E_{do}} = \frac{1}{2}\left[\frac{\cos(np+1)y}{np+1} - \frac{\cos(np-1)y}{np-1} + \frac{\cos(np+1)x_o}{np+1} - \frac{\cos(np-1)x_o}{np-1}\right] \tag{27}$$

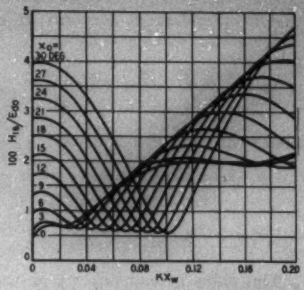
The rms value H_{pn} of the nth harmonic, expressed in per cent of the no-load unregulated voltage E_{do}, is

$$100\frac{H_{pn}}{E_{do}} = 100\sqrt{\frac{\left(\frac{A_{pn}}{E_{do}}\right)^2 + \left(\frac{B_{pn}}{E_{do}}\right)^2}{2}} \tag{28}$$

Figures 10, 11, and 12 show formula 28 plotted for the sixth, twelfth, and eighteenth harmonics, of orders 1, 2, and 3, respectively, of 6-phase rectifiers for a few values of x_o, against abscissas of KX_w. Formulas 26 and 27 contain, as variables, the product np, x_o, and y; the latter is obtained in function of x_o and KX_w from formula 17. These figures, therefore, give the values of harmonics of order n in any polyphase rectifier where pn is equal to 6, 12, and 18. In particular Fig. 11 is directly applicable to 12-phase rectifiers, in which the twelfth harmonic







Figs. 10, 11, and 12. Sixth (left), twelfth (center), and eighteenth (above) harmonic components of the output voltage

is of order 1. Theoretically the sixth and eighteenth harmonics are absent from the output voltage of 12-phase rectifiers, but unequal division of load between the 2 sets of 6 phases causes these harmonics to appear[13] and it is not improbable that, in each particular case, they vary in accordance with Figs. 10 and 12, read with larger scales of ordinates.

The different harmonics of orders n each have a phase angle equal to $\tan^{-1} B_{pn}/A_{pn}$ with respect to the origin 0 of angles in Fig. 6. When the primary voltage of the rectifier is not sinusoidal, its harmonics cause the appearance, in the output voltage, of harmonics of the same order as those due to the action of the rectifier. The harmonics from the 2 causes should be added vectorially to obtain their measurable aggregate value.

6-Phase Operation With Interphase Transformer

All the switches s in Fig. 4 being reversed, the anode voltages are retarded 30 deg and increased in the ratio of 1 to cos 60 deg; their curves e_1 to e_6 are shown in Figs. 5d and 5e, anodes 1, 3, and 5 operating as in a 3-phase rectifier, and anodes 2, 4, and 6 operating as in another 3-phase rectifier, the parallel operation of the 2 systems being insured by the interphase transformer. In Figs. 5d and 5e the heavy lines represent the output voltages of the systems when controlled by the grids, again energized as shown in Fig. 5a. These voltages are not drawn for no load operation, the interphase transformer then being inoperative, but for a low non-inductive load not less than the lowest load at which the interphase transformer operates normally, the so-called transition load.[10] The value of the transition load varies with the value x_o; it is of the order or magnitude of 2 per cent of full load for $x_o = 0$, and causes no material overlapping of the anode currents. The voltages across the 2 halves of the interphase transformer are necessarily equal so that when the interphase transformer is effective, the gross instantaneous output voltage of the rectifier is the average of the output voltages of the 2 systems, shown in Figs. 5d and 5e. This voltage is drawn in Fig. 5f, which is identical with Fig. 5b for $x_o < (\pi/2) - (\pi/p)$; its average value is given by formula 4, in which E_{do} is, however, to be replaced by the transition voltage $E_{dt} = E\sqrt{2} \sin (2\pi/p)/(2\pi/p)$. The average value of the voltage is then also represented by curve AB in Fig. 7. This operating condition obtains up to point C in Fig. 5f, at which the voltage begins presenting negative portions. Between points C and D the flow of current occurs alternately through 2 anodes and through a single anode. When the momentary voltage is positive, current is carried simultaneously by 1 anode of each system, and when it drops to zero the negative anode ceases firing and the positive anode continues alone at its own phase voltage until another anode forms a new pair with it. From the transition value of the load up, when the current is carried by a single anode, the core of the interphase transformer is highly saturated and, although the interphase transformer then operates as a reactor in the anode circuit, its effect is negligible.

This operating condition is illustrated in detail in Fig. 13, in which the origin of angles previously used in Fig. 6 is retained; the continuous voltage consists of consecutive portions of curves of e_1 and $(e_1 + e_2)/2$, represented by the formula:

$$e'_d = \left[E\sqrt{2}\cos x\right]_{\frac{\pi}{2}-\frac{\pi}{p}}^{x_o} + \left[E\sqrt{2}\cos\frac{\pi}{p}\cos\left(x-\frac{\pi}{p}\right)\right]_{x_o}^{\frac{\pi}{2}+\frac{\pi}{p}}$$

and, by integration, its average value is

$$E'_d = \frac{E\sqrt{2}}{\frac{2\pi}{p}}\left[\int_{\frac{\pi}{2}-\frac{\pi}{p}}^{x_o} \cos x\,dx + \int_{x_o}^{\frac{\pi}{2}+\frac{\pi}{p}} \cos\frac{\pi}{p}\cos\left(x-\frac{\pi}{p}\right)dx\right]$$

and

$$E'_d = \frac{E\sqrt{2}}{\frac{2\pi}{p}}\sin\frac{\pi}{p}\cos\left(x_o-\frac{\pi}{p}\right)$$

Hence, introducing E_{di} as a unit,

$$\frac{E'_d}{E_{di}} = \frac{\cos\left(x_o-\frac{\pi}{p}\right)}{2\cos\frac{\pi}{p}} \tag{29}$$

Formula 29 is represented by curve BE in Fig. 7, and is valid up to $x_o = \pi/2$.

When $x_0 > \pi/2$, each anode of one system becomes negative and ceases firing before the following anode of the other system is released; the 2 systems then carry current alternately in non-consecutive periods and operate as a single p-phase system. The voltage is then

$$E'_d = \frac{1}{\frac{2\pi}{p}}\int_{x_o}^{\frac{\pi}{2}+\frac{2\pi}{p}} E\sqrt{2}\cos\left(x-\frac{2\pi}{p}\right)dx$$
$$= \frac{E\sqrt{2}}{\frac{2\pi}{p}}\left[1-\sin\left(x_o-\frac{2\pi}{p}\right)\right]$$

and hence

$$\frac{E'_d}{E_{di}} = \frac{1-\sin\left(x_o-\frac{2\pi}{p}\right)}{\sin\frac{2\pi}{p}} \tag{30}$$

Formula 30 is represented by curve FG in Fig. 7. When x_o is varied from zero to 150 deg there is, therefore, a considerable discontinuity in the continuous voltage for $x_o = 90$ deg.

The voltage across each half of the interphase transformer is equal to the difference between the ordinates of Figs. 5d and 5f or 5e and 5f, or to half of the difference between the ordinates of Figs. 5d and 5e. In a p-phase system of frequency f, this voltage is of frequency $pf/2$, but is not sinusoidal, its value following only portions of sine curves of the form $E\sqrt{2}\sin(\pi/p)\sin x$. It is represented by the heavy line in Fig. 5g and in Fig. 13.

For $x_o < (\pi/2) - (\pi/p)$ the rms value of the voltage is

$$E'_i = \sqrt{\frac{p}{2\pi}\int_{x_o}^{x_o+\frac{2\pi}{p}}\left[E\sqrt{2}\sin\frac{\pi}{p}\sin\left(x-\frac{\pi}{p}\right)\right]^2 dx}$$

which, by integration, gives the relative values of this voltage compared to the phase voltage E:

$$\frac{E'_i}{E} = \sin\frac{\pi}{p}\sqrt{1-\frac{p}{2\pi}\sin\frac{2\pi}{p}\cos 2x_o} \tag{31}$$

Formula 31 applied to the 6-phase rectifier is represented by curve AB in Fig. 14. When $(\pi/2) - (\pi/p) < x_o < \pi/2$ the operating period of frequency $pf/2$ of the interphase transformer is less than $2\pi/p$ as its action is suspended during the period of single-anode operation. The interphase transformer voltage is then

$$E'_i = \sqrt{\frac{p}{2\pi}\int_{x_o}^{\frac{\pi}{2}+\frac{\pi}{p}}\left[E\sqrt{2}\sin\frac{\pi}{p}\sin\left(x-\frac{\pi}{p}\right)\right]^2 dx}$$

hence

$$\frac{E'_i}{E} = \sin\frac{\pi}{p}\sqrt{\frac{p}{\pi}}\sqrt{\frac{\pi}{2p}+\frac{\pi}{4}-\frac{x_o}{2}+\frac{1}{4}\sin 2\left(x_o-\frac{\pi}{p}\right)} \tag{32}$$

as represented by curve BC in Fig. 14.

For $x_o > \pi/2$ the interphase transformer acts as a saturated reactor and its voltage is generally negligible.

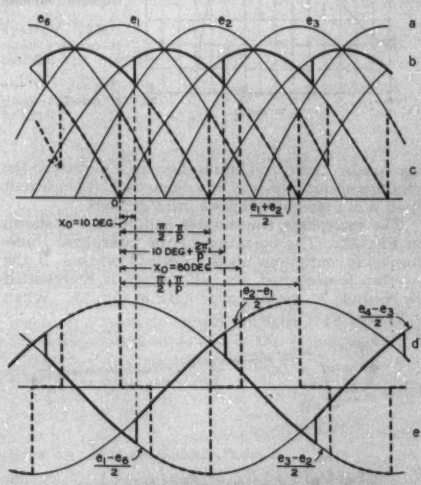


Fig. 13. Voltage output of p-phase rectifier with interphase transformer; alternate single- and 2-anode operation at resistance transition load

a—Anode voltages
b—Continous voltage, x_o — 10 deg
c—Continuous voltage, x_o — 80 deg
d—Interphase transformer coil voltage, x_o — 10 deg
e—Interphase transformer coil voltage, x_o — 80 deg

Figures 5h to 5k are the counterparts of Figs. 5d to 5g, assuming the same value of reactive load as in Fig. 5c and a working reactance of 12.25 per cent to obtain the same characteristics with both connections. Considering that at full load the working reactance of rectifier transformers is in the neigh-

borhood of 5 per cent regardless of their connections, Fig. 5c is representative of actual full-load operation, and Figs. 5h to 5k correspond to actual operation at 2.45 times full load. The load being inductive, the continuous current is maintained uninterrupted until the average continuous voltage reaches zero. Under these conditions the voltage curve in Fig. 5j is identical with the curve of Fig. 5c, and its value is given by curve ABC in Fig. 7, displaced downward by $KX_s/2$. The regulation curves for these conditions are again those of Fig. 9, except for values of load below the transition load E_{st}. When the average value of the voltage of the rectifier, with the 2 systems operating in parallel, becomes negative, alternate 1- and 2-anode operation is established, and when the average value of voltage under these conditions becomes negative, the rectifier operates instead as a diametrical 6-phase unit with non-consecutive anode firing periods.

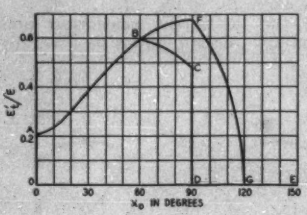


Fig. 14. Voltage (rms) of one coil of interphase transformer of a 6-phase rectifier

ABCDE—Voltage at resistance transition load

ABFGE—Voltage at inductive transition load

The interphase transformer half-voltage is shown in Fig. 5k. The operation of the interphase transformer is continuous up to $x_s = \pi/2$, so that, if the overlap is neglected, its half-voltage is represented by formula 31, giving curve ABF in Fig. 14. When $\pi/2 < x_s < (\pi/2) + (\pi/p)$

$$E'_t = \sqrt{\frac{p}{2\pi}\int_{x_s}^{\frac{2\pi}{p}+\pi-x_s}\left[E\sqrt{2}\sin\frac{\pi}{p}\sin\left(x-\frac{\pi}{p}\right)\right]^2 dx}$$

hence

$$\frac{E'_t}{E} = \sin\frac{\pi}{p}\sqrt{\frac{p}{\pi}}\sqrt{\frac{\pi}{p}+\frac{\pi}{2}-x_s+\frac{1}{2}\sin 2\left(x_s-\frac{\pi}{p}\right)} \qquad (33)$$

which is represented by curve FG in Fig. 14.

For $x_s > \pi/2$ the interphase transformer is inactive and its voltage is nearly zero. Formulas 31 and 33 are accurate only if the overlap is negligible; in general, the angles of overlap are considerably smaller than those shown in Fig. 5k, and the error is not considerable. When x_s is large, the values given by the formulas are somewhat in excess, and are, therefore, safe for interphase transformer calculations. When the rectifier load includes a back emf, or if generators are connected in parallel with the rectifier, the rectifier current will remain continuous as long as the average output voltage of the rectifier is greater than the system emf. When x_s is further increased, the rectifier operates alternately on 1 and 2 anodes, and the current is still continuous if the average voltage then obtained is greater than the system emf.

As is well known, the no-load voltage of the uncontrolled rectifier with interphase transformer is materially higher than the voltage under load. This effect is present also when the voltage is regulated by grids[14] and, although the no-load regulated voltage is always lower than the no-load unregulated voltage, the voltage rise may be greater in proportion and should be guarded against. This phenomenon can be avoided to a certain extent. For example, each grid may be so controlled as never to remain positive for any material length of time. Considering the anode voltages in Fig. 13, and remembering that at no load the rectifier operates as in diametrical 6-phase connection, if $x_s < \pi/p$, and anode the 1 is carrying current, anode 2 is released when it is negative with respect to anode 1 and it does not take the arc; when anode 2 becomes more positive than anode 1 it is again blocked by its grid, and the arc can only be transferred to anode 3. Only the system of anodes 1, 3, and 5 then operates and the continuous voltage remains at its transition value for the value of x_s utilized. The system of anodes 2, 4, and 6 may also be completely blocked by making the grids negative with a load responsive relay.[15]

Limitations of Grid Control

Voltage regulation by means of grid control is of universal application, being suited equally well to glass and to steel-clad rectifiers, regardless of the nature of the load. The advantages of its use in preference to other methods of control should, however, be determined in each case, particularly with regard to efficiency and power factor.

In an uncontrolled rectifier, if the transformer magnetizing current and the anode current overlap are neglected, the power factor of the primary current differs from unity only because of the distorted shape of the current, causing the kva taken by the rectifier to exceed its kw input, although the current is in phase with the voltage. In a 6-phase rectifier the power factor has the value 0.955. When the anode currents are delayed at constant load by an angle x_s, the primary current is simply shifted bodily by the same angle x_s, whereby the power factor is multiplied by $\cos x_s$. The curve of power factor against angle of delay is shown in Fig. 15, which shows that, for values of x_s greater than 30 deg, the power factor becomes poor. This shift of the current does not change the losses in the rectifier or in the transformer, so that the efficiency may be computed in function of x_s. At 600 volts these losses are of the order of 5.5 per cent of the unregulated output E_sI. When the anode currents are retarded by an angle x_s, the output becomes $E_sI \cos x_s$, and the efficiency decreases to

$$\frac{100 \cos x_s}{(100 \cos x_s + 5.5)} \qquad (34)$$

This value is also plotted in Fig. 15, which shows that the efficiency remains acceptable over a wide

range of values of x_e. A moderate degree of regulation can therefore be obtained by grid control without adversely affecting the characteristics of the rectifier. If a wide regulation is utilized at infrequent intervals, as for starting a constant voltage bank of electrolytic cells at reduced voltage, the low efficiency and power factor may be unimportant. When a widely variable number of cells is to be fed continuously, high power factor and efficiency may be restored by combining a coarse regulation by tap changing with only a fine regulation by means of grids.

Inductive Interference

In systems adjacent to extensive communication circuits the probability of inductive action of the power circuits on the communication circuits should be considered. In general, as appears from Figs. 10, 11, and 12, grid control increases the magnitude of the a-c components of the continuous voltage, but the involved laws of variation of these harmonics make it necessary to consider each case separately. Let the case be considered of a 60-cycle 6-phase rectifier with interphase transformer, operating at an unspecified voltage, and assuming that a flat characteristic is desired up to full load at the unregulated full-load value of voltage. The inherent regulation of the rectifier net voltage will be somewhat as follows:

Regulation due to 5 per cent reactance	2.5 per cent
Increase in arc drop from no load to full load	0.75 per cent
Resistance drop in transformer windings	1.75 per cent
	5.00 per cent

The voltage should then be maintained at 95 per cent of the net no load, or rather, transition voltage. The telephone interference factor TIF of the output voltage is given by the formula[11]

$$TIF = \frac{\sqrt{\Sigma(H_n W_n)^2}}{E_d}$$

where H_n is the rms value of the harmonic of order n, W_n a factor called weighting factor, and E_d the rms output voltage, for which the average value will be substituted as x_e will be small. When the voltage is not regulated, $E_d = E_{do}[1 - (X_w/2)]$ and

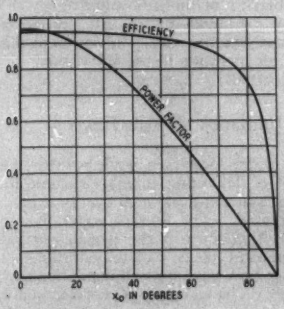
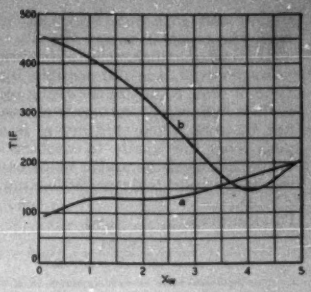


Fig. 15. Approximate efficiency and power factor of a grid-controlled 6-phase 600-volt rectifier at full load

Fig. 16. Telephone interference factor (TIF) of a 6-phase 60-cycle rectifier with interphase transformer connection

a—Without regulation
b—With flat regulation



$$TIF = \frac{\sqrt{\Sigma\left(\frac{H_n}{E_{do}}\right)^2 E_{do}^2 W_n^2}}{E_{do}\left(1 - \frac{X_w}{2}\right)} = \frac{\sqrt{\Sigma\left(\frac{H_n}{E_{do}}\right)^2 W_n^2}}{1 - \frac{X_w}{2}} \tag{35}$$

When the voltage is regulated $E_d = 0.95\ E_{do}$ and

$$TIF = \frac{\sqrt{\Sigma\left(\frac{H_n}{E_{do}}\right)^2 W_n^2}}{0.95} \tag{36}$$

The TIF values given by formulas 35 and 36 are plotted in Fig. 16 against the working reactance, but include only the sixth, twelfth, and eighteenth harmonics given by Figs. 10, 11, and 12, affected by weighting factors of 700, 3,300, and 16,300, respectively. The value of x_e is maximum at transition load, at which TIF is also maximum. Grid control, however, causes a decrease of TIF at some loads because the eighteenth harmonic, the most disturbing from a 60-cycle supply frequency, decreases for increasing values of x_e at certain values of X_w. If a greater degree of regulation is desired, the maximum TIF will be correspondingly greater, but its value can always be reduced to a reasonable figure by means of filters.

Current-Interrupting Grids

In the above considerations it was assumed that the grid could only prevent the initiation of the anode current when negative, and release the current upon becoming positive, without having any action on the current after its establishment, thus acting as a trigger for starting the anode during each cycle. This type of grid is in general use at present. It has, however, been determined[16] that when the grid has certain dimensions it can regain control of the arc upon again being made negative. The interruption of the arc occurs with extreme rapidity; if each grid is energized positively only during the firing period of its anode, each anode current is interrupted instantly while the following anode current is released, and the anode currents follow each other without any overlap. The output voltage

under load with delayed anode operation will then have the aspect shown in Fig. 5b.

Instead of utilizing the falling branch of each anode voltage curve, it is also possible, by the action of this type of grid, to utilize the rising branch; each anode is then followed by an anode of lower voltage, as cannot be done when the current is simply allowed to pass from one anode to another. The anode currents then lead the anode voltages, and the alternating line current is drawn at leading power factor.

References

1. Sur le Courant de Reaction de l'Arc Électrique, Jamin and Maneuvrier. *Compt. rend.*, v. 94, 1882, p. 1615–19.

2. The Conversazione of the American Institute of Electrical Engineers—Electric Light From Vapor Tubes, Cooper-Hewitt. *Elec. Wld. and Engr.*, 1901, p. 841.

3. Hermetically Sealing Mercury Vapor Apparatus With Mercury Packing, B. B. Schaefer. *U.S. Patent No. 1,042,592;* Vapor Electric Apparatus, B. B. Schaefer. *U.S. Patent No. 1,097,473.*

4. System of Electrical Distribution, P. H. Thomas. *U.S. Patent No. 783,482.*

5 to 11. Mercury Arc Power Rectifiers, Marti and Winograd. McGraw-Hill Book Co., New York. (5) Chapters III, IV, and V; (6) p. 50; (7) p. 409; (8) p. 164; (9) p. 88–93; (10) p. 131; (11) p. 416.

12. Grid and Plate Currents in a Grid-Controlled Mercury Vapor Tube, Seletzky and Shevki. *Jl. Franklin Inst.*, March 1933, p. 399–326.

13. Current and Voltage Wave Shape of Mercury Arc Rectifiers, Brown and Smith. A.I.E.E. Trans., v. 52, 1933, p. 974–84.

14. Théorie des Redresseurs à Arc à Commutation Retardée, Demontvignier. *Rev. Gen. de l'Elec.*, Nov. 19, 1932, p. 659–67.

15. Arrangement for Preventing Voltage Increase With Complete No-Load Operation of Mercury Vapor Direct-Current Rectifiers, E. Kern. *U.S. Patent No. 1,843,133.*

16. Untersuchung eines brennenden Anodenstromes mittels Gitter im Quecksilberdampf-Gleich- oder Wechselrichter, E. Kobel. *Schweiz. Elektrot. Verein, Bull.*, Feb. 1, 1933, p. 41–8.

A Survey of Hydroelectric Developments

A general outline of the status of modern hydroelectric developments is presented in this report by an A.I.E.E. subcommittee.* Major topics discussed are: developed water power of the world, present trends in utilization of water power, and hydraulic and hydrodynamic research. It is hoped that this report not only will present a retrospective picture of results achieved, but also will serve as a source from which general information can be obtained and conclusions drawn concerning modern trends of hydroelectric developments.

NORMAL GROWTH of the electric power generation industry was retarded considerably during the last few years. Furthermore, the nature and extent of future growth does not seem to be very clear, particularly so far as hydroelectric developments are concerned. Under such conditions it seems to be very timely to take stock of the results achieved and to outline the present status of modern hydroelectric developments. This survey is an attempt to give such an outline. It is hoped that the survey not only will present a retrospective picture, but also will serve as a source from which general information can be obtained and conclusions drawn concerning the modern trends of hydroelectric developments.

So far as possible, this survey was kept on an international basis; and although the United States and Canada take the most prominent part in the survey, all information pertaining to other countries that could be made available and was considered of interest is included. The survey is not 100 per cent complete, but an effort was made to include all important factors, based mostly upon authentic data supplemented in some cases by reasonable estimates and interpretations of such data.

The international character of the survey was made possible by the splendid assistance given by the foreign membership of the subcommittee.

Editor's Note: Extended statistical section of this report not ready in time for publication in this issue: scheduled for inclusion in the July issue.

Part of a paper recommended for publication by the A.I.E.E. committee on power generation, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 6, 1934; released for publication May 12, 1934. *Not published in pamphlet form.*

* Subcommittee on hydroelectric survey of the A.I.E.E. committee on power generation: A. V. Karpov, chairman, Pittsburgh, Pa., F. A. Allner, Baltimore, Md., E. W. Dillard, Boston, Mass., J. P. Hogan, New York, N. Y.; J. Elmer Housley, Alcoa, Tenn., A. H. Hull, Toronto, Ont., Can., S. Kloumann, Oslo, Norway, Jean Leclerc du Sablon, Toulouse, France, C. F. Mackness (deceased), London, Eng., J. M. Oliver, Atlanta, Ga., R. E. B. Sharp, Philadelphia, Pa., J. E. Stewart, Pittsburgh, Pa., and K. Tsuruta, Tokyo, Japan.

Mr. André Henry-Coüannier, civil and mining engineer, assisted by Mr. Roger Deshayes, engineer E.S.E. (Ecole Supérieure d'Electricité) both of Paris, France, were instrumental in collecting the data pertaining to the production of hydraulic turbines in Europe. The map showing the major hydroelectric developments of the North American continent was prepared by Mr. F. K. Mayhood.

Present Trend in Utilization of Water Power

Utilization of water power is governed by the basic requirement of delivering energy economically to localities where a demand for such energy is present or can be created. The flow of water in any stream shows variations even if the stream is regulated by large natural lakes. Flow variations in streams that do not have such natural regulation may become very large. The economy of a water power

development depends largely on the degree of utilization of the available water, optimum utilization being obtained with synchronization of flow and energy demand. The most obvious method of accomplishing this is to create an artificial water storage to regulate the stream flow so as to make water available at all times to supply the energy demand. In any water power development, a certain amount of storage is created by the building of a dam and impounding water back of it. Only in very rare cases, however, can such incidental storage have much regulating influence. In practically all cases the creating of artificial storage large enough to regulate the flow satisfactorily will require a heavy expenditure. In localities that are well suited for use as storage sites, as for instance in Switzerland and some parts of Canada, such natural advantages usually are fully utilized.

The Boulder Dam plant, now under construction on the Colorado River, is the most outstanding example of a plant on a river having extreme flow fluctuations that will be regulated artificially for irrigation and power purposes; these fluctuations will be regulated to an extent never previously attempted and that probably will not be repeated for many years on such a scale.

In many cases the cost of the desirable amount of storage is prohibitive, and best economy is obtained by partial regulation of the water flow and complementary adjustment of the energy demand.

Influence of Electrochemical and Electrometallurgical Industries

In the last few decades several industries using large amounts of electric energy were developed. The modern trend decidedly favors the substitution of processes based upon the utilization of electric energy for the purely chemical processes previously used. The manufacture of hydrogen and the electrical methods of producing aluminum oxide from bauxite, the basic ore, are a few of the indications of that trend. The processes in most of these industries are of such character that the energy demand can be adjusted within wide limits.

Energy cost is a major factor for an industry using large quantities of electric energy per unit of product, so that it may be economical to locate the production plant close to a source of cheap electric energy even though the location may be remote from the source of raw materials and from the market for the finished product.

The financing of most of the water power developments in outlying poorly populated districts, was made possible only by the demand for electric energy that was created by such industries. This not only turned the wasted water energy to useful purposes, but incidentally resulted in these districts becoming modern highly developed communities.

The latest developments at the upper part of the Saguenay River in Canada are quite representative in that respect. The Saguenay flows from the Lake St. John, which acts as a natural regulator of the water flow of the river, and consequently the flow fluctuations are somewhat moderated. The plants already built or proposed on that river are to supply large blocks of power to electrometallurgical and paper industries. The economical justification of these developments is based upon the fact that the power demand of these industries may be regulated so that for the largest part of the time the demand will be synchronized with the available supply of energy.

The recent considerable increase of developed water power in Norway follows along the same line. The utilization of the vast available, but undeveloped, water powers of the Asian mainland, of Africa, and of South America in all probability will be made possible by the same gradual process of establishing industries demanding large blocks of cheap electric energy.

The Dneiperstroy development, on the Dneiper River in Russia, is a sample of such a development built on a very flashy river with a limited amount of artificial regulation. The economical justification of this development is based upon the expectation that the power demand of the industries yet to come can be regulated to the necessary extent.

Interconnections

A hydroelectric plant located in an outlying district and supplying energy in large blocks to a limited number of industries has primarily the one purpose of transferring the maximum possible amount of available water power into useful energy. A hydroelectric plant located in close proximity to populated or highly industrialized districts has to carry a diversified utility load; this means the supplying of the necessary amount of energy when the demand occurs. The economical operation of such plants is made possible by the wide use of interconnections.

In the past it was a common practice to operate plants independently. Even at present they may be operated in such way if the industrial energy demand can be suitably regulated. However, the modern trend is to make hydroelectric plants links in power systems to obtain better economy in supplying increased energy demands.

The advantages of interconnection are such that no development of any importance can overlook them, and even if an immediate interconnection between existing systems cannot be justified, the way is left open for future interconnections. Consequently, all developments of appreciable size put into operation during the last decade were alternating current developments even in cases where the bulk of the generated electric energy had to be transformed into direct current for the ultimate use in the electrochemical or electrometallurgical industries. The Lochaber direct current development of the British Aluminum Company is the only exception.

Interconnections provide economical and operating benefits that sometimes make it possible to break through territorial boundaries. The interconnections between the power systems of Switzerland and those of France, Germany, Austria, and Italy, are the most outstanding instances of an in-

ternational widespread interconnected energy supply system.

Present interconnected systems are of different character. The combination of many water power developments of different kind and character often located on different drainage basins, some with storage capacity and some without, may result in a satisfactorily regulated system even without including any thermal plants in the system.

The developments that are combined by the Hydroelectric Power Commission of Ontario may be cited as an example. Here the backbone is formed by the Niagara Falls developments, and the utilization of the system is improved by supplying blocks of power to industries the power demand of which can be regulated.

In most cases the interconnected systems include thermal as well as water power plants. The systems located in the western part of the United States and the interconnected plants in Sweden may be cited as interconnections in which the main part of energy is supplied by hydroelectric plants.

During later years hydroelectric developments are gaining in importance in such localities, as, for instance, the eastern part of the United States, where very large loads are carried by thermal plants.

Capacity needed for short periods to meet peak load requirements often may be provided economically in hydroelectric plants. The comparatively small increment cost of additional capacity of hydroelectric plants makes it advantageous to provide equipment many times in excess of the average load. If such plants are operated only a limited number of hours comparatively large peak loads can be handled. The recent Susquehanna River developments at Conowingo (Md.) and Safe Harbor (Pa.) are typical not only in that respect, but also as developments that could not be justified economically without a previously developed large thermal capacity.

In systems having relatively large thermal capacities, the hydroelectric plants may fulfill advantageously several functions in addition to the main one of supplying electric energy. In a modern hydroelectric plant a unit may be started from standstill, brought to proper speed, synchronized, connected with the system and deliver its rated capacity within a very few minutes. A steam unit under stand-by conditions may pick up the load quickly, but ordinarily requires a long time if both boilers and unit are cold. Consequently the hydroelectric unit is better adapted for stand-by service or for use as a spare unit. Very often the stand-by characteristics are improved by having the unit permanently connected to the system, idling the turbine and utilizing the generator as a synchronous condenser, to improve the electrical characteristics of the system.

The energy consumption of such idling units is reduced sometimes by automatically breaking the vacuum or by forcing the water from the turbine runner by means of compressed air. If a failure occurs in some part of the system, such an idling unit may be loaded to full capacity within a few seconds.

Pumped Storage Plants

In the past, small pumping plants were used in high head European developments. These plants did not operate on a complete pumping cycle, but collected in a single intake the water of several small streams. Since usually the pumping head was low compared with the total head, the resulting increase of the plant output was much larger than the amount of energy spent in pumping. At present the use of pumped storage plants operating on a complete pumping cycle is rapidly gaining in importance, due to the wide use of interconnections.

The economical value of energy to a system having daily or seasonal load peaks depends to a large extent on the time at which the energy may be made available. If the power demand cannot be synchronized entirely with the available power, then the power required to meet peak load conditions has a high value, whereas the excess of power available during low load periods has a much lower value.

It may be economical to increase the utilization of the available storage capacity by using a pumping scheme. In spite of the fact that under average conditions the efficiency of a complete pumping cycle is only about 60 per cent, it may be economical to invest 100 kwhr at times of low demand to secure a return of 60 kwhr when energy is needed badly.

Most of the pumped storage plants are located in Europe, the Rocky River (Conn.) development being the only plant of appreciable size in the United States. Some of these plants are located in Switzerland, being used to cover the season deficiency of power. Several are located in Germany and France, being used to take care of the daily peaks. It is of interest that one of the largest pumping storage plants located at Niederwartha near Dresden in Germany is built to meet the peak load requirements of a purely thermal system. The economical justification of such a scheme is based upon the high over-all efficiency of a steam plant with base load operation and the low aggregate steam plant capacity that may be well below peak load demands.

In spite of the small storage capacity of the Safe Harbor plant, it is proposed to take care of the anticipated increase of the peak load of the system to which that plant supplies power by introducing a pumping cycle at Safe Harbor, using steam power for pumping, instead of increasing the steam generating capacity.

Economy in Design and Operation

Considerable advance was made during the past few years in improving the economy of modern developments. Work in that direction still goes ahead on all important phases, the tendency being to reduce the first cost, to improve the over-all efficiency, and to reduce the cost of operation.

So far as the structural design is concerned, more economical designs of gravity and arch dams are possible if knowledge is increased regarding the actual distribution of stresses in dams. In that respect the most extensive study was made on arch dams, by means of measurements made on such dams and

by several model studies. This work should result in safer and more economical designs of such dams.

In power plant design the most important economy was achieved along 2 lines: first, the increase of the size of units, and second, the increase of specific speed in particular of units for low head developments. Both are results of extensive theoretical and experimental studies, and in all probability future improvements in these directions are possible.

The extensive use of interconnections made it possible to improve the utilization of the available water energy by increasing the installed power plant capacity.

For an isolated hydroelectric plant the economical capacity usually will correspond fairly closely to the average water flow. Under ordinary conditions, the interconnection of several hydroelectric plants will increase the economical capacity of each plant. Finally, for hydroelectric plants that are linked to a large thermal system, the economical capacity may be still higher and will approach more closely the capacity corresponding to the maximum flow.

So far as improvement in efficiency is concerned, the efficiencies of some of the hydraulic units approach 94 per cent at their best points, so that not much opportunity is left for further improvement in that direction. The main efforts are directed toward the improvement of efficiency for conditions of head and loading different from that of the maximum efficiency.

Both Pelton and Francis turbines sometimes are installed in plants having sufficiently high heads. Then the Francis turbines carry the base load at favorable efficiency conditions and the Pelton turbines, having the better efficiency at part loadings, carry the fluctuating loads. For medium head developments Francis turbines of different characteristics sometimes are used, again adding to the over-all efficiency of the plant.

Introduction of the Kaplan turbine, with its very flat efficiency curve under different load and head conditions, puts low head developments in a favorable position so far as average efficiency is concerned. Since Kaplan turbines may be overloaded considerably without an undue reduction of efficiency, it is possible in large installations to reduce the cost by the elimination of spare units. In such cases the electric generators have to be of larger size so that in case of failure of some of the units the rest of them can be used to carry the same total load. The introduction of a pumping scheme in some cases may be the next step in improving the over-all economy of a development.

Reduction of operating cost has been very much influenced by the introduction and successful operation of automatic and semi-automatic plants.

The 54,000-hp Alexander development on the Nipigon River in Canada, represents the largest automatic plant put into operation to date. Experience gained in the design and operation of automatic plants is being utilized to a large extent in manually operated plants. Many of the different remote control systems used in automatic plants are being applied at least partly to manually operated plants, centralizing the control of the plant at a very few places, reducing the size of the operating crew, and insuring a safer, more nearly perfect, and more economical operation.

Hydraulic and Hydrodynamic Research

The necessity of extensive hydraulic laboratory research for the economical design of hydraulic structures was realized some time ago. The latest development of turbines of high specific speed stressed the necessity of extended hydrodynamic research.

In some European countries, particularly Switzerland, Germany, and Sweden, several laboratories have been operated and an extensive study conducted along the lines of both hydraulic and hydrodynamic research.

In the United States the Massachusetts Institute of Technology gave a new impulse to such research by starting a series of lectures by the well-known authorities, de Thierry, Rehbock, Thoma, and Spannhake. The late John R. Freeman was responsible to a great extent for the increased activity in the scientific study of hydraulic problems as well as in the creation of the national hydraulic laboratory at Washington, D. C., which is expected to take an important part in the study of such problems. Numerous other laboratories in the United States and Canada make it possible at present to study experimentally the hydraulic problems that are so plentiful in connection with new or existing water power developments.

The importance of high specific speed turbines was realized in the United States some time ago; but only lately came the realization that advanced design of such turbines necessitated extensive research in hydrodynamics and particularly the study of cavitation. These ideas were promoted by far-seeing individuals, the A.I.E.E. and other engineering societies taking their share in that movement by making possible the presentation and discussion of papers in which the hydrodynamic research problems were particularly stressed.

L. F. Moody and F. H. Rogers have done important pioneer work in the development of the cavitation theory, but construction of cavitation laboratories lagged considerably until the recent opening by the Safe Harbor Water Power Corporation of the complete cavitation laboratory at Holtwood, Pa. Additional commercial laboratories of this type now are being undertaken. Fundamental theoretical research in that direction is made possible by the opening in 1932 of the first scientific cavitation laboratory in the United States at the Massachusetts Institute of Technology. During his visit to the United States, Doctor Thoma was instrumental in forming plans and ideas for the building of both the Holtwood and the M.I.T. laboratories. The last named laboratory is the direct result of the work of Doctor Spannhake. In spite of the short time that this laboratory has been in operation, studies of theoretical interest and of practical importance have been made particularly in regard to pressure distribution in cavitation areas.

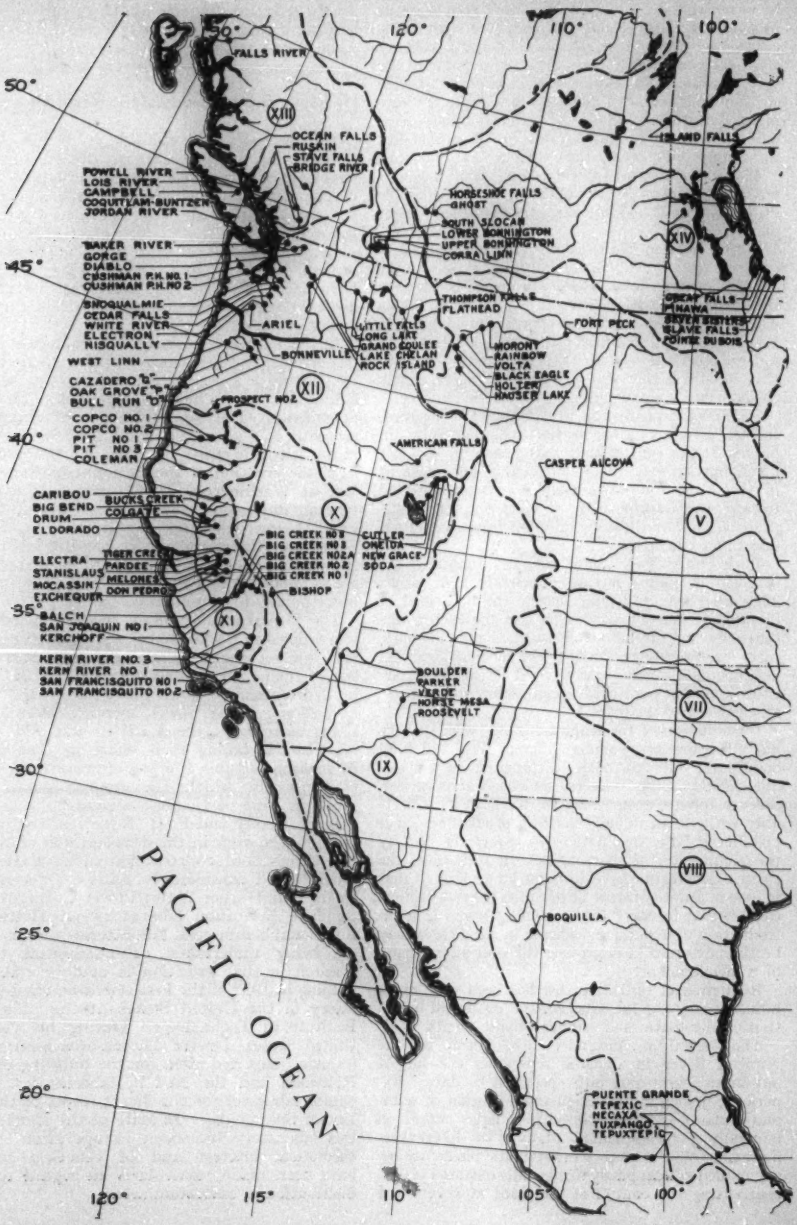

FALLS RIVER
OCEAN FALLS
RUSSIN
STAVE FALLS
BRIDGE RIVER
POWELL RIVER
LOIS RIVER
CAMPBELL
COQUITLAM-BUNTZEN
JORDAN RIVER
BAKER RIVER
GORGE
DIABLO
CUSHMAN P.H. NO. 1
CUSHMAN P.H. NO. 2
SNOQUALMIE
CEDAR FALLS
WHITE RIVER
ELECTRON
NISQUALLY
WEST LINN
CAZADERO "C"
OAK GROVE "P"
BULL RUN "D"
COPCO NO. 1
COPCO NO. 2
PIT NO. 1
PIT NO. 3
COLEMAN
CARIBOU
BIG BEND
DRUM
ELDORADO
BUCKS CREEK
COLGATE
ELECTRA
STANISLAUS
MOCASSIN
EXCHEQUER
TIGER CREEK
PARDEE
MELONES
DON PEDRO
BALCH
SAN JOAQUIN NO. 1
KERCHOFF
KERN RIVER NO. 3
KERN RIVER NO. 1
SAN FRANCISQUITO NO. 1
SAN FRANCISQUITO NO. 2
ARIEL
BONNEVILLE
PROSPECT NO. 2
HORSESHOE FALLS
GHOST
SOUTH SLOCAN
LOWER BONNINGTON
UPPER BONNINGTON
CORRA LINN
THOMPSON FALLS
FLATHEAD
LITTLE FALLS
LONG LAKE
GRAND COULEE
LAKE CHELAN
ROCK ISLAND
MORONY
RAINBOW
VOLTA
BLACK EAGLE
HOLTER
HAUSER LAKE
FORT PECK
GREAT FALLS
NAWA
SEVEN SISTERS
GLAVE FALLS
POINTE DU BOIS
ISLAND FALLS
AMERICAN FALLS
CASPER ALCOVA
BIG CREEK NO. 3
BIG CREEK NO. 2
BIG CREEK NO. 2A
BIG CREEK NO. 2
BIG CREEK NO. 1
BISHOP
CUTLER
ONEIDA
NEW GRACE
SODA
BOULDER
PARKER
VERDE
HORSE MESA
ROOSEVELT
BOQUILLA
PUENTE GRANDE
TEPEXIC
NECAXA
TUXPANGO
TEPUXTEPIC
PACIFIC OCEAN
XIII
XII
XI
X
IX
VIII
VII
V
XIV
50°
45°
40°
35°
30°
25°
20°
120°
115°
110°
105°
100°

Fig. 1. Hydroelectric developments in North America having ultimate installed capacities of more than 20,000 hp

A 7,000-Ampere Station Bus

Inductive heating and space limitations complicated the problem of redesigning a 4,000-amp bus to carry 7,000 amp, without structural changes in existing cells and runways. A general discussion of the unusual problems involved is given in this paper, together with the methods of solution and supporting test results.

By
H. L. UNLAND
ASSOCIATE A.I.E.E.
United Engrs. and Constructors, Inc., Philadelphia, Pa.

W. B. MORTON
MEMBER A.I.E.E.
Philadelphia Elec. Co., Philadelphia, Pa.

V. R. BACON
ASSOCIATE A.I.E.E.
United Engrs. and Constructors, Inc., Philadelphia, Pa.

INITIALLY, the development at the Richmond Generating Station of the Philadelphia Electric Company consisted of 2 50,000-kw 80 per cent power factor 13,800-volt 60-cycle turbine-generators; later these were re-rated to 60,000 kw. Space was provided and reserved at each end of the building for one additional unit of the same capacity.

These initial units were connected to a 13.2-kv vertically isolated phase bus located in a separate switch house along with its associated switching equipment. This bus was of the conventional flat bar construction, designed for 4,000-amp maximum capacity, and consisted of 7 $4 \times 1/4$-in. bars at the center tapering to 3 $4 \times 1/4$-in. bars at the ends. The generator leads were of similar construction, designed for 3,000 amp and consisted of 3 $5 \times 1/4$-in. bars housed in concrete compartments. Identical lead compartments were provided for the future units.

The General Problem

When conditions indicated the need of additional generating capacity, economic studies showed the necessity of taking advantage of recent developments in turbine design by installing a unit of greater physical dimensions and considerably greater capacity than was originally contemplated. Accordingly, a new 165,000-kw 90 per cent power factor 13,800-volt turbine-generator was purchased.

Thus, it became necessary to install a 165,000-kw machine and its accessory devices in an existing building in space originally intended for a 50,000-kw unit. The installation of the new machine required:

1. That the capacity of the isolated phase main bus be increased from 4,000 to 7,000 amp at 60 cycles, meanwhile adhering to the original enclosure dimensions of 24x24 in. and maintaining necessary electrical ground clearance.

2. That the new generator lead runs, designed to carry 5,000 amp per phase, be installed in enclosures originally designed for 3,000 amp per phase and having general dimensions of 24x24 in. but varying in width and height to as little as 21 and 17 in., respectively.

3. That all steel members in the vicinity of the above conductors be protected from dangerous temperatures resulting from magnetic induction.

These structural restrictions resulted in the 7,000-amp main bus passing concrete-fireproofed structural members with clearance of 16 in. and 5,000-amp generator lead runs having corresponding clearances as low as $4^7/_8$ in. The increased range of effect of the higher currents also brought minor miscellaneous steel, such as framing and supports for the bus and lead-run enclosures, metallic doors and door framing, etc., well within the magnetic influence of the conductors.

Thus, 2 major problems were involved in the consideration of the bus: first, the selection of a satisfactory conductor; and second, the prevention of inductive heating, or its reduction to harmless values. As a result of extensive laboratory and other tests, the following conclusions were reached:

1. For conductors to carry heavy currents and to be installed in restricted space, the 2-piece copper channel construction described in this paper has outstanding advantages.

2. With the continually increasing tendency toward larger generating units and greater concentrations of energy, protection against inductive heating will become an important factor in station design and must be given definite consideration. Where adequate spacings are not obtainable and other expedients are not feasible, the judicious application of short circuited bands and amortisseur grids will greatly reduce the heating.

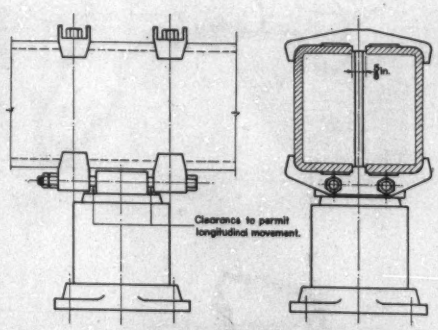


Fig. 1. Sliding clamp bus support for copper channel

Full text of a paper recommended for publication by the A.I.E.E. power generation committee, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 9, 1934; released for publication April 30, 1934. *Not published in pamphlet form.*

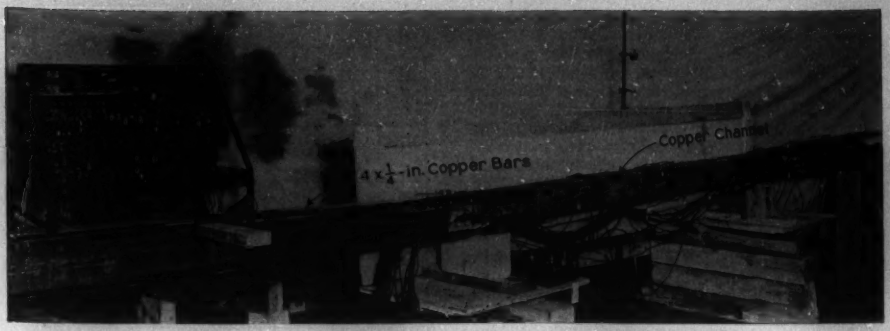


Fig. 2. Copper channel bus ready for a-c resistance test

Although no attempt has been made in this investigation to formulate generalized laws covering the phenomena of inductive heating, there has been accumulated a mass of elemental data suitable for abstract study and development by those theoretically inclined. It is felt, however, that the information in this paper will provide a useful if not infallible guide for the solution of similar practical problems.

Selection of Conductor

The size of the conductor for main bus and lead runs was limited by the necessity of maintaining adequate ground clearance in the restricted enclosure space. Low resistance was greatly to be desired because the complete enclosure of these conductors forced serious consideration of the means of disposing of the resistance heat losses. The use of cables for the generator leads was impracticable because of lack of space for ducts and manholes.

Multiple flat copper bars to carry currents of 5,000 and 7,000 amp were not feasible because of the diminishing value of additional bars above 5,[1] and the large number of bars necessary could not be accommodated in the space available. Flat copper bars arranged in a hollow square have been used for carrying heavy currents,[2] but this involves complicated fittings for clamping the conductors in position and for making heavy current taps. Inability to maintain ground clearance, particularly at certain beam crossings and at connections and taps to the main bus, precluded the use of this construction.

The most economical section for a heavy-current conductor is of course a hollow cylinder. Published data indicated that the optimum wall thickness is approximately $^1/_2$ in.,[1] and further that a copper tube to carry 5,000 amp would be approximately 6 in. in diameter, even with this special wall thickness. This in itself was not objectionable but the fittings for splices and taps are necessarily bulky and, in the limited space available, it was impossible to maintain the established minimum ground clearance. These disadvantages were even more pronounced in the case of the 7,000-amp main bus. An effort was made to increase the capacity and thus reduce the size of tubular conductors by cutting slots in the top and bottom. A superficial test showed that the small amount of air circulation provided by this means did not result in material improvement. Heavy-current conductors consisting of 2 aluminum channels have been used to some extent, but it was found that the dimensions of such channels to carry the currents

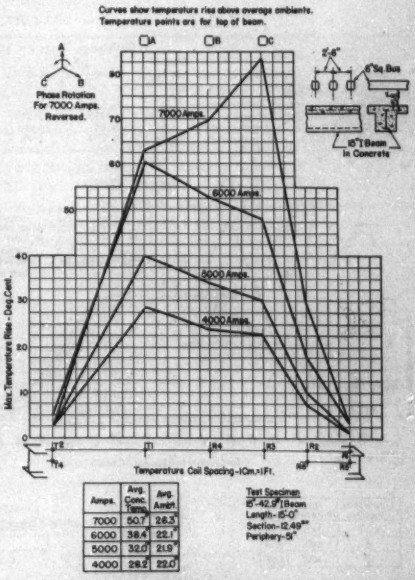


Fig. 3. Shift of hottest spot in I-beam by reversal of phase rotation

1. For numbered references see bibliography at end of paper.

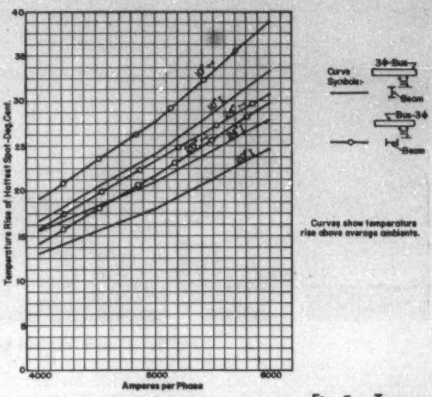
involved were too great for the space limitations to be encountered.

The use of copper conductors fabricated in special channel sections assembled to form practically a hollow square offered considerable promise. In order to be economical of metal, it was desirable that the thickness be uniform and approximate the optimum thickness of $^1/_2$ in. Such channels were naturally new. No quantitative data were directly obtainable as to a-c resistance, ability to dissipate heat, or current rating. The method of manufacture was uncertain, and the necessary tolerances to permit their use would have to be determined.

Preliminary calculations indicated that for currents of from 5,000 to 7,000 amp the channels should be approximately 8-in. in height, and for currents from 3,000 to 5,000 amp a 6-in. height was indicated.

The usual $^1/_4$-in. copper bars are relatively flexible, and will bend to compensate for variations in size and alignment in splicing, and will bow without imposing excessive strains on supports. On the contrary, the proposed bus forming a hollow box 6- to 8-in. square and $^1/_2$-in. thick would be extremely rigid in torsion and bending, as well as in column action, so that definite provisions would have to be made to take care of longitudinal thermal expansion. (Fig. 1.)

Sections of the size and uniform thickness desired could not be obtained by mere adjustment of the rolls used for producing structural shapes. The amount of conductor involved could not carry the added expense of design and manufacture of special rolls. Limitations of size and straightness are of minor importance in the use of structural rolled sections but the splicing of these heavy copper sections imposes severe restrictions on dimensions and straightness. This was accomplished by using plates of carefully selected material, rolled and cut to closely controlled dimensions, and finally drawn through dies to form and size the product.



Test Specimens			
	10"-25.4#	20"-70#	24"-79.9#
Length	20'-0"	20'-0"	20'-0"
Section	7.38 in²	20.46 in²	23.33 in²
Periphery	38"	64"	75"

Fig. 5. Temperature rise in I-beam vs current, size, and position of beam

Carrying Capacity

A great amount of theoretical investigation of "skin effect" in cylindrical hollow or solid conductors has been done by H. B. Dwight and others, and their data have been, to some extent, substantiated by experience.[3] However, no reference could be found on the calculation of the "skin effect" for hollow sectional conductors having rectangular outlines.

In order to determine the magnitude of this effect, the formulas, curves, etc., evolved by Dwight were used for the hollow square arrangements, assuming that the ratio of thickness to diameter for a cylindrical conductor could be replaced by the ratio of thickness to the side of the square in the case of a hollow square conductor. With this assumption, the values of 60-cycle a-c resistance at 60 deg C of several conductor shapes were computed and are shown in Table I.

From these calculated resistances, the expected conductor losses were obtained.

The manufacturer rated the 6-in.

Table I

Item	Conductor	Section Sq In.	Resistance, Ohms Per Ft × 10^{-7} D-C	Resistance, Ohms Per Ft × 10^{-7} A-C
1....4	6x1/4-in. and			
4	4x1/4-in. bars in hollow square.	10.0	8.510	11.70
2....4	5x1/4-in. in hollow square	10.0	8.510	11.21
3....2	6x0.490-in. copper channels	9.88	8.617	12.00
4....2	8x0.470-in. copper channels	13.28	6.409	8.65

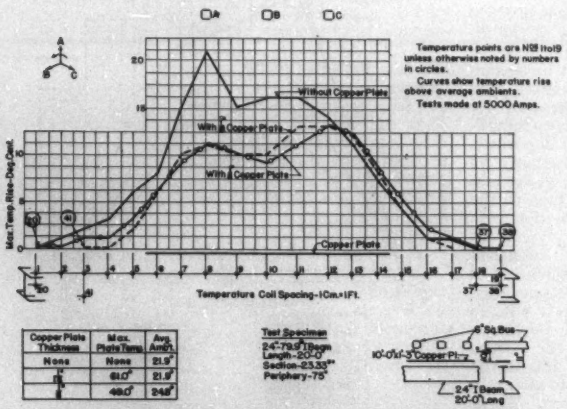


Fig. 4. Shift of hottest spot in I-beam by interposition of copper plate

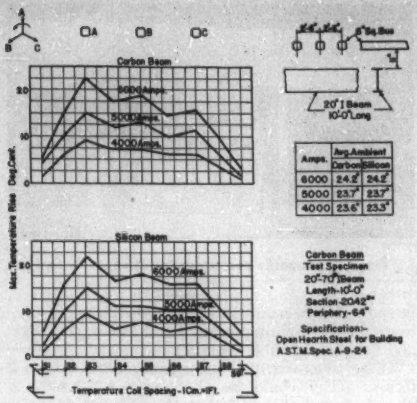
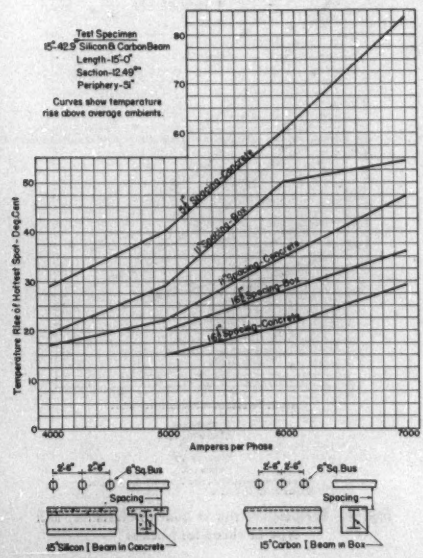


Fig. 6. Comparison of inductive heating characteristics of carbon and silicon steel I-beams

Fig. 7. Temperature rise in I-beam vs current and clearance



copper channels at 5,000 amp in the enclosures to be used, and the 8-in. channel at 7,000 amp, based entirely on calculations. However, observation of temperature conditions in existing conductor runs indicated that due to the unsatisfactory heat dissipating qualities of the enclosures, the losses from the increased currents would probably necessitate forced ventilation even with the most favorable conductor obtainable. Laboratory tests were made on sample conductors 10-ft long to determine experimentally the current carrying capacity. The current was led into the channel sections by 8 $4 \times 1/4$-in. bars in a hollow square arrangement for the 6-in. channel and 12 $4 \times 1/4$-in. bars in the case of the 8-in. channel. (Fig. 2.) This provided an opportunity to directly compare the temperature rise of the built-up $1/4$-in. bars with that of the channel. (Table II.) In order to gain some idea of the heating to be expected after installation in the concrete enclosures a test box was built from insulating board. Heating of the channels both in open air and in the box is also shown in Table II. Even though this box could not be considered as similar to the actual concrete structures, the heating confirmed the feeling that the problem of removing heat from the conductor enclosures would require forced ventilation. The crowding of current into the outer bars of the built-up hollow square arrangement is clearly shown by the temperatures observed.

The unsatisfactory heat dissipating qualities of the concrete enclosures increased the desirability of additional data on the heat losses to be expected, which in turn depended on the 60-cycle resistance. To measure directly the a-c resistance of large conductors of irregular section considerable difficulty and expense would be encountered, and even then the accuracy would be subject to question. An indirect method suggested by D. C. Prince was finally adopted. Briefly, a 10-ft sample of the channel assembly was set up with thermocouples liberally distributed over the surface. A heat run was made at the desired current until the temperature was steady, from which the average temperature rise was obtained. A cooling curve was then taken by further raising the temperature of the bus and, after quickly removing all connections, recording the

Table II—60-Cycle Heating of Copper Bus

Bus Channel	Bars	Cross Sec Sq In.	Amp	Temperature Rise in Deg C: Max	Min	Avg Outer Bars	Avg Inner Bars	Gen Avg
Copper channel in heat-insulated test box								
2	8 in.	13.28	7,000	51.5	39.5			48.3
2	8 in.	13.28	6,000	38.2	30.2			35.7
2	6 in.	9.88	5,000	37.3	31.3			35.0
2	6 in.	9.88	4,400	29.2	23.2			27.2
Copper channel in air								
2	8 in.	13.28	7,000	23.5	19.5			21.0
2	8 in.	13.28	6,000	17.8	13.8			15.3
2	6 in.	9.88	5,000	20.2	16.2			17.4
2	6 in.	9.88	4,400	14.2	12.2			13.0
$4 \times 1/4$-in. copper bars, hollow square arrangement, in air								
	12	12.0	7,000	37.5	17.5	31.3	25.8	28.6
	12	12.0	6,000	27.8	11.8	23.8	19.4	21.6
	8	8.0	5,000	27.2	10.2	19.6	16.2	17.9
	8	8.0	4,400	21.2	7.2	13.6	12.0	12.8

time-temperature readings during the cooling period, and plotting the average temperature rise against time. The slope of this curve at any temperature is the rate of cooling and by combining this with the weight and specific heat of the channels, the Btu loss dissipated at that temperature is obtained. It is a simple matter to convert this to watts and, with the current known, to get the resistance.

Following is a comparison of the calculated and test values of 60-cycle resistance in ohms per ft:

	Calc. Res.	Test Res.
8-in. channels	8.65×10^{-7}	9.79×10^{-7}
6-in. channels	12.0×10^{-7}	13.78×10^{-7}

With the channels in open air, the cooling curves were exceptionally uniform. The results obtained were consistent but they were found to be from 10 to 15 per cent greater than the calculated values. An unsuccessful effort was made to check these results with the channels enclosed in the test box, but the heat inertia of the diverse parts of the thermal circuit caused inconsistent results.

Inductive Heating

Superficial calculations and tests indicated that total temperatures of 70 deg C (158 deg F) could be developed in a bare carbon-steel I-beam in open air when located at about 10 in. spacing inside of a 90 deg bend in a single-phase bus carrying 4,400 amp, and that greater temperatures might be expected for smaller clearances.

Although a total temperature of 70 deg C in open air did not justify great alarm, it did prompt speculations as to what temperatures and effects might be expected in the actual silicon steel structure, fireproofed with concrete:

1. Would the greater currents and smaller clearances result in intolerable temperature elevations?

2. Would the concrete tend to thermally insulate the hot spots or would it conduct the heat to the surface or to other sections and thus lower the hot-spot temperature?

3. Was there any likelihood that the temperatures might be high enough and so distributed as to cause expansion buckling between fixed points or so confined as to actually weaken the steel?

4. Could these high temperatures, resulting in unequal expansion, cause slippage between the steel and concrete, destroying the composite characteristics of the structure?

All of these were logical questions, based on fundamentals. Unfortunately, the gap between the questions and their answers could be bridged only by a chain of loosely connected and doubtful assumptions, making rational answers practically impossible. Assuming that dangerous temperatures would exist, such remedial expedients as multiple buses, bus transpositions, or increased physical clearance between buses and steel were quickly eliminated. This left but 2 choices: first, to provide for heat dissipation at rates which would prohibit excessive temperatures; and second, to prevent or diminish heating. The former was obviously expensive and unreliable. The latter, if capable of accomplishment, was direct in that it struck at the source of the difficulty and had possibilities of permanency. The

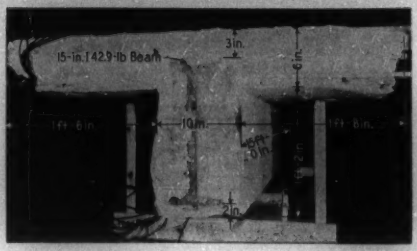


Fig. 8. Composite steel-concrete section used in tests

introduction of neutralizing fields by means of nonferrous short-circuited turns fell in the second class and held considerable promise.

These short-circuited turns could take either of 2 forms. They could be short circuited bands so placed around the steel that the plane of the band would lie in the plane of the current flow in the inducing conductor or they could take the form of amortisseur grids with their long axes parallel to that of the inducing conductor. While the use and characteristics of both of these expedients are old and well understood in machine design, the procedure for their application to a structural problem left much to be learned. Recourse to obtainable literature and

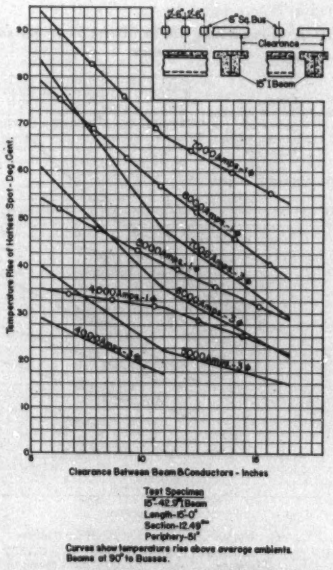


Fig. 9. Temperature rise vs current, clearance, and type of circuit for I-beams

discussions with the engineers of various electrical manufacturers indicated that the information available was so limited in scope and so specific in purpose that it was of little use for the immediate problem.[4] Thus it was obvious that tests held the only promise of a successful solution.

Test Procedure

The idea of tests on the existing structure to determine the remedial measures was immediately abandoned because it was feared that the building might be damaged by overheating. It was further believed that the mass effect (complex thermal behavior) would preclude any understanding of the variables. Laboratory tests had all the desired advantages but there was no assurance that laboratory conclusions could be accurately translated into practical situations. These considerations led to a series of coördinated tests in the laboratory and on the existing structure, since the fundamental work could be done in the laboratory and then cautiously verified on the structure with minimum hazard. The investigation was limited to obtaining only data having a direct application to the construction problems.

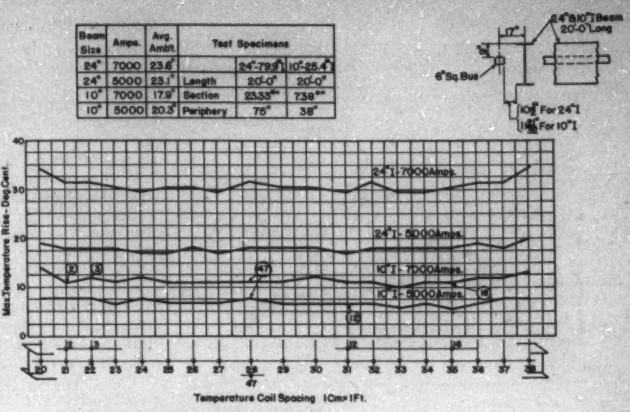


Fig. 11. Temperature rise in I-beam vs current and beam size

It was clearly impossible to set up any reasonable laboratory test for the determination of the maximum permissible rise. There was a general feeling that there must be some inductive heating in the already operating structure and that, if such heating were excessive, its results would have already been discovered or indicated by cracks in the concrete. One of the generators was selected for a test and thermocouples were embedded in the fireproofing against the structural steel adjacent to the lead runs and bus conductors. The current was held approximately constant at 2,750 amp for 57 hr. The maximum steel temperature recorded during the test was $82^1/_2$ deg C ($180^1/_2$ deg F). Visual inspection showed no evidence of distress of any kind. Therefore 80 deg C (176 deg F) was arbitrarily adopted as the maximum permissible temperature in the steel, since the test current used represented the maximum long time load encountered in previous normal operation and judgment indicated that temperatures of the order encountered should cause no damage. This test clearly demonstrated the danger of attempting to account for the mass effect. One point opposite a dead bus showed a greater rise than a similar point identically located with reference to a live bus.

The laboratory tests were made at the Philadelphia Works of the General Electric Company. This work was carried on continuously 24 hr a day for approximately 100 days, with but slight interruption. Tests were made on structural I-beam sections, conduit, conduit loops, cell doors, and ferrous bus support

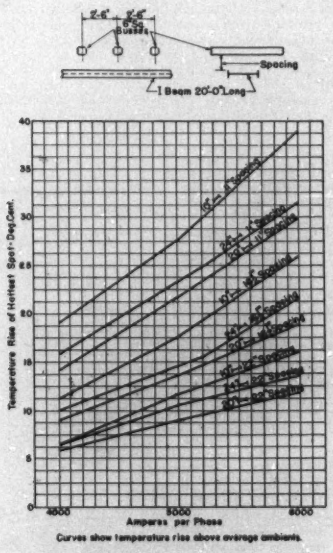
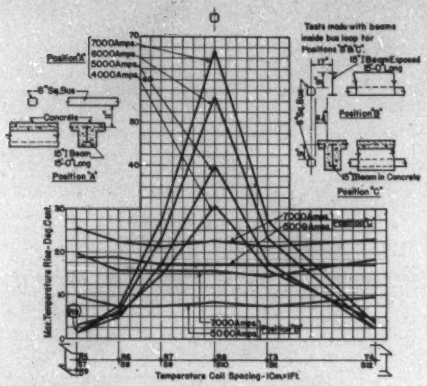


Fig. 10. Temperature rise in I-beam vs current, clearance, and beam size



Position	Amps.	Avg. Conc. Temp.	Avg. Amb't.
A	7000	35.5°	24.4°
	6000	31.8°	22.6°
	5000	31.7°	24.6°
	4000	27.8°	21.8°
B	7000	—	18.3°
	5000	—	20.5°
C	7000	33.4°	22.5°
	5000	33.1°	22.8°

Fig. 12. Temperature rise in I-beam vs current and beam position

fittings. The I-beams used ranged from 10 to 24 in. in depth and from 10 to 24 ft in length. Clearance effects were investigated for spacings from $5^1/_2$ to $27^1/_2$ in. between conductors and ferrous materials. The current values employed ranged from 2,600 to 7,000 amp per phase at 60 cycles for both single-phase loops and 3-phase flat conductor arrangements.

The heating characteristics of I-beam sections, both of carbon and silicon steels, were examined in open air, in heat insulated boxes, and encased in concrete, a composite concrete-steel section having been removed from Richmond Station for this purpose. (Fig. 8.) The heating characteristics of straight and looped conduits were determined, and the characteristics of short-circuited bands and amortisseur grids were observed under many conditions. No tests were made on reenforcing because of the impracticability of such investigation and the belief that there was little likelihood of serious heating because of the small cross section of the bars and the expected high resistance of the joints.

Results of Laboratory Tests

Some seemingly new phenomena and inconsistent data obtained from these tests are as yet unexplained. Figures 3 and 4 illustrate some rather unexpected phenomena for which no satisfactory explanation has been found. Casual consideration would indicate that, with the physical arrangement shown in Fig. 3, there should be 3 points of elevated temperatures, one under each of the 3 buses. This was not the case; there was but one such point and it was always under one of the outside phases. The position of this point for beams in either concrete or open air could be shifted by the reversal of the phase rotation or by the insertion of a copper plate between the bus and the beam but the point was invariably under one of the outside phases. Another case not yet accounted for is shown in Fig. 5, where it is obvious that factors other than the depth of the beam determine the heating.

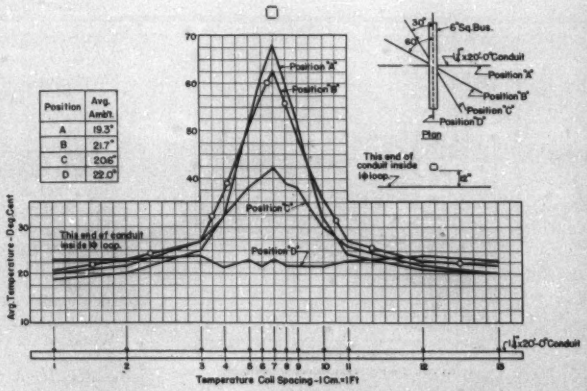
The following deductions can be made from the results of the complete series of laboratory tests:

General Relationships

Carbon vs. Silicon Steel. Any differences which might exist between the magnetic and thermal properties of the carbon and silicon structural steels used were unimportant in so far as this particular problem was concerned. A comparison of the 2 alloys is shown in Fig. 6.

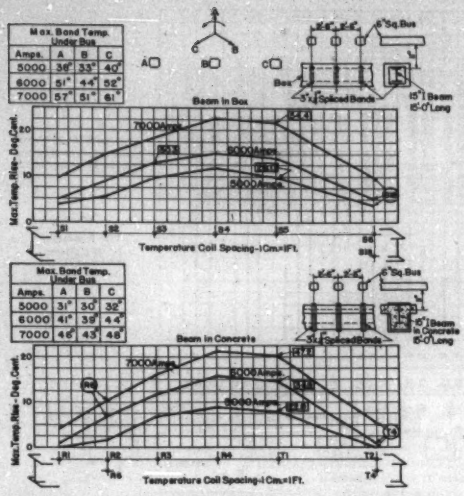
Temperature Rise vs. Current. The temperature rise in I-beams is a direct function of the current for fixed physical relationship. Within the limits of observations (7,000 amp maximum), there is no thermal saturation effect (Fig. 7). Other tests showed that the conclusion is also valid for beams in open air.

Temperature Rise vs. Clearance. The temperature rise in I-beam sections, conduit, and conduit loops is an inverse function of the clearance between the steel and the nearest conductors. The temperature rise for a given current and clearance is materially affected by the shapes and relative positions of conductors and steel members. For example, tests indicated that greater heating occurs with the web of a beam parallel to a 3-phase circuit than with the flange in that position. It is impossible, even in the case of a bare I-beam, to draw a reliable conclusion as to the ultimate temperature for a stated current and clearance unless all of the details are known (Figs. 9 and 5).



Position	Avg. Amb't.
A	19.3°
B	21.7°
C	20.6°
D	22.0°

Fig. 13. Temperature rise in straight conduit vs angular position of conduit



Numbers in rectangles are maximum temperature rises of beam without bands.

Amps.	Avg. Temp. Box	Avg. Temp. Conc.	Avg. Ambt. Box	Avg. Ambt. Conc.
7000	27.6°	27.8°	21.2°	21.5°
6000	27.4°	27.4°	24.0°	24.1°
5000	21.8°	21.1°	19.2°	20.1°

Temperature points are for top of beam unless otherwise noted by numbers in circles.
Curves show temperature rise above average ambients.

Fig. 14. Temperature rise in I-beam vs current with and without short-circuited bands

Temperature Rise vs. Size of Section. The temperature rise in an I-beam appears to be an inverse function of depth of beam when the beam and conductor axes are at right angles and a direct function when their axes are parallel. These generalizations are based on Figs. 10 and 11. The first is subject to the same comments as made in connection with Fig. 5 and is apparently inconsistent. Conclusions on this relationship should, therefore, be used with caution.

Temperature Rise vs. Axial Relationships. The temperature rise in an I-beam or single straight conduit is a direct function of the angle between the conductor and beam or conduit, being maximum at 90 deg and minimum at 0 deg (Figs. 12 and 13).

Temperature Rises With 1- and 3-Phase Circuits. Single-phase circuits induce greater temperature rises in I-beams, conduits, and conduit loops than 3-phase circuits (Fig. 9).

Protective Devices

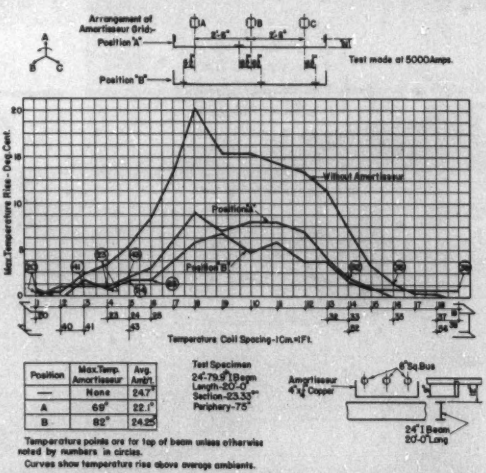
Short-Circuited Bands vs. Amortisseur Grids. In cases where buses and I-beams cross at right angles, short-circuited bands are considerably more effective in reducing temperature rises in the beam than amortisseur grids (Figs. 14 and 15). Conversely, when the conductor and beam axes are parallel, the amortisseur grids are most effective. The ineffectiveness of short-circuited bands under this condition seemed so obvious that no confirmatory tests were made.

Short-Circuited Bands With I-Beam at Right Angles to Bus. The effectiveness of short-circuited bands is not greatly altered by the cross section of the band or the length of band circuit, the temperature rise in the steel, within relatively narrow limits, being an inverse function of the gross cross section of the band. The temperature rise of the band follows a reverse reaction and increases rapidly as the band cross section or number of grouped bands is decreased. When a single band is used, the minimum temperature rise in the steel occurs when the band is placed directly opposite the conductor. With multiple bands, the steel temperature is lowest for symmetrical dispositions of bands or groups of bands relative to the point opposite the conductor. Under these conditions the temperature reduction is very pronounced, but it is affected by so many variables that it is probably changed radically for every different section and space relationship between the beam and conductor. Multiple bands, properly placed, are seemingly much more effective than single bands for the same cross section. Woven metal braids applied either as series turns or as multiple paths will produce about the same over-all results as bands of solid metal, provided that the gross cross section is comparable in both cases. The manner of closing the bands, whether bolting or welding, has little influence on the results as long as the resistance of the joints is kept low. As a general statement, bands properly installed can reduce steel temperatures somewhat in excess of 50 per cent (Fig. 16).

Amortisseur Grids. Amortisseur grids placed parallel to conductors are most effective in reducing temperature rises in I-beams and conduit loops which are also parallel to the conductors. They are least effective when beams or single conduits cross the conductors at right angles.

The results attained in all cases, for a given cross section of amortisseur, will depend upon the physical interrelationship between the conductors, the individual amortisseur bars, and the beam or conduit loop. Disproportionate variations in results are produced by relatively slight differences in bar locations. Since the effectiveness of the grid is determined primarily by the number and arrangement of the bars and to a much lesser extent by cross section, it is impossible to draw any conclusion as to the relationship between the steel temperature reduction and the total cross section of the grid. Fortunately, the best results seem to come from a dispersion of grid metal rather than a concentration and this tends toward a minimum grid rise for a given reduction in steel temperature. Amortisseurs can become a partial liability because of their own heat losses. They should only be installed after careful consideration of their contribution to the general ambient temperature as well as the mechanical details providing for expansion and insuring premanent clearances. The prevention of objectional rattles and hum also warrants some thought to the manner of their installation (Figs. 15 and 17).

Copper Plates. Copper plates interposed between the conductors of a 3-phase bus and an I-beam when the conductors are equidistant

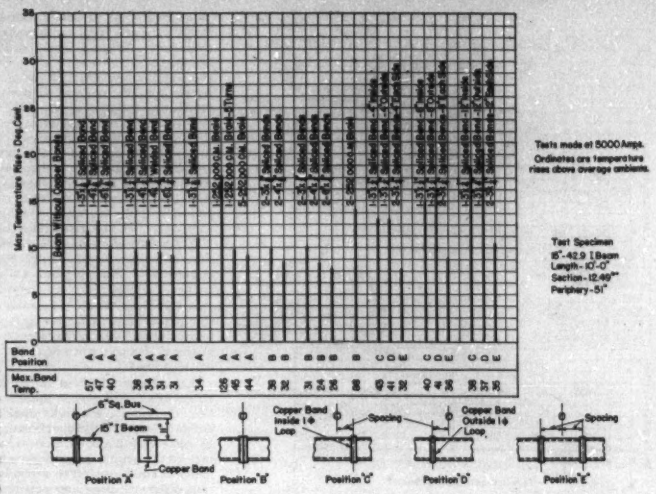


Position	Max. Temp. Amortisseur	Avg. Ambt.
—	None	24.7°
A	69°	22.1°
B	82°	24.25°

Temperature points are for top of beam unless otherwise noted by numbers in circles.
Curves show temperature rise above average ambients.

Fig. 15. Temperature rise in I-beam vs position of amortisseur bars

Fig. 16. Temperature rise in I-beam vs number, size, grouping, and position of short-circuited bands



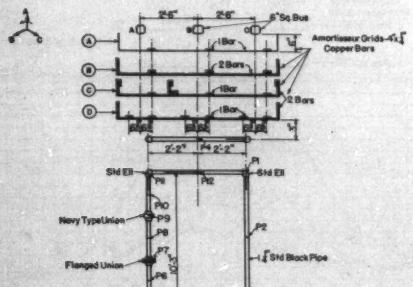
from and at right angles to the beam, are active in reducing the temperature rise in the steel. There is little choice between plates $^1/_{16}$ and $^1/_8$ in. thick, although the operating temperature of the plate is increased considerably for the thinner section (Fig. 4). No single-phase tests were made with plates because they appeared to be less effective than bands and amortisseurs.

Practical Observations

Conduit Loops. The current carrying capacity of conductors in conduits can be materially decreased and the conductor placed in jeopardy by inductive heating in the conduit. The most pronounced danger zones occur where conduits cross high current conductors at angles approaching 90 deg. At such points local heating due to eddy currents and hysteresis may be superimposed on losses resulting from circulating currents originating in other elements of the conduit system. The greatest hazard from circulating currents appears to arise from high resistance joints in the conduit where conduit loops parallel inducing conductors. The hazard is a function of the length of the parallel. It was accidently demonstrated in the laboratory that a single-phase bus carrying 7,000 amp and crossing a flat conduit network at a distance of about 24 in. could produce sufficient circulating current to burn through a $1^1/_2$-in. conduit at its junction with a box.

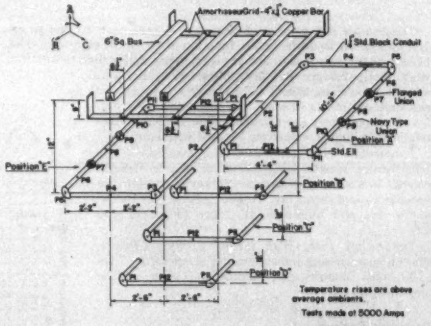
In the design of conduit systems to be installed in the vicinity of heavily loaded conductors, it is advisable to maintain as much clearance as possible between conduits and conductors, to cross the conductors with conduits as obliquely as possible, and to maintain the electrical resistance of conduit circuits as low as reasonably feasible.

The order of the temperatures which may be expected in conduit loops, exclusive of excessive temperatures at high resistance joints,



Arrgt. of Amort.	Avg. Amb't.	Max. Amort. Temp.	Temperature Rise - Degrees Centigrade											
			P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
None	20.4°	None	27.6°	23.6°	26.6°	33.6°	13.6°	16.6°	21.6°	20.6°	15.6°	20.6°	24.6°	33.6
A	20.1°	68°	6.9°	5.9°	5.9°	10.9°	6.9°	3.9°	2.9°	2.9°	2.9°	3.9°	7.9°	11.9
B	21.2°	57°	8.8°	5.8°	9.8°	12.8°	6.8°	5.6°	3.6°	4.6°	5.6°	5.8°	5.8°	10.8°
C	23.5°	59°	5.5°	2.5°	6.5°	7.5°	4.5°	3.5°	2.5°	2.5°	3.5°	3.5°	3.5°	8.5°
D	21.5°	56°	1.5°	2.5°	2.5°	4.5°	3.5°	3.5°	2.5°	2.5°	2.5°	2.5°	2.5°	4.5°

Fig. 17. Temperature rise in conduit loop vs position of amortisseur bars



Position of Loop	Avg. Amb't.	Max. Amort. Temp.	Temperature Rise - Degrees Centigrade											
			P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
A	22.2°	None	12.8°	2.8°	12.8°	5.8°	1.8°	0.8°	0.8°	0.8°	0.8°	1.8°	1.8°	5.8°
A	21.3°	78.0°	1.7°	1.7°	1.7°	0.7°	0.7°	-0.3°	-0.3°	-0.3°	0.7°	-0.3°	0.7°	0.7°
B	21.7°	None	12.3°	6.3°	11.3°	22.3°	7.3°	3.3°	3.3°	3.3°	2.3°	4.3°	7.3°	24.3°
B	20.1°	67.0°	2.9°	2.9°	2.9°	7.9°	1.9°	0.9°	-0.1°	-0.1°	0.9°	0.9°	1.9°	7.9°
C	20.7°	None	21.3°	14.3°	21.3°	20.3°	20.3°	12.3°	11.3°	11.3°	8.3°	17.3°	21.3°	21.3°
C	19.7°	70.0°	9.3°	3.3°	8.3°	7.3°	4.3°	2.3°	1.3°	1.3°	1.3°	2.3°	4.3°	7.3°
D	20.4°	None	27.6°	23.6°	26.6°	33.6°	13.6°	14.6°	21.6°	20.6°	15.6°	20.6°	24.6°	33.6°
D	20.1°	68.0°	6.9°	5.9°	5.9°	10.9°	6.9°	3.9°	2.9°	2.9°	2.9°	3.9°	7.9°	11.9°
E	22.8°	None	8.5°	4.8°	7.8°	27.5°	9.5°	4.5°	2.5°	4.5°	4.5°	4.5°	8.5°	29.5°
E	23.6°	93.0°	8.5°	3.5°	7.5°	13.5°	6.5°	3.5°	2.5°	4.5°	3.5°	3.5°	6.5°	13.5°

Fig. 18. Temperature rise in conduit loop, with and without amortisseur vs position of loop

Table III—Temperatures in Building Steel Before and After Installation of Bands and Amortisseurs

Size of Beam	Bands and Amortisseurs Installed	Clearance in Inches	Amperes Per Phase	Temperature Deg C
40 in. I	No	11	2750	*82.5
	Yes	10 3/4	4830	*27.0
40 in. I	No	9	2750	58.0
	Yes	4 7/8	4830	44.0
40 in. I	No	9	2750	71.0
	Yes	4 7/8	4830	45.5
18 in. I	No	9	2750	74.0
	Yes	5 3/8	4540	51.5
14 x 12 in. H	No	26	2750	42.0
	Yes	25 1/2	4670	**42.5
14 x 12 in. H	No	26	2750	54.5
	Yes	25 1/2	4830	**49.0
12 x 10 in. H	No	27	2750	46.5
	Yes	26 1/2	4670	**61.5

* The points corresponding to these temperatures were similarly located with reference to both bus and structure but the first was within the influence of a reactor, while the second was not. This accounts for the wide difference of temperature.

** The bands associated with these readings were not properly located due to structural obstruction. Proper location would probably produce a marked decrease in temperature.

is indicated by Fig. 18. This figure also gives an idea of what may be accomplished by the use of amortisseurs.

Cell Doors. Results of tests on sheet steel and steel frame doors indicate that objectionable magnetic heating may be expected in the metal parts when located in proximity to conductors carrying currents in excess of 3,000 amp. When the position or construction of the doors provides a metallic loop or circuit unsymmetrical with the conductor, there will be additional heating resulting from circulating currents. This occurs whether the metal is magnetic or not.

Bus Clamps. Bus clamps having ferrous parts will not show excessive temperature elevations when used on conductors carrying up to 7,000 amp, provided that a loop of magnetic material is not formed around the conductor.

In order to determine the efficacy of the protective measures, a second test was made after all bands and amortisseur networks had been installed. The test current was applied to only a short section of the run initially in order to observe reactions. This trial test being satisfactory, an average current of 4,680 amp was maintained for approximately 84 hr to bring the structure to stable temperature, which was then held for approximately 8 hr.

It was possible to locate many thermocouples for this test in the same physical relationship to the steel structure and the conductor as in the earlier structure test, so it was possible to obtain an index of the effectiveness of the bands and grids. (Table III) The 2 tests were conducted under practically the same weather conditions.

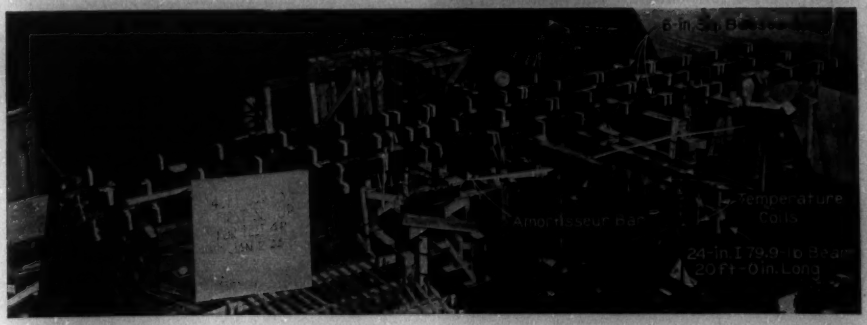
This test clearly demonstrated the justification for the laboratory tests. The amortisseur grids had been installed in advance of final laboratory information in order to meet the demands of construction schedules. The data showed that the single bar grid as installed could be expected to heat excessively and this was confirmed in the test. It was found necessary to reënforce the single bar section with an additional bar throughout.

The losses in the amortisseur grids materially increase the amount of heat liberated in the conductor enclosures. This added confirmation to previous indications that forced ventilation would be required.

During the test, excessive heating was observed in the metal framework of the lead run compartments

Fig. 20. Single-phase test on single conduit and conduit loop

Fig. 19. 3-phase test on I-beam with amortisseur



from loops formed by multiple ground connections. In some instances the circulating currents produced points of incandescence at high resistance joints in the metal framework. Heating was substantially reduced by removing from each section all grounds except one and opening the metallic circuit of the ironwork at intervals to prevent forming of loops.

No attempt was made to measure temperatures in conduit and in reënforcing steel due to their inaccessibility. However, all parts of the building were carefully examined by hand for elevated temperatures, but none were found, so it was assumed that the protective devices were functioning successfully.

Valuable advice and coöperation from Messrs. D. C. Prince, R. M. Spurck, and C. E. Merris of the General Electric Company, and Messrs. H. W. Papst and L. A. Kilgore of the Westinghouse Electric & Manufacturing Company are gratefully acknowledged.

References

1. Current Carrying Capacity of Hollow Conductors, H. W. Papst. *Electric Journal*, 1931, p. 411.
2. Carrying Capacity of 60-Cycle Buses for Heavy Currents, T. G. LeClair. A.I.E.E. Trans., v. XLV, 1926, p. 203.
3. Skin Effect and Proximity Effect in Tubular Conductors, H. B. Dwight. A.I.E.E. Trans., v. XLI, 1922, p. 189.
4. Temperature Rise and Losses in Solid Structural Steel, O. R. Schurig and H. P. Kuehni. A.I.E.E. Trans., v. XLV, 1926, p. 184.

Cross Current of a 5-Arm Network

By
A. C. SELETZKY
ASSOCIATE A.I.E.E.

J. R. ANDERSON
ENROLLED STUDENT A.I.E.E.

Case School of Applied Science, Cleveland, Ohio

This paper treats the loci of cross currents in 5-arm networks with constant coefficients at constant applied voltage. It is shown that at constant frequency of applied voltage, the locus of the cross current is a circle when any one of the network arms is varied at constant phase angle or along one of its components. When the network arms are fixed and the frequency is varied the locus of the cross current is the sum of several circles, the number depending upon how many of the impedance arms vary with frequency. The general 5-arm network is treated analytically and the application of the method in determining the loci is illustrated by a typical network for which the cross current is evaluated for constant and for varying frequency.

THE study of circuits consisting of 4 impedances arranged in conventional bridge form, involves, in general, 1 of the 2 following considerations:

1. Variation of the cross potential difference appearing across the midpoints of the network.
2. Variation of the cross current which would flow through an impedance connected across the midpoints of the network.

When such a network is employed in conjunction with a device which draws no current, or a negligible amount, the variation of cross potential difference is sufficient to determine the performance of the circuit. Such is the case with bridge measuring or control networks where the detector arm consists of a properly biased tube circuit. The variation of cross potential difference has been treated in a previous paper (see "Cross Potential of a 4-Arm Network," by A. C. Seletzky, Elec. Engg., v. 52, 1933, p. 861–7) where it was shown that the locus of the cross potential difference is:

1. A circle when the network is operated at constant applied voltage at constant frequency and any one of its arms is varied at constant phase angle or along one of its components.
2. The sum of several circles when the arms remain fixed and the frequency of the applied voltage is varied.

If a current drawing instrument such as a transformer or galvanometer is placed across the midpoints of the network, the problem becomes the determination of the locus of the cross current which flows through this additional impedance. It is the purpose of the present paper to treat this condition for both fixed and varying frequencies. To facilitate comparison between the determination of the loci for cross potential difference and cross current, the same network and constants will be used in this paper as in the preceding one.

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted Jan. 25, 1934; released for publication March 12, 1934. *Not published in pamphlet form.*

General 5-Arm Network

In Fig. 1 is shown a general 5-arm impedance network having impedances Z_a, Z_b, Z_c, Z_d, and Z_e, with constant applied voltage E at constant frequency. The current I_e flowing through the cross impedance Z_e is

$$I_e = \frac{E(Z_bZ_c - Z_aZ_d)}{Z_c[Z_aZ_e + Z_bZ_e + Z_eZ_b] + Z_d[Z_a(Z_e + Z_c) + Z_b(Z_e + Z_a + Z_e)]} \quad (1)$$

If I_e is the current in amperes per volt of applied voltage, then

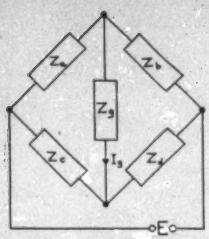


Fig. 1. General 5-arm network

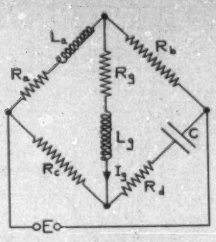


Fig. 2. Network used for example

$$I'_g = \frac{I_g}{E} = \frac{Z_bZ_c - Z_aZ_d}{Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] + Z_d[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)]} \tag{2}$$

To treat the loci of the cross current under various conditions, the equation of a circle in the form of a linear fractional transformation as given by Schenckel (see "Geometrische Oerter an Wechselstromdiagrammen," by M. Schenckel, *E. T. Z.*, v. 22, 1901, p. 1043–4) will be taken as the canonical form. This is

$$S = \frac{\alpha + \beta\rho}{\gamma + \delta\rho} \tag{3}$$

Here S is a vector describing a circle as the scalar variable ρ ranges from minus to plus infinity and α, β, γ, and δ are constants. Methods of determining the circle from these constants and of drawing a scale line have been described in the previously mentioned paper by one of the present authors (Elec. Engg., v. 52, 1933, p. 861–7). This scale line is any line drawn perpendicular to the line joining the center of the circle with the point on the circle corresponding to $\rho = \infty$. Lines drawn from the latter point to any other points on the circle such as those corresponding to $\rho = 0$ and $\rho = 1$ fix the scale on the scale line. This scale is then extended linearly along the scale line. In the problems which follow, the circles will be determined by evaluating S at 3 points, corresponding to ρ equal to zero, infinity, and some convenient third point. These points will also be sufficient to determine the scale line.

Five-Arm Network at Constant Frequency

A number of conditions which at constant frequency of applied voltage give rise to circular loci for the cross current will now be studied.

When one of the network arms, as Z_d, is varied at constant phase angle, this arm may be written as $Z_d = Z'_d\rho$, where Z'_d is a unit vector having the phase angle of Z_d and ρ is the scalar variable. Substituting this form into eq 2 gives eq 4.

Equation 4 is in the form of a circle, since from eq 3, S becomes I'_g and the constants are as given in eq 5.

In the same manner, if the resistance component of one of the arms, as Z_d, is varied, then $Z_d = R_d + jX_d$ is substituted into eq 2 giving eq 6.

Equation 6 is likewise in circular form having the constants given in eq 7.

When the quadrature component of one of the arms, as Z_d, varies, the same substitution is performed as for a variable resistance component and the terms are arranged as given in eq 8. This is a circle having the constants given in eq 9.

Thus eqs 4, 6, and 8 demonstrate that with constant applied voltage at constant frequency, the locus of cross current is a circle when any one of the network arms varies at constant phase angle or along one of its components. In this respect the behavior of cross current is precisely the same as that of cross potential difference. That there is no further complication at constant frequency in the form of eq 2 for cross current as compared to the equation for cross potential difference is due to the fact that the addition of the fifth arm, Z_g, introduces additional terms in the denominator only, and in such a way that the equation for cross current may always be written to conform to the circular form of eq 3.

As a practical example of the use of the equations just derived, the same resistance, inductance, and capacitance network used in the previous paper to illustrate the locus of cross potential difference will

$$I'_g = \frac{Z_bZ_c - Z_aZ_d'\rho}{Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] + [Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)]Z_d'\rho} \tag{4}$$

$$\left.\begin{aligned} \alpha &= Z_bZ_c & \gamma &= Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] \\ \beta &= -Z_aZ_d' & \delta &= [Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)]Z'_d \end{aligned}\right\} \tag{5}$$

$$Ig' = \frac{Z_bZ_c - jZ_aX_d - Z_aR_d}{Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] + jX_d[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)] + R_d[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)]} \tag{6}$$

$$\left.\begin{aligned} \alpha &= Z_bZ_c - jX_aZ_a \\ \beta &= -Z_a \\ \gamma &= Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] + jX_d[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)] \\ \delta &= Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c) \\ \rho &= Rd \end{aligned}\right\} \tag{7}$$

$$I'_g = \frac{Z_bZ_c - Z_aR_d - jZ_aX_d}{Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] + R_d[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)] + j[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)]X_d} \tag{8}$$

$$\left.\begin{aligned} \alpha &= Z_bZ_c - Z_aR_d \\ \beta &= -jZ_a \\ \gamma &= Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] + R_d[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)] \\ \delta &= j[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)] \\ \rho &= Xd \end{aligned}\right\} \tag{9}$$

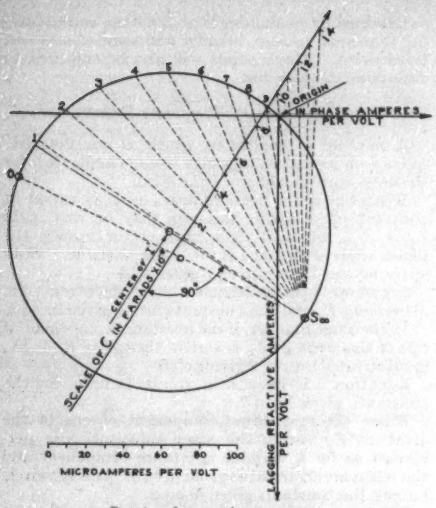


Fig. 3. Locus of cross current

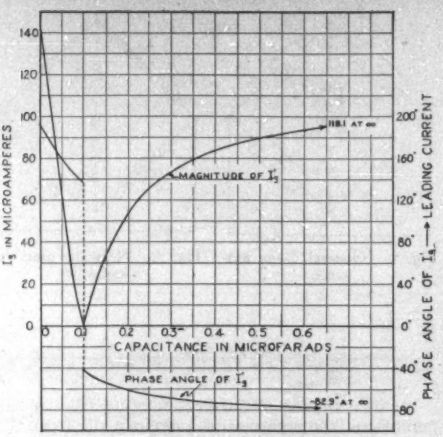


Fig. 4. Variations of cross current as a function of capacitance

be employed, with the addition of the cross arm Z_g, which will be considered to be inductive. This network is shown in Fig. 2. As before, the fixed arms will be taken as Z_a, Z_b, Z_c, and the capacitance C in the arm Z_d will be varied from zero to infinity. The constants of this network are:

$$Z_a = R_a + j\omega L_a$$
$$Z_b = R_b$$
$$Z_c = R_c$$
$$Z_d = R_d - \frac{j}{\omega C}$$
$$Z_g = R_g + j\omega L_g$$

Inserting these constants in eq 2 for cross current:

$$I'_g = \frac{R_bR_c - (R_a + j\omega L_a)\left(R_d - \frac{j}{\omega C}\right)}{R_c[(R_a + j\omega L_a)(R_g + j\omega L_g) + R_b(R_g + j\omega L_g) + R_b(R_a + j\omega L_a)] + \left(R_d - \frac{j}{\omega C}\right)[(R_a + j\omega L_a)(R_g + R_c + j\omega L_g) + R_b(R_g + j\omega L_g + R_a + R_c + j\omega L_a)]} \quad (10)$$

Since C is now the scalar variable representing ρ in the linear fractional transformation equation, the above expression for cross current must be rewritten in an appropriate circular form with C as a factor of a single term in the numerator and denominator. Rearranging the terms in eq 10 accordingly:

$$I'_g = \frac{j(R_a + j\omega L_a) + \omega[R_bR_c - R_d(R_a + j\omega L_a)]C}{-j[(R_a + j\omega L_a)(R_g + R_c + j\omega L_g) + R_b[R_g + R_a + R_c + j\omega(L_a + L_g)]] + C[\omega R_c[(R_g + j\omega L_g)(R_b + R_a + j\omega L_a) + R_b(R_a + j\omega L_a)] + \omega R_d[(R_a + j\omega L_a)(R_c + R_g + j\omega L_g) + R_b(R_g + R_a + R_c + j\omega[L_a + L_g])]]} \quad (11)$$

The constants for the circular locus of cross current above are:

$$\left.\begin{aligned}
\alpha &= j(R_a + j\omega L_a)\\
\beta &= \omega[R_bR_c - R_d(R_a + j\omega L_a)]\\
\gamma &= -j[(R_a + j\omega L_a)(R_g + j\omega L_g + R_c) + R_b[R_g + R_a + R_c + j\omega(L_a + L_g)]]\\
\delta &= \omega R_c[(R_g + j\omega L_g)(R_b + R_a + j\omega L_a) + R_b(R_a + j\omega L_a)] + \omega R_d[(R_a + j\omega L_a)(R_g + R_c + j\omega L_g) + R_b(R_g + R_a + R_c + j\omega[L_a + L_g])]\\
\rho &= C
\end{aligned}\right\} \quad (12)$$

Obtaining the position of the critical points necessary to determine the circle, for $C = \infty$

$$(I'_g)_\infty = \frac{R_bR_c - R_d(R_a + j\omega L_a)}{R_c[(R_g + j\omega L_g)(R_b + R_a + j\omega L_a) + R_b(R_a + j\omega L_a)] + R_d[(R_a + j\omega L_a)(R_g + R_c + j\omega L_g) + R_b(R_g + R_a + R_c + j\omega[L_a + L_g])]}$$

for $C = 0$, $$(I'_g)_0 = \frac{-(R_a + j\omega L_a)}{(R_a + j\omega L_a)(R_g + R_c + j\omega L_g) + R_b[R_g + R_a + R_c + j\omega(L_a + L_g)]}$$

Referring to the foregoing paper, eq 20, it will be noticed that when

$$R_d = \frac{R_a R_b R_e}{R_a^2 + \omega^2 L_a^2} = R'_d$$

$$C = \frac{R_a^2 + \omega^2 L_a^2}{R_b R_e \omega^2 L_a} = C'$$

the cross potential difference is zero. Thus for these values the cross current will also be zero. If $R_d = R'_d$, a convenient value for C to determine the third point on the circle is then C'. If this is not the case, some other value of C must be taken and the corresponding value of I'_g computed. With these 3 points the circle is completely determined together with its scale line.

Numerical Example

To illustrate this problem numerically, the same values of impedance will be employed in the network arms, namely:

$R_a = 1{,}130$ ohms

$L_a = 0.2870$ henries

$R_b = R_e = 2{,}000$ ohms

$R_d = 1{,}000$ ohms

$-\infty < C < +\infty$

If the network be operated at 1,000 cycles, the values of R'_d and C' for null cross current are 1,000 ohms and 10^{-7} farads, respectively. The value of R_d is fixed at 1,000 ohms; hence there will be zero cross current for $C = 10^{-7}$ farads. For the cross impedance arm, let the following constants be assumed:

$R_g = 1{,}000$ ohms

$L_g = 0.0742$ henries

Substituting these constants in the expressions for α, β, γ, and δ as given by eqs 12:

$$\alpha = (-1.803 + j1.130)10^3$$

$$\beta = (18.03 - j11.33)10^9$$

$$\gamma = (10.48 - j10.81)10^6$$

$$\delta = (125.1 + j152.1)10^{12}$$

The cross current of eq 11 may then be represented by:

$$I'_g = \frac{(-1.803 + j1.130)10^3 + (18.03 - j11.33)10^9 \times C}{(10.48 - j10.81)10^6 + (125.1 + j152.1)10^{12} \times C} \qquad (13)$$

The critical points necessary to determine the circle and its scale line are:

for $C = 0$

$$(I'_g)_0 = \frac{(-1.803 + j1.130)10^3}{(10.48 - j10.81)10^6}$$

$$= (-137.3 - j33.78)10^{-6}$$

for $C = \infty$

$$(I'_g)_\infty = \frac{(18.03 - j11.33)10^9}{(125.1 + j152.1)10^{12}}$$

$$= (13.71 - j107.3)10^{-6}$$

for $C = C' = 10^{-7}$ farads

$$I'_g = 0$$

The locus of I'_g is shown in Fig. 3. The points $I'_g = 0$ for $C = 10^{-7}$ farads and $(I'_g)_0$ for $C = 0$ determine the linear scale of C on the scale line as indicated. The value of cross current for any value of C may now be read directly on Fig. 3. The variation of the phase angle and magnitude of I'_g as a function of the capacitance is plotted in Fig. 4. It is interesting to compare this plot with the one drawn for cross potential and note the similarity in the shapes of the curves.

Thus any type of 5-arm network with constant coefficients, in which one arm varies at constant phase angle or along one of its components, may be treated exactly as in the foregoing example.

Five-Arm Networks at Varying Frequency

As compared to the locus of cross potential difference for a 4-arm network, the expression for cross current in the fifth impedance element connected across the midpoints assumes a more complicated form, when the network arms remain fixed and the frequency of the applied voltage is varied. This, as may be seen from eq 2, is due to the presence of the impedance of the fifth arm in the denominator, especially when, as is usually the case, this impedance varies with frequency.

The method of determining the locus of cross current when the frequency is varied, is the same as was employed for the cross potential difference. Using the fundamental equation for cross current, eq 2, the constants of the particular network are substituted in it; the terms of the numerator and denominator are then arranged in descending powers of the angular velocity ω and this expression may then be resolved into a sum of several linear fractional transformations. Each of these linear fractional transformations has a circle for its locus and the resultant locus of cross current is obtained by adding corresponding points on the several circles.

The most complicated case involving a 5-arm network at varying frequency is the one in which each arm contains resistance, inductance, and capacitance. If the form $Z_k = R_k + j\omega L_k - \frac{j}{\omega C_k}$ be substituted in eq 2 and the terms arranged in descending powers of ω, then eq 2 will assume the following form:

$$I'_g = \frac{A_6\omega^6 + A_5\omega^5 + A_4\omega^4 + A_3\omega^3 + A_2\omega^2 + A_1\omega + A_0}{B_6\omega^6 + B_5\omega^5 + B_4\omega^4 + B_3\omega^3 + B_2\omega^2 + B_1\omega + B_0} \qquad (14)$$

in which $A_0 \ldots\ldots A_5$ and $B_0 \ldots\ldots B_6$ are constants free of ω, involving the resistance, inductance, and capacitance of the network arms only. To evaluate I'_g in eq 14, the denominator is equated to zero and then solved as an equation in ω for the 6 roots $\omega_1 \ldots\ldots \omega_6$. Rewriting eq 14 as the sum of 6 linear fractional transformations:

$$I'_g = \frac{A_6\omega^6 + A_5\omega^5 + A_4\omega^4 + A_3\omega^3 + A_2\omega^2 + A_1\omega + A_0}{B_6\omega^6 + B_5\omega^5 + B_4\omega^4 + B_3\omega^3 + B_2\omega^2 + B_1\omega + B_0} =$$

$$\frac{M_1}{\omega - \omega_1} + \frac{M_2}{\omega - \omega_2} + \frac{M_3}{\omega - \omega_3} + \frac{M_4}{\omega - \omega_4} + \frac{M_5}{\omega - \omega_5} + \frac{M_6}{\omega - \omega_6} \qquad (15)$$

Equating coefficients of like powers of ω, the M's may be evaluated in terms of the A's and B's and the roots $\omega_1 \ldots\ldots \omega_6$ or in terms of A's and B's only since $\omega_1 \ldots\ldots \omega_6$ may be expressed in terms of the B's alone. The denominator occurring to the sixth degree, the solution for the 6 roots and for the M's from the 6 resulting simultaneous equations makes the computations rather involved. However, this is the most general case encountered; in practice the networks are generally such that the cross current may be expressed by 2 or more linear fractional transformations, the maximum number of transformations necessary usually being 3 or 4.

As an example of this type of problem, the network used to illustrate the constant frequency problem in Fig. 2 will suffice. Rearranging eq 10 in descending powers of ω the cross current becomes:

$$I'_g = \frac{\dfrac{1}{L_g(R_c + R_d)}\left[jR_g\omega^3 - \dfrac{\omega}{L_a}\left(R_bR_c - R_aR_d - \dfrac{L_a}{C}\right) - \dfrac{jR_a}{L_aC}\right]}{D} \quad (16)$$

in which the denominator D is:

$$D = \omega^3 - \frac{\omega^2 j}{L_aL_gC(R_c + R_d)}\{CL_g(R_a + R_b)(R_c + R_d) + CL_a[(R_c + R_b)(R_c + R_d) + R_cR_d] + L_aL_g\} - \frac{\omega}{L_aL_gC(R_c + R_d)}\{C[(R_aR_g + R_bR_g + R_aR_b)(R_c + R_d) + R_gR_c(R_a + R_b)] + L_a(R_g + R_c + R_b) + L_g(R_a + R_b)\} + \frac{j}{L_aL_gC(R_c + R_d)}[(R_a + R_b)(R_c + R_g) + R_aR_b] \quad (17)$$

Equating the denominator to zero and solving for ω, 3 roots are obtained, ω_1, ω_2, and ω_3. The cross current may then be written:

$$I'_g = \frac{\dfrac{1}{L_g(R_c + R_d)}\left[jR_g\omega^3 - \dfrac{\omega}{L_a}\left(R_bR_c - R_aR_d - \dfrac{L_a}{C}\right) - \dfrac{jR_a}{L_aC}\right]}{D} = \frac{M_1}{\omega - \omega_1} + \frac{M_2}{\omega - \omega_2} + \frac{M_3}{\omega - \omega_3} \quad (18)$$

Here M_1, M_2, and M_3 are coefficients free of the variable ω and involving impedance components and ω_1, ω_2, and ω_3 only. Thus the cross current is seen to be composed of 3 circles:

$$S_1 = \frac{M_1}{\omega - \omega_1}; \quad S_2 = \frac{M_2}{\omega - \omega_2}; \quad S_3 = \frac{M_3}{\omega - \omega_3}$$

that is:

$$I'_g = S_1 + S_2 + S_3 \quad (19)$$

These 3 circles may now be plotted together with their respective scale lines of frequency; corresponding vectors on each circle are then added producing the resultant locus of I'_g.

The computations involved in a problem of this type will be given for the network just discussed using the same constants as before with the exception that the capacitance will be maintained at 10^{-7} farads, which value renders the cross current zero at 1,000 cycles. Substituting these constants into eq 16, the expression for cross current becomes:

$$I'_g = \frac{j4.492\omega^3 - j1.769 \times 10^8}{\omega^3 - j6.364 \times 10^4\omega^2 - 6.121 \times 10^8\omega + j1.824 \times 10^{12}} \quad (20)$$

Solving the denominator as a cubic in ω, the roots are:

$\omega_1 = j5.268 \times 10^4$

$\omega_2 = (0.2140 + j0.5481)10^4$

$\omega_3 = (-0.2140 + j0.5481)10^4$

The cross current is now written as the sum of 3 linear fractional transformations:

$$\frac{j4.492\omega^3 - j1.769 \times 10^8}{\omega^3 - j6.364 \times 10^4\omega^2 - 6.121 \times 10^8\omega + j1.824 \times 10^{12}} = \frac{M_1}{\omega - \omega_1} + \frac{M_2}{\omega - \omega_2} + \frac{M_3}{\omega - \omega_3}$$

Thus, since the roots ω_1, ω_2, and ω_3 have just been evaluated, M_1, M_2, and M_3 may be found to have the following values, by equating coefficients of like powers of ω in the above equation:

$M_1 = j5.664$

$M_2 = 1.415 - j0.5857$

$M_3 = -1.415 - j0.5857$

Thus the locus of cross current is composed of 3 circles, S_1, S_2, and S_3 as given in eq 19, in which

$$\left.\begin{aligned} S_1 &= \frac{M_1}{\omega - \omega_1} = \frac{j5.664}{\omega - j5.268 \times 10^4} \\ S_2 &= \frac{M_2}{\omega - \omega_2} = \frac{1.415 - j0.5857}{\omega - (0.2140 + j0.5481)10^4} \\ S_3 &= \frac{M_3}{\omega - \omega_3} = \frac{-1.415 - j0.5857}{\omega - (-0.2140 + j0.5481)10^4} \end{aligned}\right\} \quad (21)$$

To locate the 3 circles, values of ω equal to 0, ∞, and $2\pi \times 1{,}000$ are substituted in the above expressions giving:

for $\omega = 0$

$S_1 = -0.1075 \times 10^{-3}$

$S_2 = (0.005258 + j0.2603)10^{-3}$

$S_3 = (0.005258 - j0.2603)10^{-3}$

for $\omega = 2\pi \times 1{,}000$

$S_1 = (-0.1060 + j0.0126)10^{-3}$

$S_2 = (0.1922 + j0.1129)10^{-3}$

$S_3 = (-0.0863 - j0.1257)10^{-3}$

for $\omega = \infty$

$S_1 = S_2 = S_3 = 0$

The points just evaluated are sufficient to determine the 3 circles and their respective scale lines. The construction of the locus of cross current is shown in Fig. 5. With the circles drawn as indicated in the plot, additional points corresponding to any desired frequencies are determined on the several circles by use of the scale lines. In the figure, such points are shown for 0, 1,000, 2,000, 3,000, 6,000, 8,000, and 16,000 cycles on all 3 circles. The vectors S_1, S_2, and S_3 for each of these frequencies are added together forming the resultant locus of I'_g as indicated. This addition of vectors is shown in the diagram for 1,000 and 6,000 cycles. It should be noticed that the addition of the 3 vectors for 1,000

cycles gives a resultant cross current of zero which is as it should be, since the constants of the network were so chosen as to give null cross current at this frequency.

The locus of I'_e is shown in the figure drawn through the small open circles which represent the terminal points of the summations of S_1, S_2, and S_3 for the various frequencies. For the sake of clarity, the origin in Fig. 5 has been labeled only as I'_e for 1,000 cycles. However, this is also the point corresponding to infinite frequency for all 3 circles and for the locus of I'_e itself, since the cross impedance is infinite at this frequency.

Summary

In a 5-arm network with constant coefficients, consisting of 4 impedance elements arranged in the usual bridge array, with the fifth arm connected across the mid-points, the locus of the cross current flowing through this fifth impedance arm with constant applied voltage at constant frequency is a circle when any one of the network arms is varied at constant phase angle or along one of its components. The circular locus may be determined readily from the network constants and gives the values of cross current as the variable ranges from minus to plus infinity.

When the same network is operated with all its arms fixed at constant applied voltage and the frequency is varied, the locus of the cross current consists of the sum of one or more circles, depending upon the number of network arms which vary with the frequency. In this case the equation for cross current is expressed as the sum of several linear fractional transformations, each of which has a circle for its locus and the resultant locus is obtained by adding corresponding vectors of each circle.

Thus by following the methods described in this paper, the variation of cross current, as any one of the network arms or the frequency of the applied voltage varies, may be readily determined with a minimum of computation. Although the equations for the typical network, used as an illustration, appear somewhat lengthy, it is necessary to evaluate each term of these equations for only one point. This point may be chosen as any positive or negative value of the variable scalar desired, whichever is the most convenient to use under the particular conditions encountered in the network. The other 2 points required to determine the circle are taken at zero and infinity, respectively; both of these values eliminate a considerable number of terms from the equations. The 3 points are sufficient to draw not only the circle but the scale line as well. The result is a diagram from which may be read the magnitude and phase of the cross current for any value of the variable.

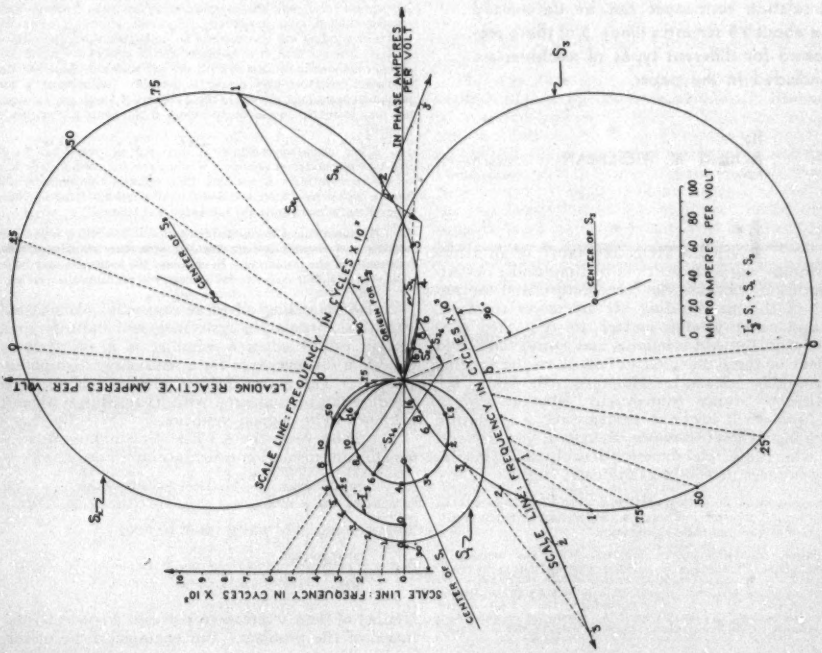


Fig. 5. Construction of the locus of cross current

Insulation Resistance of Armature Windings

Insulation resistance of the windings of an electric machine may be used as a barometer for indicating the condition of the windings. On the basis of tests on many machines of different types it is recommended that all insulation resistance readings be taken after the application of 500 volts (d-c) for one minute. The slope of the resistance-time curve at that point gives a combined indication of the moisture content and the quality of the insulation. In this paper are given formulas for the insulation resistance of different types of windings derived from the winding insulation dimensions and expressed in terms of the rated voltage, capacity, and speed of the machine. By the use of nomographs, insulation resistances can be determined in about 15 second's time; 5 of these prepared for different types of machines are included in the paper.

By
ROBERT W. WIESEMAN
MEMBER A.I.E.E.

General Elec. Co.,
Schenectady, N. Y.

INSULATION resistance of an armature winding varies from time to time under operating conditions because the temperature and the humidity of the surrounding air are never constant. Dust and other foreign matter are deposited continuously on the end windings and connections, and the effect of these depends on how often the winding is thoroughly cleaned. Moisture will lower the insulation resistance temporarily, whereas acid or alkali fumes will lower it permanently. Armature winding insulation resistance, therefore, varies over a rather wide range, and experience in obtaining insulation resistances of windings indicates that:

1. A single value of insulation resistance taken at random without knowing the kind of insulation, its construction, and a "bench mark" value for comparison has little significance.

2. Insulation resistance varies inversely with the amount of moisture in the insulation and the amount of solvent left in the bonding varnish of the coil. From this standpoint the insulation resistance should increase gradually with age if the machine is operated in a clean dry place.

3. Insulation resistance varies inversely with temperature. If the winding is clean and dry, its insulation resistance at room temperature (21 deg C) may be 10 or more times the insulation resistance at 75 deg C. Class *A* insulation varies much more with temperature than does class *B* insulation.

4. Insulation resistance varies somewhat with the applied voltage; usually it decreases as the applied voltage increases.

5. Insulation resistance varies with the time of voltage application; usually it increases during the first 10 minutes of voltage application. This variation (dielectric absorption) makes the measurement of a very high insulation resistance somewhat difficult.

6. Duplicate machines built at the same time and under the same manufacturing conditions may have different insulation resistances. Duplicate machines built at different times, but in the same factory, may have *widely* different insulation resistances.

7. A high value of insulation resistance does not necessarily give assurance that the insulation is in good condition and free from cracks, etc., which eventually may result in a failure. A winding that has failed on the end portion, although clean and dry may have a relatively high insulation resistance.

8. A machine that has a relatively low insulation resistance may have sufficient dielectric strength to operate satisfactorily for a long time.

9. The current that flows through the insulation and the leakage current that flows along the surface of the end winding and connections determine the insulation resistance. A low value of resistance, therefore, does not indicate whether the insulation itself has deteriorated or whether the surface leakage is excessive.

10. Machines having the same rating, but different types of insulation, have different insulation resistances. For example, varnished fabric insulation will absorb more moisture than vacuum-dried compound-filled mica insulation. Thus the insulation resistance of a mica winding will give more of an indication of the end surface leakage, whereas that of a varnished fabric insulated winding will give a combined indication of both the end surface leakage and the insulation resistance from copper to ground. Furthermore, if the insulation has a joint at each of the 4 corners of a coil, the end leakage may lower the insulation resistance if the joints are not made properly.

11. A low insulation resistance is the result of several months of moisture accumulation because a winding requires considerable time to absorb moisture. A machine that operates continuously will have a higher insulation resistance than a machine that operates intermittently and allows the insulation to "breathe."

12. Measurement of insulation resistance of a winding whose end winding and connections are encased with dirt will give a false impression of the insulation. In this case the insulation may be in good condition, but excessive end leakage will condemn the winding.

Notwithstanding all these somewhat complicated variations, insulation resistance will indicate to a certain extent when a winding is in satisfactory condition for service or for a reasonably high potential test. This is true if the insulation resistance of a winding can be compared with its resistance when it is known to be in good condition.

For many years the A.I.E.E. STANDARDS specified a minimum insulation resistance at 75 deg C of

$$R_i = \frac{\text{rated voltage}}{\text{rated kva} + 1{,}000}$$

This rule recently was revised to read

$$R_i = \frac{\text{rated voltage}}{\dfrac{\text{rated kva}}{100} + 1{,}000}$$

Neither of these expressions can give a true interpretation of the problem. For example, a d-c motor,

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 3, 1934; released for publication April 18, 1934. *Not published in pamphlet form.*

an induction motor, and an a-c generator, all of the same voltage and capacity, have the same minimum insulation resistance with these formulas. This is not logical because these 3 machines have different constructions, different insulations, and different ratios of insulation thickness to insulation area (t/A). Furthermore, a low speed machine of a given capacity and voltage has inherently a lower insulation resistance than a high speed machine of the same capacity and voltage.

The object of this paper is to describe insulation resistance characteristics of armature windings and to devise formulas for armature winding insulation resistance that take into account:

1. The speed of the machine as well as its capacity and voltage.
2. The different types of machines, such as synchronous, induction, and d-c machines.
3. The kind of coil insulation (class A or class B).
4. Coefficients that will give an "average" value of the insulation resistance when a machine is new; when a machine has had favorable operating conditions (clean and dry); and the minimum insulation resistance which indicates when a winding should be carefully inspected and reconditioned if necessary.

Measurement of Insulation Resistance

Insulation resistance of an armature winding may be measured with an instrument such as a megger, "megohmer," etc.; or with a voltmeter or a microammeter connected in series with the winding and a direct voltage. The megger has been used for many years, and it gives reliable readings if it is calibrated periodically and if it is operated long enough to eliminate the electrostatic capacity effect of the winding. With the voltmeter method, the maximum resistance that can be measured with reasonable accuracy is about 10 megohms when an ordinary voltmeter is used and about 100 megohms when a high resistance voltmeter is used. From the operator's viewpoint, however, a resistance above 100 megohms for any machine is considered satisfactory. The microammeter method is very accurate for measuring high insulation resistances if a storage battery furnishes the voltage.

Variation of Insulation Resistance

When a constant voltage from a d-c source is impressed on insulation, the current is a maximum at the instant of voltage application; it then decreases at a variable rate in accordance with the type and condition of the insulation. The current is composed of 3 distinct components with different time-constants somewhat as the short-circuit current of an a-c generator is composed of the subtransient, transient, and synchronous reactance components. The corresponding insulation current components are due to electrostatic capacity, dielectric absorption, and conduction-leakage.

Immediately on the application of a constant voltage from a d-c source a normal charging current will flow corresponding to the capacitance of the winding (and to the resistance and inductance of the circuit). This normal charging current, however, usually disappears in less than a second and it should be neglected by short-circuiting the meter for a few seconds after the voltage is applied. After the normal charging current has disappeared, the insulation continues to draw a polarization charging current at a decreasing rate. This polarization current is caused by dielectric absorption; and if the insulation is relatively dry, the polarization current may decrease slowly for several hours (in the case of cables for several days). The polarization current is not proportional to the applied voltage, but varies somewhat as the magnetizing current of iron. After the dielectric absorption current dies away, the conduction and leakage currents of the winding continue.

The true resistance is obtained by dividing the applied voltage by the current when it has reached its constant minimum value. The true resistance can be obtained also by dividing the applied voltage by the difference between the charging current at a given time and the discharge current at the same time interval. Both of these methods of measuring the true insulation resistance are somewhat cumbersome in the field; consequently, it is more practical to measure an "apparent" insulation resistance which includes some absorption. It is obvious, therefore, that in measuring the apparent insulation resistance,

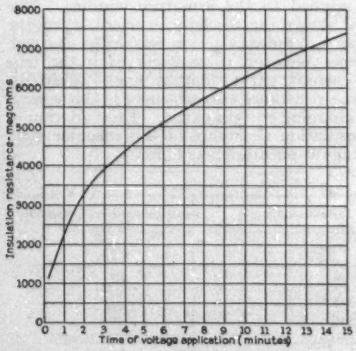


Fig. 1 (left). Armature winding insulation resistance of a new 750-kva 327-rpm 2,400-volt class A insulated a-c generator

Applied voltage 500 volts (d-c), winding temperature 17 deg C. Insulation resistance measured on a dry winter day

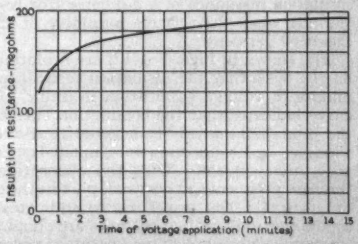


Fig. 2 (right). Armature winding insulation resistance of a new 2,450-kva 750-rpm 6,600-volt class A insulated synchronous motor

Applied voltage 500 volts (d-c), winding temperature 26 deg C. Insulation resistance measured on a warm humid day

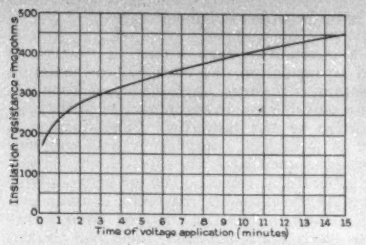
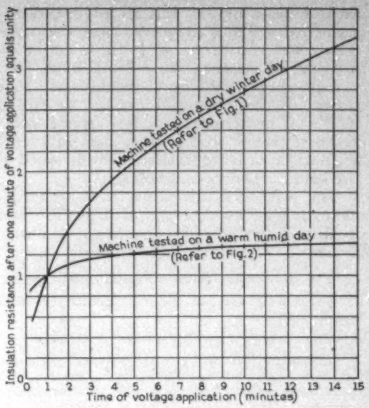


Fig. 3 (left). Armature winding insulation resistance of a new 1,250-kw 750-rpm 600-volt d-c generator

Applied voltage 500 volts (d-c); winding temperature 22 deg C

Fig. 4 (right). Per-unit insulation resistance



the applied voltage and the time of voltage application should be taken into consideration.

Dielectric absorption, notwithstanding its variable characteristics, can be used to advantage in determining the condition of armature insulation. If the conduction current is large, it will over-shadow the polarization current so that the polarization effect cannot be observed. In this case the current will reach its minimum value very quickly. If the insulation is dry, its conduction current will be small and the polarization effect can readily be observed. If the insulation resistance-time curve of a winding, therefore, increases appreciably after 2 or 3 minutes of voltage application, the insulation has a low moisture content. If the resistance-time curve does not increase to any extent after 2 or 3 minutes of voltage application, the insulation either has a high moisture content or the end leakage is excessive.

The insulation resistance of a large number of new machines was measured by the microammeter method for a 15-min voltage application from a 500-volt storage battery. The current was not recorded until 10 seconds had elapsed after the voltage was applied in order to eliminate the capacitance effect of the winding. The insulation resistance of the machines also was checked with a megger.

Figure 1 shows an insulation resistance-time curve of a synchronous machine that was built and tested in the winter when the insulation was dry and cold. Figure 2 shows the insulation resistance of a synchronous machine that was built in the summer and tested on a warm humid day. Figure 3 shows the insulation resistance of a d-c generator tested in the summer when the relative humidity of the air was about 60 per cent.

The curves in Figs. 1 and 2 are replotted in Fig. 4 on the basis that the insulation resistance after one minute of voltage application is unity. The lower curve indicates that the conduction current through the insulation and the leakage current over the end windings and connections are much larger than the absorption current. Thus the absorption effect in this case plays only a *very small* part in the resistance-time curve. The upper curve indicates that the conduction and leakage currents are small and so the absorption current plays an *important* part in shaping the resistance-time curve.

Figure 5 shows curves of several new a-c and d-c machines similar to the curves in Fig. 4, but plotted on a log-log scale. Curves 1 and 2, Fig. 5, show the insulation resistance characteristics of machines in the summer, curves 3 and 4 in the spring, curves 5, 6, and 7 in the fall, and curves 8, 9, and 10 in the winter. In other words, the slope of the curve increases as the moisture content of the insulation decreases. From 0.2 to 0.8 min of voltage application, insulation resistance-time characteristics, Fig. 5, are curved slightly. At 1 minute of voltage application the curve is a straight line (that is, a simple power function of time) and the slope of the curve has a constant value. After 2 or 3 minutes it may curve again slightly or it may continue as a straight line up to 10 minutes. A voltage application of 1 min, therefore, was chosen as the time of voltage application for measuring insulation resistances of armature windings.

How the insulation resistance varies with the time of voltage application, with the applied voltage, and with the winding temperature, is shown in Fig. 6. In Fig. 7 the upper curve shows a polarization charging current curve of a new 10,000-kva 214-rpm 6,900-volt Class-*B*-insulated a-c generator when 500 volts was applied to the armature winding. The lower curve shows the discharge current when the winding was grounded after it was fully charged. The difference between these 2 curves is the true resistance current curve (dotted line). Theoretically the true resistance current curve is the asymptote of the charging current curve. The variation of apparent insulation resistance of this machine with time of voltage application is as follows:

Time of Voltage Application, Minutes	Insulation Resistance, Megohms
0.25	310
0.5	500
1	820
2	1,350
3	1,730
5	2,400
10	3,600
∞	6,000

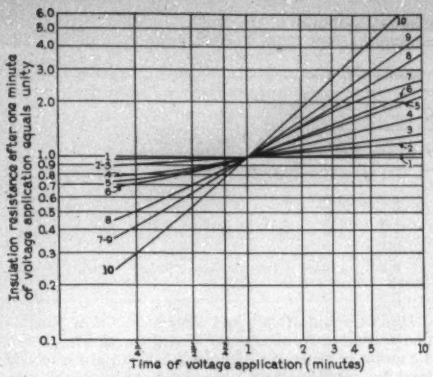


Fig. 5. Per-unit insulation resistance

1. 625-kva 150-rpm 2,300-volt a-c generator
2. 300-kva 225-rpm 2,200-volt synchronous motor
3. 312-kva 360-rpm 240-volt a-c generator
4. 1,250-kw 750-rpm 600-volt d-c generator
5. 400-kw 750-rpm 300-volt d-c generator
6. 750-kw 750-rpm 600-volt d-c generator
7. 2,100-kva 514-rpm 11,000-volt synchronous motor
8. 850-kva 750-rpm 10,500-volt synchronous motor
9. 800-hp 400-rpm 600-volt d-c motor
10. 10,000-kva 214-rpm 6,900-volt a-c generator

The importance of specifying the conditions under which armature winding insulation resistance is measured is shown by Figs. 6 and 7. In order to obtain consistent results, therefore, it is proposed to measure the apparent insulation resistance of armature windings with 500 volts after a voltage application of 1-min duration.

Formulas for Armature Winding Insulation Resistance

To obtain a formula for the insulation resistance of an armature winding in a simplified form (see Appendix) it is necessary to make reasonable assumptions and to use "average values" for factors such as electric and magnetic loading, number of slots, size of slot, thickness of insulation, and diameter and length of a machine, which vary somewhat from one machine to another. The following formulas, therefore, apply to maximum continuous rated (50 deg C rise by thermometer or 60 deg C rise by imbedded temperature detector) a-c and d-c machines and to induction motors of normal design and standard construction that are rated for a 40 deg C rise. In determining the insulation resistance of a special machine or of an old machine, the capacity rating as just outlined and the corresponding speed and voltage should be used. A single-phase machine should have its capacity rating increased about 50 per cent if the machine is wound with a 3-phase Y-connected winding. A suitable allowance also should be made for special features of a machine.

It is somewhat cumbersome, and in fact unnecessary, to take into account all the insulation features of small machines of less than 100 kva or hp. Furthermore, these machines can be and are used with relatively lower insulation resistances than large machines. It is suggested, therefore, that for machines of less than 100 kva or hp, 100 be used when substituting in the formulas regardless of the actual rating of the machine.

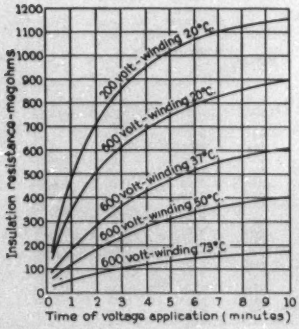


Fig. 6. Variation of insulation resistance of a new 2,100-kva 514-rpm 11,000-volt synchronous motor with applied voltage and temperature

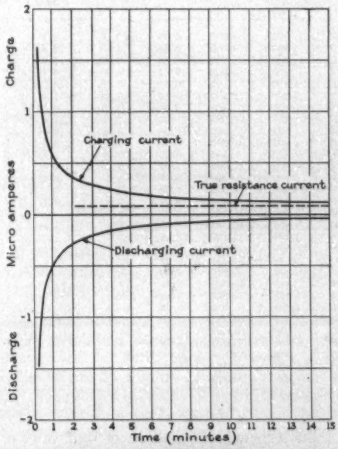


Fig. 7. Insulation charging and discharging current curves of a new 10,000-kva 214-rpm 6,900-volt class B insulated armature winding

Applied voltage 500 volts (d-c), winding temperature 17 deg C

Synchronous Motors and Generators. The insulation resistance R_i of a stator winding of a synchronous machine (a-c generator, synchronous motor, synchronous condenser, and synchronous rotary phase converter) expressed as a function of the machine rated voltage, speed in revolutions per minute (rpm), and kilovoltamperes (kva), as meas-

Table I—Insulation Resistance Coefficients

Condition of Machine	Winding Temperature, Degrees C	Synchronous Machines: Above 1,000 Kva k_s, Class A Insulated	Synchronous Machines: Above 1,000 Kva k_s, Class B Insulated	Synchronous Machines: Below 1,000 Kva k_{ss}, Class A Insulated	Synchronous Machines: Below 1,000 Kva k_{ss}, Class B Insulated	Induction Motors k_i, Class A Insulated	Induction Motors k_i, Class B Insulated	D-C Machines k_d	Synchronous Converters k_c
1. New, clean, and dry (built in the winter; relative humidity 10%)	21	2.0	3.0	0.35	0.50	0.1	0.14	0.1	0.1
2. New and clean (built in the summer; relative humidity 90%)	21	0.4	1.0	0.07	0.15	0.02	0.04	0.02	0.02
3. Good operating conditions (clean and dry)	21	0.5	1.4	0.07	0.2	0.015	0.04	0.01	0.008
4. The winding should be carefully inspected, reconditioned, cleaned, dried, and the end winding varnished if the resistance is less than the values given by these coefficients	75	0.005	0.1	0.0008	0.015	0.0002	0.004	0.0001	0.00007

Table II—Comparison of Present and Proposed Minimum Insulation Resistances (Megohms) of Synchronous Machine Armature Windings at 75 Deg C

Machine Rating: Kva	Machine Rating: Speed Rpm	Machine Rating: Voltage	Present A.I.E.E. Standards $\frac{E}{\text{Kva}+1{,}000}$	Proposed A.S.A. Standards $\frac{E}{\frac{\text{Kva}}{100}+1{,}000}$	Proposed Formula $k_s=0.005$ or $k_{ss}=0.0008$, Class A Insulated	Proposed Formula $k_s=0.1$, Class B Insulated
100	100	200	0.18	0.20	1.4	
100	100	4,000	3.64	4.00	2.8	
100	600	200	0.18	0.20	2.6	
100	600	4,000	3.64	4.00	5.1	
100	1,800	200	0.18	0.20	3.7	
100	1,800	4,000	3.64	4.00	7.4	
1,000	100	500	0.25	0.49	0.53	
1,000	100	10,000	5.00	9.90	1.8	35
1,000	600	500	0.25	0.49	0.97	
1,000	600	10,000	5.00	9.90	3.2	64
1,000	1,800	500	0.25	0.49	1.4	
1,000	1,800	10,000	5.00	9.90	4.6	93
10,000	100	2,000	0.18	1.8	0.13	2.6
10,000	100	15,000	1.36	13.6		8.6
10,000	600	2,000	0.18	1.8	0.24	4.7
10,000	600	15,000	1.36	13.6		15.7
10,000	1,800	2,000	0.18	1.8	0.34	6.8
10,000	1,800	15,000	1.36	13.6		22.6
50,000	100	5,000	0.10	3.3		1.2
50,000	100	15,000	0.29	10.0		2.6
50,000	600	5,000	0.10	3.3		2.2
50,000	600	15,000	0.29	10.0		4.7
50,000	1,800	5,000	0.10	3.3		3.1
50,000	1,800	15,000	0.29	10.0		6.7
100,000	100	10,000	0.10	5.0		1.1
100,000	100	20,000	0.20	10.0		2.0
100,000	600	10,000	0.10	5.0		2.1
100,000	600	20,000	0.20	10.0		3.5
100,000	1,800	10,000	0.10	5.0		3.0
100,000	1,800	20,000	0.20	10.0		5.1

ured after a 1-min application of 500 volts is approximately

$$R_i = k_s \frac{(\text{voltage} + 3{,}600)\ \text{rpm}^{1/2}}{\text{kva}^{3/4}} \quad \text{for machines of more than 1,000 kva} \tag{1}$$

$$R_i = k_{ss} \frac{(\text{voltage} + 3{,}600)\ \text{rpm}^{1/2}}{\text{kva}^{1/2}} \quad \text{for machines of less than 1,000 kva} \tag{2}$$

Induction Motors. The insulation resistance R_i of a stator winding of an induction motor expressed as a function of the machine rated voltage, speed in revolutions per minute (rpm), and horsepower, as measured after a 1-min application of 500 volts is approximately

$$R_i = k_i \frac{(\text{voltage} + 3{,}600)\ \text{rpm}^{1/2}}{\text{hp}^{1/2}} \tag{3}$$

Direct-Current Motors and Generators. The insulation resistance R_i of a rotor armature winding of a d-c motor or generator expressed as a function of the machine rated voltage, speed in revolutions per minute, and kilowatts (kw), as measured after a 1-min application of 500 volts is approximately

$$R_i = k_d \frac{(\text{voltage} + 1{,}400)\ \text{rpm}^{1/2}}{\text{kw}^{1/2}} \tag{4}$$

Synchronous Converters. The insulation resistance R_i of a rotor armature winding of a synchronous converter expressed as a function of the machine rated voltage, speed in revolutions per minute (rpm), and kilowatts (kw), as measured after a 1-min application of 500 volts is approximately

$$R_i = k_c \frac{(\text{voltage} + 1{,}000)\ \text{rpm}^{1/2}}{\text{kw}^{1/4}} \tag{5}$$

For d-c machines R_i is the insulation resistance of only the armature winding and commutator. No attempt was made to include the insulation resistance of the brushholders, brushholder supports, and field windings because they vary greatly in type and

Table III—Comparison of Present and Proposed Minimum Insulation Resistances (Megohms) of D-C Machine Armature Windings at 75 Deg C

Machine Rating: Kw	Machine Rating: Speed Rpm	Machine Rating: Voltage	Present A.I.E.E. Standards $\frac{E}{\text{Kw}+1{,}000}$	Proposed A.S.A. Standards $\frac{E}{\frac{\text{kw}}{100}+1{,}000}$	Proposed Formula $kd=0.0001$
100	100	100	0.09	0.10	0.32
100	100	600	0.55	0.60	0.43
100	2,000	100	0.09	0.10	1.44
100	2,000	600	0.55	0.60	1.92
500	100	200	0.13	0.20	0.20
500	100	600	0.40	0.60	0.25
500	1,000	200	0.13	0.20	0.64
500	1,000	600	0.40	0.60	0.80
1,000	100	200	0.10	0.20	0.16
1,000	100	600	0.30	0.60	0.20
1,000	720	200	0.10	0.20	0.43
1,000	720	600	0.30	0.60	0.54
2,500	100	200	0.057	0.20	0.12
2,500	100	600	0.17	0.59	0.15
2,500	500	200	0.057	0.20	0.26
2,500	500	600	0.17	0.59	0.33
5,000	100	600	0.10	0.57	0.12
5,000	300	600	0.10	0.57	0.20
10,000	100	600	0.055	0.55	0.09

Table IV—Comparison of Present and Proposed Minimum Insulation Resistances (Megohms) of Synchronous Converter Armature Windings at 75 Deg C

Machine Rating			Present A.I.E.E. Standards	Proposed A.S.A. Standards	Proposed Formula
Kw	Speed Rpm	Voltage	$\frac{E}{kw+1{,}000}$	$\frac{E}{\frac{kw}{100}+1{,}000}$	$k_c = 0.00007$
100	1,200	100	0.09	0.10	0.84
100	1,200	300	0.27	0.30	1.00
300	1,200	200	0.15	0.20	0.70
300	1,200	600	0.46	0.60	0.93
500	750	200	0.13	0.20	0.50
500	750	600	0.40	0.60	0.67
500	1,200	200	0.13	0.20	0.61
500	1,200	600	0.40	0.60	0.82
1,000	500	200	0.10	0.20	0.33
1,000	750	600	0.30	0.59	0.55
1,000	900	600	0.10	0.20	0.45
1,000	900	600	0.30	0.59	0.60
2,000	300	200	0.07	0.20	0.22
2,000	375	600	0.20	0.59	0.33
2,000	450	200	0.07	0.20	0.36
2,000	600	600	0.20	0.59	0.41
3,000	400	600	0.15	0.58	0.34
5,000	240	600	0.10	0.57	0.21

construction. Thus in measuring the insulation resistance of a d-c machine or a synchronous converter, all brushes should be raised from the commutator and collector.

Insulation Resistance Coefficients k_s, k_m, k_i, k_d, and k_c. Table I gives values of the insulation coefficients for eqs 1 to 5 for different types of machines. The average range of insulation resistance variation of new machines at room temperature (21 deg C) is given by conditions 1 and 2. If a machine is built in the winter and its insulation resistance measured when the temperature is below 21 deg C, the value of k will be much more than that given for condition 1. Condition 3 gives the values of k for good operating conditions. Machines operating in some localities, however, may not have insulation resistances as high as those corresponding to condition 3.

Condition 4 gives values of k for the minimum insulation resistance of a winding at 75 deg C. Values of k for conditions 3 and 4 were purposely made a little high in order to encourage operators to clean the machines frequently. It is emphasized that a winding having a lower resistance than the minimum value will not necessarily fail. In fact under ordinary operating conditions the resistance occasionally may fall a little below the minimum value. It is believed, however, that if the resistance is maintained at or above that corresponding to k for condition 4, the winding should give reliable service.

In deriving eqs 1, 2, 3, 4, and 5, all constants were incorporated in the coefficient k for simplicity. The fact that different machines have different values of k for the same class of insulation, Table I, does not prove that the insulation resistivity of these machines is necessarily different or that the insulation on one type of machine is superior to that of another.

Tables II, III, IV, and V show how the minimum value of insulation resistance obtained by the equations developed compare with those of the present A.I.E.E. Standards and those proposed by the American Standards Association. In some cases the difference is not appreciable, but in others a marked difference results when the type of machine, its speed, and its class of insulation are taken into consideration.

Variation of Insulation Resistance With Temperature and High Humidity

Values of k for condition 4 were determined by test for different kinds of insulation exposed to a high relative humidity. The variation of resistivity

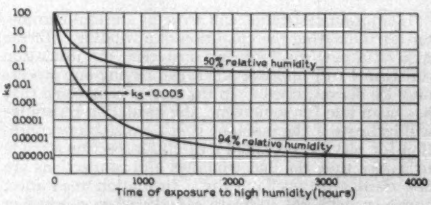


Fig. 8. Variation of resistivity coefficient k_s of class A insulation with time of exposure to high relative humidity at 30 deg C

of Class A insulation as measured after a 1-min application of 500 volts with time of exposure to high humidity is shown in Fig. 8. For convenience the resistivity was plotted in terms of k_s for synchronous machines of more than 1,000 kva so that a comparison can be made with the values of k_s in Table I. The insulation was "bone-dry" when the test was

Table V—Comparison of Present and Proposed Minimum Insulation Resistances (Megohms) at 75 Deg C

Machine Rating							All Machines	
Kva	Speed Rpm	Voltage	Synchronous Machines	Induction Motors	D-C Machines	Synchronous Converters	A.I.E.E. Standards	A.S.A. Standards
100	1,000	200	3.0	2.4	1.1	0.84	0.18	0.5
500	1,000	200	1.4	1.1	0.64	0.56	0.13	0.2
500	1,000	600	1.5	1.2	0.80	0.75	0.3	0.5
1,000	300	200	0.72	0.42	0.28	0.26	0.1	0.2
1,000	300	1,000	0.87	0.51	0.42	0.43	0.5	1.0
1,000	1,000	200	1.07	0.76	0.51	0.47	0.1	0.2
1,000	1,000	1,000	1.29	0.92	0.76	0.79	0.5	1.0
5,000	300	1,000	0.26	0.23	0.24	0.29	0.17	0.95

begun, which accounts for the high initial value of k_s.

The variation of k_s in Fig. 8 with time of exposure to high humidity does not take into account the accumulation of dirt and other foreign matter on the winding. A practical test to include all variables is somewhat difficult to make and so the effect of each of these should be determined separately. Table I, therefore, is a composite evaluation of k for different types of machines as determined by resistivity tests on insulation samples and on old and new machines.

The resistivity of dry varnished fabric insulation (Class A) was found by test to decrease about 75 times as much as the resistivity of mica insulation (Class B) for a temperature increase from 21 deg C to 75 deg C as measured after a one-minute application of 500 volts. Tests also show that the resistivity of varnished fabric insulation decreases 10 or more times as much as the resistivity of mica insulation when exposed to high humidities. Higher values, therefore, were assigned to k, Table I, for mica insulation than for varnished fabric insulation. Furthermore, mica insulated machines are usually large, important machines and they should be maintained at a relatively higher insulation resistance than varnished fabric insulated machines.

Summarization

Insulation resistance will serve as a useful barometer for indicating the condition of a winding. In the case of a new machine just installed, the insulation resistance will indicate when the drying-out process may be discontinued. In the case of a machine that has been idle for some time, the insulation resistance will indicate if the machine is in a satisfactory condition for service, provided a careful inspection is made to insure that the end windings and connections are not damaged mechanically. Insulation resistance, however, will not indicate exactly when a winding will fail. Judgment, therefore, must be used in interpreting insulation readings and in deciding when a winding should be reconditioned or reinsulated.

Insulation resistance readings of a machine should be taken after an application of 500 volts for one minute. The winding temperature always should be recorded, and readings should be taken at regular intervals. The trend or slope of the curve of insulation resistance will indicate the condition of the insulation better than insulation resistance values themselves. If an insulation resistance curve of a machine is not available, insulation resistance obtained by the formula for conditions 3 and 4, Table I, can be used as a basis for comparison.

An insulation resistance-time curve plotted on a log-log scale (see Fig. 5) will give a very good indication of the condition of the insulation. If the curve tends to increase after 1 or 2 minutes of voltage application, the moisture content and the end surface leakage are small. The more the curve continues as a straight line after 1 or 2 minutes of voltage application, the better the condition of the winding insulation. Conversely, if the slope of the curve at one-minute voltage application is small, the insulation has absorbed moisture or the end leakage is excessive.

Insulation resistance formulas based on the dimensions of a machine are recommended in the place of formulas that include only the machine voltage and capacity rating, but make no allowance for the type of machine, its speed, and its kind of insulation. Insulation resistance in accordance with the method recommended in this paper can be determined in about 15 seconds from nomographs, Figs. 9 to 13.

Insulation resistance may not indicate if the insulation has localized weak spots or whether the insulation has a high power factor. An insulation resistance test, therefore, does not take the place of either a power factor test or a high potential test. Periodic insulation resistance tests, however, are recommended as a fundamental method of checking the condition of the winding insulation.

Appendix—Insulation Resistance of Synchronous Machines of More Than 1,000 Kva

The insulation resistance in megohms of an armature winding after a 1-min application of 500 volts is

$$R_i = k\,\frac{t}{A} \tag{6}$$

where

k = a function of the winding moisture content, kind of insulation, operating conditions, and average resistivity of armature insulation after a one-minute application of 500 volts

t = average insulation thickness from copper to ground, in inches

$t = 0.052 + 0.0000145\,E$ approximately (7)

E = machine rated voltage

A = effective area of insulation from copper to ground, in square inches

The stator slot pitch in inches is approximately

$$t_0 = 0.9 + 0.000088\,E \tag{8}$$

The stator slot periphery minus the stator slot wedge depth and the stator slot width is approximately

$$p = 4.5 + 0.00044\,E \tag{9}$$

The gap diameter in inches is approximately

$$D = 127\,\frac{\text{kva}^{\frac{0.42}{\text{rpm}^{0.1}}}}{\text{rpm}^{0.30}} \tag{10}$$

The stator core length in inches, increased slightly to allow for end leakage currents, is approximately

$$L = 0.41\,\text{rpm}^{0.08}\cdot\text{kva}^{0.33\,\text{rpm}^{0.08}} \tag{11}$$

$$A = \frac{\pi D}{t_0}\,pL \tag{12}$$

Substituting eqs 8, 9, 10, and 11 in eq 12,

$$A = 815\,\frac{\text{kva}^{\frac{0.74}{\text{rpm}^{0.04}}}}{\text{rpm}^{0.34}} \tag{13}$$

This expression was checked with a large number of machines and it was found that it can be written

$$A = 420\,\frac{\text{kva}^{3/4}}{\text{rpm}^{1/4}}\ \text{approximately} \tag{14}$$

Substituting eqs 7 and 13 in eq 6,

$$R_i = k_s\,\frac{(3{,}600 + E)\text{rpm}^{1/4}}{\text{kva}^{3/4}} \tag{15}$$

In this manner R_i can be obtained for induction motors, d-c machines, and synchronous converters.

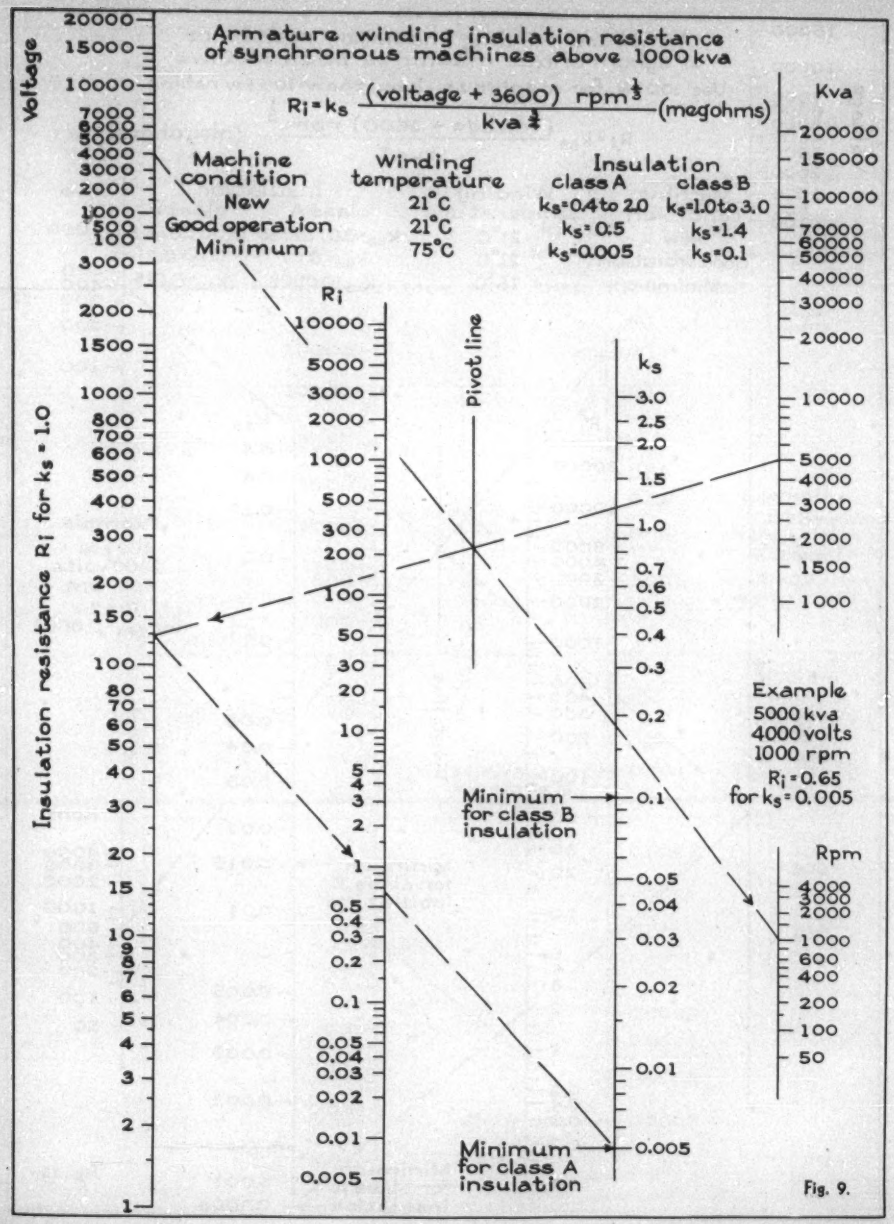

Armature winding insulation resistance of synchronous machines above 1000 kva
$R_i = k_s \frac{(\text{voltage} + 3600)\ \text{rpm}^{\frac{1}{3}}}{\text{kva}^{\frac{1}{4}}}$ (megohms)
Voltage
Insulation resistance R_i for $k_s = 1.0$
Machine condition
Winding temperature
Insulation
class A
class B
New
21°C
k_s=0.4 to 2.0
k_s=1.0 to 3.0
Good operation
21°C
k_s=0.5
k_s=1.4
Minimum
75°C
k_s=0.005
k_s=0.1
R_i
Pivot line
k_s
Kva
Rpm
Minimum for class B insulation
Minimum for class A insulation
Example
5000 kva
4000 volts
1000 rpm
R_i = 0.65
for k_s = 0.005

Fig. 9.

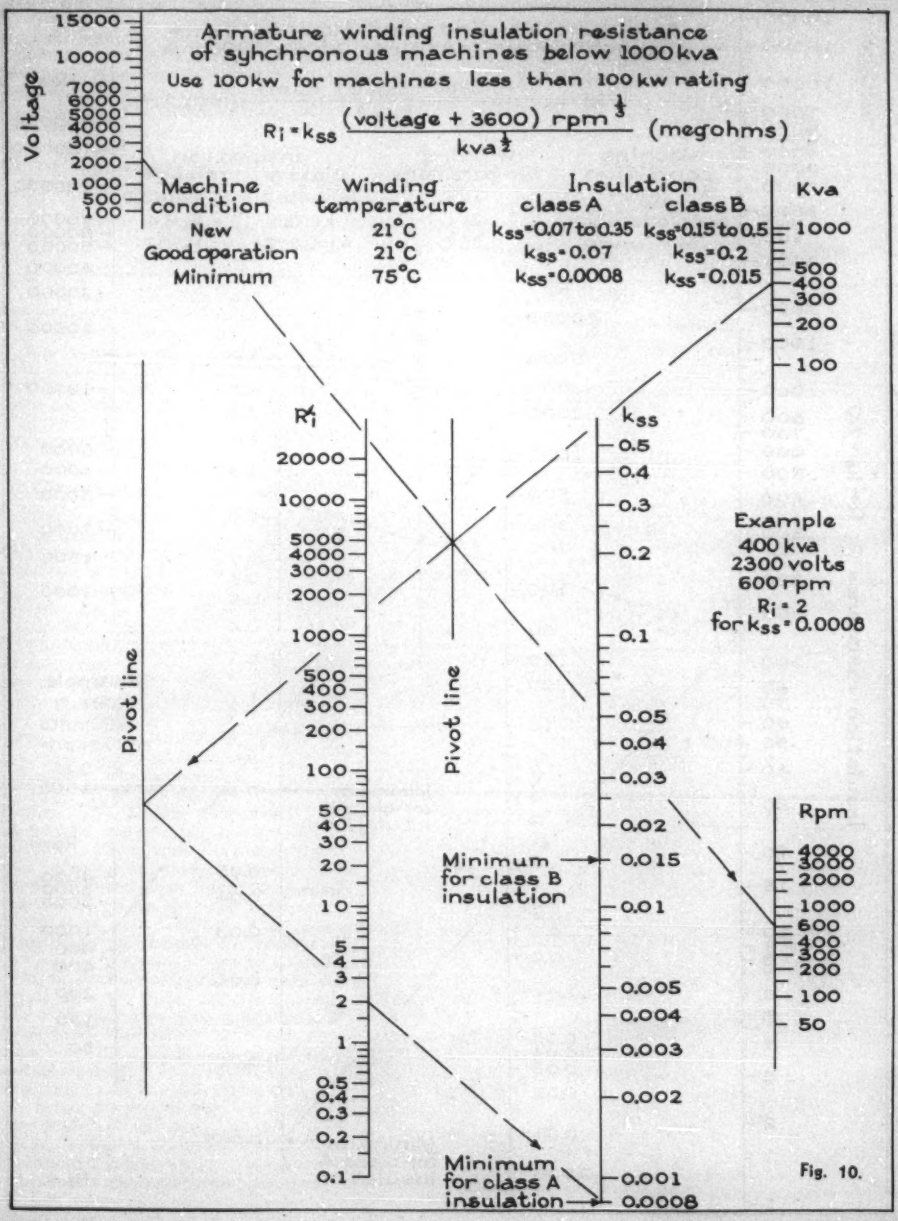

Armature winding insulation resistance
of syhchronous machines below 1000 kva
Use 100 kw for machines less than 100 kw rating
$R_i = k_{ss} \frac{(\text{voltage} + 3600)\ \text{rpm}^{\frac{1}{3}}}{\text{kva}^{\frac{1}{2}}}$ (megohms)
Voltage
15000
10000
7000
6000
5000
4000
3000
2000
1000
500
100
Machine condition
Winding temperature
Insulation
class A
class B
New
21°C
k_{ss}=0.07 to 0.35
k_{ss}=0.15 to 0.5
Good operation
21°C
k_{ss}=0.07
k_{ss}=0.2
Minimum
75°C
k_{ss}=0.0008
k_{ss}=0.015
Kva
1000
500
400
300
200
100
R_i
20000
10000
5000
4000
3000
2000
1000
500
400
300
200
100
50
40
30
20
10
5
4
3
2
1
0.5
0.4
0.3
0.2
0.1
k_{ss}
0.5
0.4
0.3
0.2
0.1
0.05
0.04
0.03
0.02
0.015
0.01
0.005
0.004
0.003
0.002
0.001
0.0008
Pivot line
Pivot line
Example
400 kva
2300 volts
600 rpm
R_i = 2
for k_{ss} = 0.0008
Minimum for class B insulation
Minimum for class A insulation
Rpm
4000
3000
2000
1000
600
400
300
200
100
50

Fig. 10.

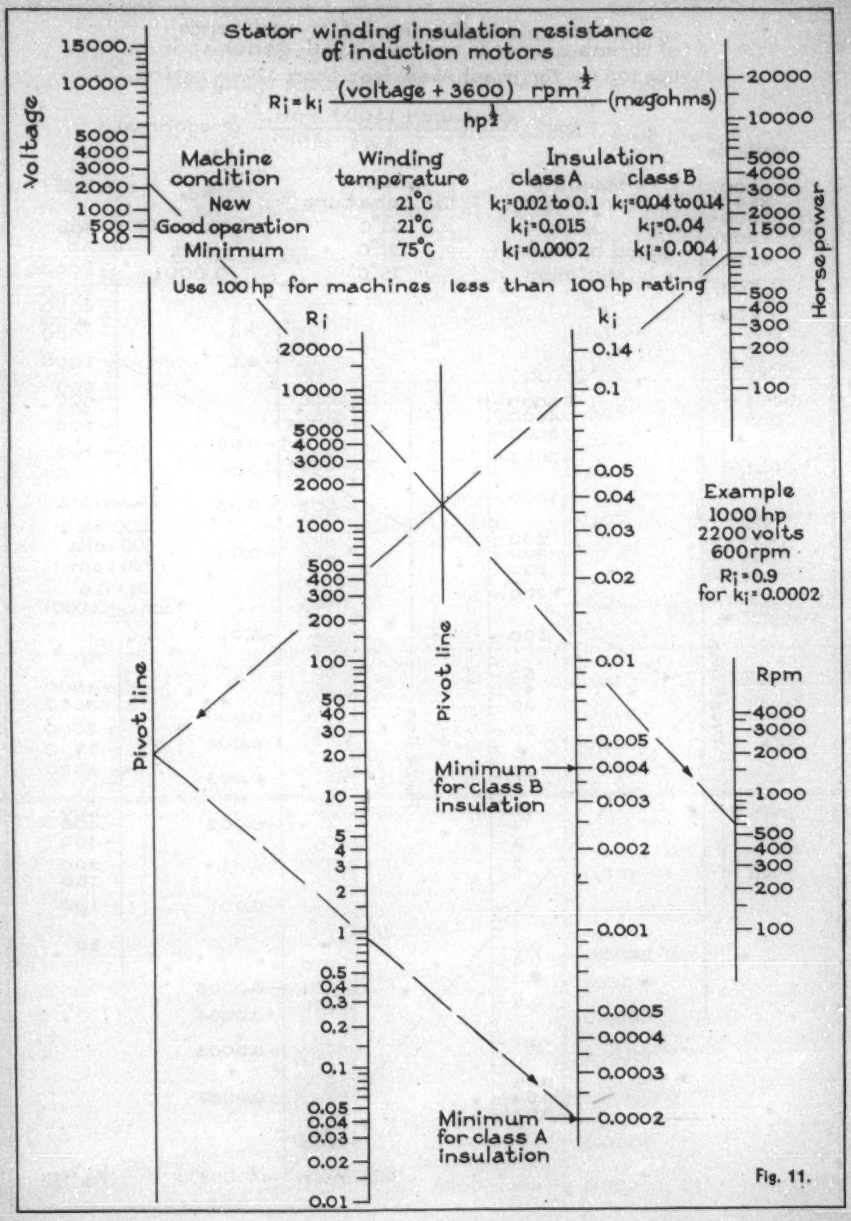

Stator winding insulation resistance of induction motors
$R_i = k_i \frac{(\text{voltage} + 3600)\ \text{rpm}^{\frac{1}{2}}}{\text{hp}^{\frac{1}{2}}}$ (megohms)
Voltage
15000
10000
5000
4000
3000
2000
1000
500
100
Machine condition
Winding temperature
Insulation
class A
class B
New
21°C
k_i=0.02 to 0.1
k_i=0.04 to 0.14
Good operation
21°C
k_i=0.015
k_i=0.04
Minimum
75°C
k_i=0.0002
k_i=0.004
Use 100 hp for machines less than 100 hp rating
Horse power
20000
10000
5000
4000
3000
2000
1500
1000
500
400
300
200
100
R_i
20000
10000
5000
4000
3000
2000
1000
500
400
300
200
100
50
40
30
20
10
5
4
3
2
1
0.5
0.4
0.3
0.2
0.1
0.05
0.04
0.03
0.02
0.01
k_i
0.14
0.1
0.05
0.04
0.03
0.02
0.01
0.005
0.004
0.003
0.002
0.001
0.0005
0.0004
0.0003
0.0002
Pivot line
Pivot line
Minimum for class B insulation
Minimum for class A insulation
Example
1000 hp
2200 volts
600 rpm
R_i=0.9
for k_i=0.0002
Rpm
4000
3000
2000
1000
500
400
300
200
100

Fig. 11.

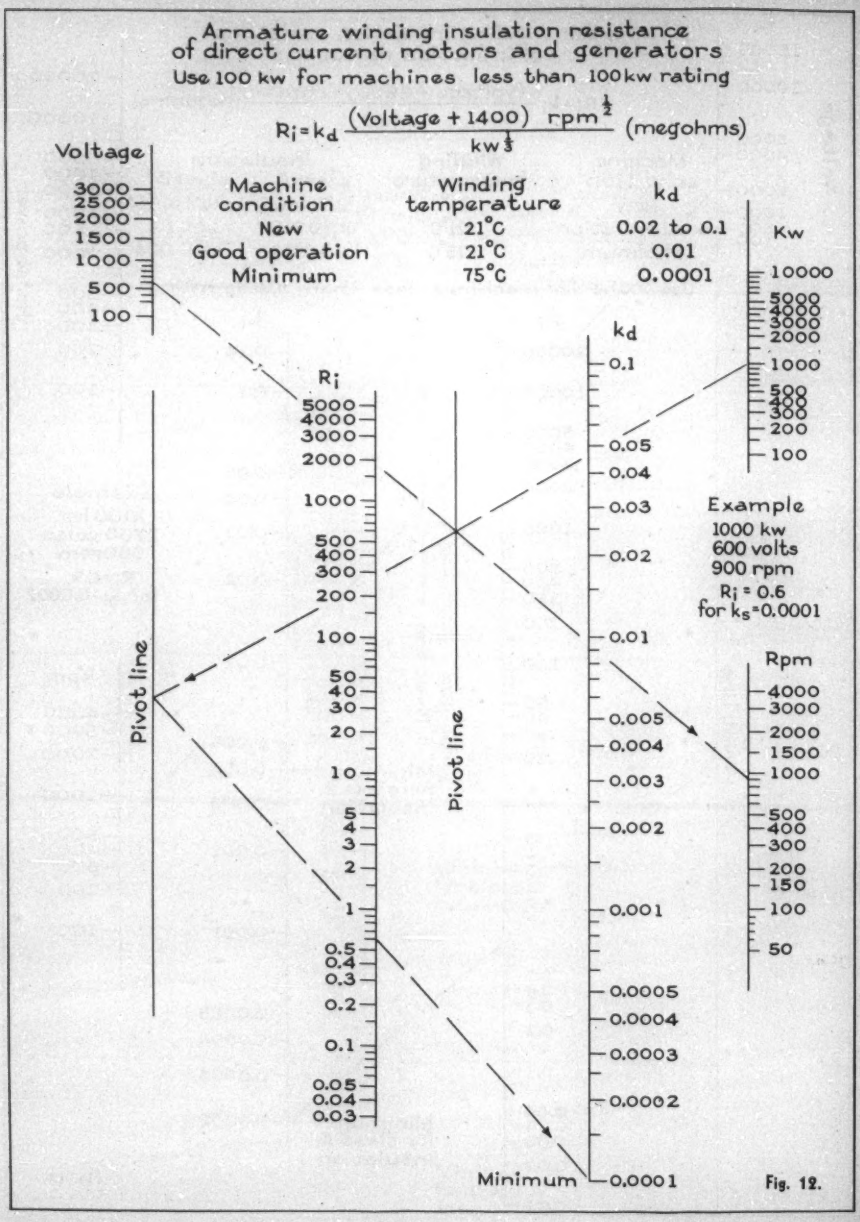

Armature winding insulation resistance
of direct current motors and generators
Use 100 kw for machines less than 100kw rating
$R_i = k_d \frac{(\text{Voltage} + 1400)\ \text{rpm}^{\frac{1}{2}}}{\text{kw}^{\frac{1}{3}}}$ (megohms)
Voltage
3000
2500
2000
1500
1000
500
100
Machine condition
New
Good operation
Minimum
Winding temperature
21°C
21°C
75°C
kd
0.02 to 0.1
0.01
0.0001
Kw
10000
5000
4000
3000
2000
1000
500
400
300
200
100
Ri
5000
4000
3000
2000
1000
500
400
300
200
100
50
40
30
20
10
5
4
3
2
1
0.5
0.4
0.3
0.2
0.1
0.05
0.04
0.03
kd
0.1
0.05
0.04
0.03
0.02
0.01
0.005
0.004
0.003
0.002
0.001
0.0005
0.0004
0.0003
0.0002
0.0001
Minimum
Example
1000 kw
600 volts
900 rpm
Ri = 0.6
for ks=0.0001
Rpm
4000
3000
2000
1500
1000
500
400
300
200
150
100
50
Pivot line
Pivot line

Fig. 12.

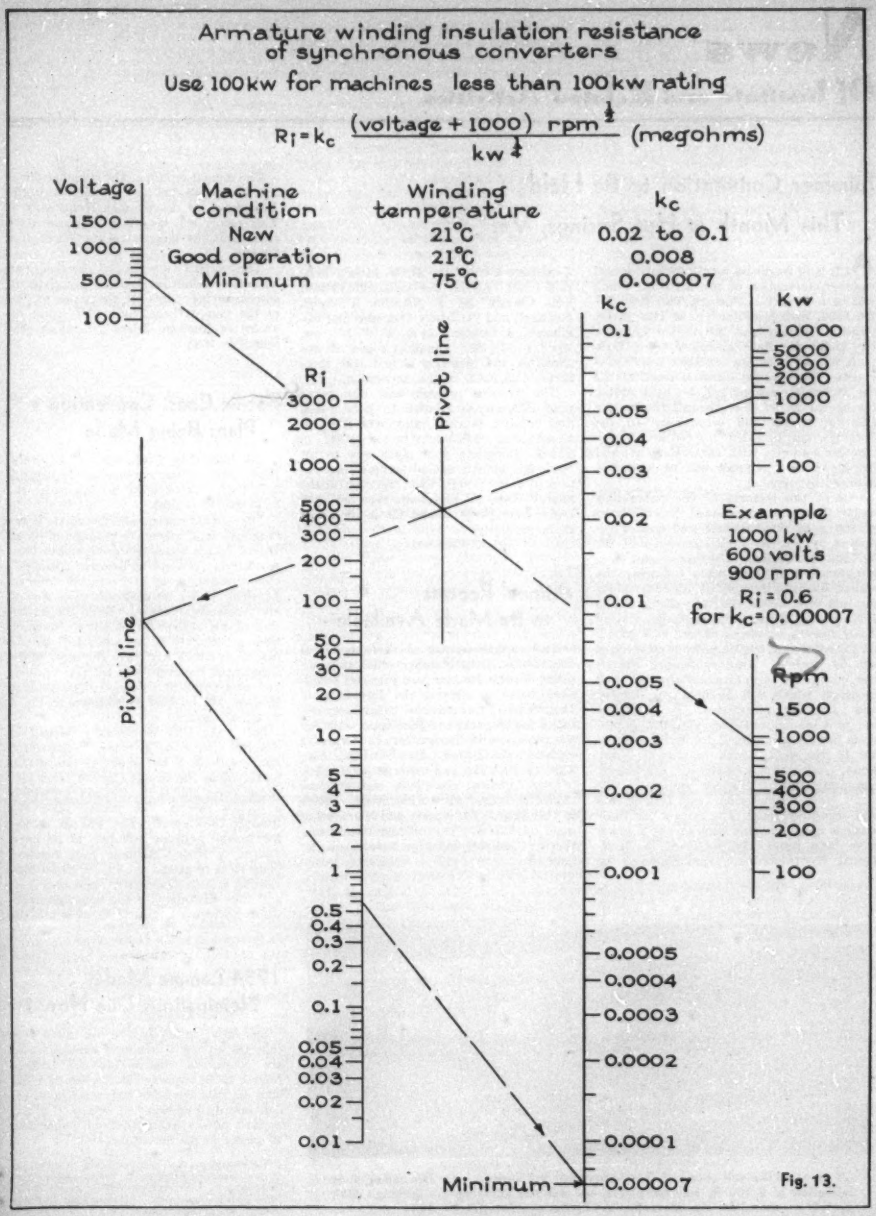

Armature winding insulation resistance of synchronous converters
Use 100 kw for machines less than 100 kw rating
$R_i = k_c \frac{(\text{voltage} + 1000)\ \text{rpm}^{\frac{1}{2}}}{\text{kw}^{\frac{1}{4}}}$ (megohms)
Voltage
1500
1000
500
100
Machine condition
New
Good operation
Minimum
Winding temperature
21°C
21°C
75°C
k_c
0.02 to 0.1
0.008
0.00007
Pivot line
R_i
3000
2000
1000
500
400
300
200
100
50
40
30
20
10
5
4
3
2
1
0.5
0.4
0.3
0.2
0.1
0.05
0.04
0.03
0.02
0.01
Pivot line
k_c
0.1
0.05
0.04
0.03
0.02
0.01
0.005
0.004
0.003
0.002
0.001
0.0005
0.0004
0.0003
0.0002
0.0001
0.00007
Minimum
Kw
10000
5000
3000
2000
1000
500
100
Example
1000 kw
600 volts
900 rpm
$R_i = 0.6$
for $k_c = 0.00007$
Rpm
1500
1000
500
400
300
200
100

Fig. 13.

News
Of Institute and Related Activities

Summer Convention to Be Held This Month at Hot Springs, Va.

ALL is in readiness for the fiftieth annual summer convention of the A.I.E.E., which will be held in Hot Springs, Va., June 25–29, 1934, with headquarters in The Homestead. The summer convention committee, under the chairmanship of W. S. Rodman, has arranged an excellent schedule of events. The annual business meeting and the technical sessions will be held during the mornings so that the afternoons are free for sports and recreation. In the evenings, the president's reception, a get-together banquet with entertainment, and the convention banquet will be held and followed by dancing.

One of the features of the convention will be the commemoration of the fiftieth anniversary of the Institute and special addresses by Dr. W. E. Wickenden and Dr. William McClellan. The commemoration ceremonies will take place following the annual business meeting on Monday morning and it is hoped that all officers of the Institute, all living past-presidents, and all living charter members, as well as a goodly representation of engineers from all sections will be present. Another feature will be the conference of officers, delegates, and members which will be held on Monday and Tuesday afternoons. To complete the professional activities a technical program has been scheduled during the remainder of the week, which consists of 7 sessions: education, electrical machinery, communication, insulators, automatic stations, power generation, and instruments and measurements. The papers for these sessions appear in this issue except 3 which have been previously published in ELECTRICAL ENGINEERING: "Iron Shielding for Telephone Cables" by H. R. Moore, Feb., p. 274–80; "Recent Developments in Power Line Carrier" by T. Johnson, Jr., April, p. 542–7, and "Industry Demands and Engineering Education" by L. W. W. Morrow, April, p. 518–22. Pamphlet copies are not available and members should take these issues with them to the convention.

The complete program and other pertinent information relative to hotel rates, and reduced railroad rates, was given in ELECTRICAL ENGINEERING for May, p. 842–4. Complete your plans now to attend this fiftieth annual summer convention at Hot Springs, Va. Members in the nearby districts who have received mail registration cards should fill in and post them promptly.

Annual Reports to Be Made Available

The annual reports of those technical committees of the Institute which are compiling reports for the past year are scheduled for publication in the July issue of ELECTRICAL ENGINEERING. The heavy demand for space in the June issue made by the papers to be discussed at the Institute's summer convention, Hot Springs, Va., June 25–29, 1934, and the lateness of a few of the technical committee reports, precluded complete publication of the reports in this issue. All reports which are being made available by the technical committees therefore are scheduled for inclusion in the next issue.

The annual report of the board of directors is also scheduled for publication in the July issue of ELECTRICAL ENGINEERING. This report will be officially presented at the Institute's summer convention at Hot Springs.

The annual reports on Section and Branch activities for 1933–34 are given on accompanying pages of the news section of the present issue, as is the report on award of Institute prizes for papers presented in 1933.

A green on the golf course of The Homestead, Hot Springs, Va. This course, at an elevation of 2,300 ft, may be played by members attending the Institute's 50th annual summer convention at Hot Springs, June 25–29, 1934

Pacific Coast Convention Plans Being Made

Salt Lake City, Utah, will be host to the 1934 Pacific Coast convention, September 3–7, 1934. Convention headquarters will be in the Hotel Utah.

The general convention committee is arranging a most attractive program of broad appeal. Five technical sessions have been tentatively arranged as follows: communication, management and selected subjects, lightning, power transmission and stability, and protective devices. With the exception of one session on Monday afternoon, these sessions will be scheduled in the mornings, which will leave the other afternoons open for inspection trips, recreation, and entertainment features. Two student sessions will be held in addition to the 5 technical sessions.

Salt Lake City is centrally located in America's vacation grounds. Yellowstone National Park is but a night's ride to the north, while the Grand Canyon, Zion National Park, and Bryce Canyon are within a night's ride to the south. Also the Boulder Dam construction will be, during the present summer and fall, at its most interesting stage. Arrange your vacation plans so as to attend the Pacific Coast convention at Salt Lake City, September 3–7, and take advantage of the unusual opportunities which its natural location affords.

1934 Lamme Medal Nominations Due Nov. 1

Special attention is directed to the fact that the names of Institute members who are considered eligible for the Lamme Medal, to be awarded in the fall of 1934, may be submitted by any member in accordance with Section 1 of Article VI of the by-laws of the Lamme Medal committee, as quoted in the following:

The committee shall cause to be published in one or more issues of ELECTRICAL ENGINEERING, or of its successors, each year, preferably including the June issue, a statement regarding the "Lamme Medal" and an invitation for any member to pre-

sent to the national secretary of the Institute by November 1, the name of a member as a nominee for the medal, accompanied by a statement of his "meritorious achievement" and the names of at least 3 engineers of standing who are familiar with the achievement.

Each nomination should give concisely the specific grounds upon which the award is proposed, and also a complete detailed statement of the achievements of the nominee to enable the committee to determine its significance as compared with the achievements of other nominees. If the work of the nominee has been of a somewhat general character in coöperation with others, specific information should be given regarding his individual contributions. Names of endorsers should be given as specified above.

The Lamme Medal, founded as a result of a bequest of the late Benjamin Garver Lamme, chief engineer of the Westinghouse Electric and Manufacturing Company (deceased July 8, 1924), provides for the annual award by the Institute of a gold medal —together with bronze replica thereof— to a member of the A.I.E.E. "who has shown meritorious achievement in the development of electrical apparatus or machinery"; and for the award of 2 such medals in some years if the accumulation of funds warrants.

The sixth (1933) Lamme Medal has been awarded to Lewis B. Stillwell (A'92, M'92, F'12, member for life and past-president) consulting engineer, New York, N. Y., "for his distinguished career in connection with the design, installation, and operation of electrical machinery and equipment." Presentation will be made during the summer convention at Hot Springs, Va., June 25–29, 1934.

North Eastern District Holds Tenth Annual Meeting at Worcester, Mass.

THE Worcester Section played host to those who attended the tenth annual meeting of the Institute's North Eastern District in Worcester, Mass., May 16–18, inclusive. The official registration was 337, including more than 100 Enrolled Students.

The District meeting idea was pioneered by the North Eastern District in 1924 as a major contribution toward the Institute's effort so to decentralize and distribute its major activities as to make them more available to the membership. From its New England birthplace, the District meeting idea spread to several other Districts with excellent results. Further pioneering was undertaken by that District in 1932 when, in connection with its Providence meeting, the then prevalent tradition of having pamphlet copies of all technical papers available for general distribution was, in the interest of economy, dispensed with successfully. Still further pioneering was undertaken by the District this year when, in spite of the fact that no appropriation for a North Eastern District meeting was included in the national budget for 1933–34, the District decided to hold the Worcester meeting "on its own," with the coöperation and support of national headquarters, but without any expense to the Institute as a whole. The result reflects credit upon those who conceived the idea and upon those who carried it through to its successful conclusion.

Of course, the Institute's new unified publication plan contributed its part to the foundation underlying the success of the technical sessions. Except for a few special papers of particular local interest, the program committee was able to select most of the papers for discussion from among those that had been published in ELECTRICAL ENGINEERING in advance of the meeting and thus distributed to the entire membership of the Institute. This arrangement obviated the publication expense usually involved in a meeting, as well as providing an opportunity for broader discussion of the technical papers. A desirable simplicity in the entertainment and other special features of the meeting program, together with the coöperation of the various committees that handled the details, contributed toward reducing the meeting expense to a point where it constituted only a very nominal drain on the District's treasury (all Sections in the District contribute proportionately toward joint District activities).

Except for minor modifications the program for the 4 general sessions and for the student session was carried out as published previously in ELECTRICAL ENGINEERING. Louis S. Leavitt, local general chairman, presided at the opening session, which was made very brief in order to give maximum time to the first technical session that followed immediately. Chairman Leavitt and District Vice-President J. Allen Johnson both spoke briefly in welcome to those attending.

The usual general session convened the second morning featuring the addresses of Past-President Charles F. Scott, and Presidential Nominee J. Allen Johnson. Doctor Scott presented a brief and interesting résumé of the Institute's 50 years of history, outlining some of the material covered in his article in the May issue of ELECTRICAL ENGINEERING, and inspiring those present to continue the successful development of the Institute. J. Allen Johnson in his address spoke at some length on "An Insight Into the Workings of the A.I.E.E.," in which he described and explained many of the more important phases of the Institute's work and of its functioning as a national organization. He summed up his address by stating that the Institute's "Aims and activities are routed in a spirit of mutual helpfulness . . . and disinterested service to humanity . . . the principal obligation of membership . . . is to cultivate that spirit, the possession of which, after all is said and done, yields the most lasting satisfactions in the professional life." Mr. Johnson's address is scheduled for publication in an early issue of ELECTRICAL ENGINEERING; time and space available precluded its inclusion in this issue.

Chairmen presiding at the various technical sessions were: Wednesday morning, Prof. T. H. Morgan of Worcester Polytechnic Institute; Wednesday afternoon, I. E. Moultrop, Boston, past vice-president; Thursday morning, Louis F. Leavitt, chairman of the Worcester Section; Friday morning student session, Prof. L. W. Hitchcock, University of New Hampshire, Durham, N.H.; Friday afternoon, C. A. M. Weber, Westinghouse Elec. and Mfg. Company, Springfield, Mass. Sessions Wednesday and Thursday were held in the Ball Room of the Bancroft Hotel, Friday at Worcester Polytechnic Institute.

STUDENT SESSION

Upholding the North Eastern District's tradition, the Friday morning student session, held in a lecture hall at Worcester Polytechnic Institute, was one of the liveliest and best attended of all the sessions. The student papers presented included:

1. TELEVISION, Gordon K. Burns, Massachusetts Institute of Technology.

2. SOLVING THE CONDENSER MICROPHONE EQUATIONS, R. B. Gray, Cornell University.

3. STUDY OF PHASE SHIFT OF ISOCHRONOUS BROADCAST STATIONS, J. B. Campbell, Worcester Polytechnic Institute.

4. LIGHTNING EFFECTS, D. D. Terwilliger, Massachusetts Institute of Technology.

Cloth Bound Copies of 50th Anniversary Issue

Numerous inquiries have been received with reference to the possible availability of cloth bound copies of the special May 1934 issue of ELECTRICAL ENGINEERING, which commemorated the 50th anniversary of the founding of the Institute. On the strength of these inquiries, several hundred sets of forms have been printed and laid aside pending a determination of just how many may wish to procure cloth bound copies of that issue.

To the extent that bound copies are to be issued, it is contemplated that these volumes will include the entire content of the issue including the covers. The price is $2.50 per copy, postage paid; no discounts to be allowed.

Any persons wishing to reserve a copy of this contemplated issue of bound volumes, should so inform the Order Department at Institute headquarters as early as possible. It is important to note that the stock, available for bound volumes is definitely limited, and that all orders will be filled in the order of their receipt up to the limit of the available stock. An allotment has been set aside to protect foreign orders received at Institute headquarters by September 15, 1934.

5. Applications of the Thyratron in Industry, Amos Kent and G. H. Durfee, Rhode Island State College.

6. The Place of Operational Calculus in Undergraduate Study of Electrical Engineering, A. E. French, Clarkson College of Technology.

7. Interesting Effects of Series Transformers With Capacitance Burdens, E. D. Bassett and F. M. Potter, Worcester Polytechnic Institute.

Attentiveness of the audience and extent of the discussion following presentation indicated the keen interest in each of these papers. As before, the North Eastern District had offered prizes on the basis of the content and clarity of the presentation and the personality and ability of the author to handle his subject. The competition was keen and the judges were faced with some difficulty in announcing their decision:

First, Gordon K. Burns, Massachusetts Institute of Technology, $10.

Second, J. B. Campbell, Worcester Polytechnic Institute, $5.

Third, A. E. French, Clarkson College of Technology, $3.

Graduate prize, F. M. Potter and E. D. Bassett, Worcester Polytechnic Institute, $10.

A Warning Against Fraud

Attention of Institute headquarters has been called to the activities of an individual who has requested employment and financial assistance in different parts of the country, and has defrauded those who helped him. This man usually claims to be Ralph E. Adams, a graduate of either Massachusetts Institute of Technology or of Yale University in the class of 1904, and to have taken graduate work at Stanford University, Glasgow University, and in universities in Germany and Spain. He is a short, thick set, stocky man, height 5 ft. 8½ in., weight 182 lb., about 52 years of age. His hair is silver-grey; he is well dressed, neat in appearance, with well kept hands. He gives every evidence of acceptable social refinement, and is an entertaining talker.

He apparently has done work in the examination of oil leases, and has had some experience in physical and chemical investigations. He frequently claims that his clothes, possessions, money, and automobile have been stolen from him by riders to whom he has given a "lift," and that he is in need of a loan to cover living expenses for a few weeks until he has become oriented on a new position which has been offered him in another city.

Since this man may try the same game elsewhere, members should be on the watch for him. The police are now in search of this imposter, and warrants will be issued immediately upon locating him.

Attention should also be given the fact that during recent months a number of instances has come to light of persons claiming past or present Institute membership when applying for jobs or for assistance. To guard against possible misrepresentation, it is recommended that inquiries covering all items of this character be sent promptly to Institute headquarters to be checked.

Entertainment and Special Features

Several definitely organized inspection trips and other opportunities for individual or small-party inspections were provided by the local committee. The largest crowd, 100 or more, spent an afternoon in the South Works of the American Steel and Wire Company where they were shown the spring mill, the cable works, the open hearth furnaces, the rolling mills, the automatic electric welding machines used in the manufacture of rail bonds, and the wire drawing mill. Other parties visited local plants and stations of the Worcester Electric Light Company, and nearby substations of the New England Power Association. Other technical inspection trips included the plant of the Norton Company, manufacturers of abrasive and grinding machinery; the Heald Machine Company, manufacturers of precision tools and automatic machinery, and the Worcester Pressed Steel Company. The John W. Higgins Armory, at the plant of the latter company, with its library, laboratory, and collection of representative pressed steel products, ancient and modern and collected from all parts of the world, proved to be of great interest to all who saw it. The exhibits ranged all the way from utensils of the stone age and of the bronze age, including Greek and Roman armor, through the early iron age, the era of the Crusader's armor, and on to the modern steel age where one of the most striking exhibits was an aeroplane crankshaft and mountings in polished steel that emphasized the symmetry and simple beauty of thoughtful modern design.

Trips and activities arranged especially for the women guests included the Worcester Art Museum, a tea in the home of Mrs. Albert S. Richey, who headed the local women's committee, luncheon and bridge at the Worcester Country Club, an automobile trip to the summit of Mt. Wachusett, and an inspection and tea at the John W. Higgins Armory.

General activities included an informal entertainment held Wednesday evening, at which representatives of the General Electric Company presented a colorful exhibition of remote (vacuum tube) control and blending of stage and other color lighting effects, and representatives of the Westinghouse company presented a demonstration reflecting modern possibilities in control apparatus, by means of which it was possible to start, stop, and reverse an electric motor by means of voice impulses variously translated through sound- and light-sensitive devices. One of the principal features of the entertainment was the Worcester Polytechnic Institute's male quartet which responded to numerous encores.

With Thursday night open for various informal affairs, the District meeting was brought officially to a close by the traditional annual dinner meeting held Friday evening in the dining room of the Sanford Riley Dormitory at Worcester Polytechnic Institute. This gathering of more than 125 was presided over by Vice-President J. Allen Johnson and was addressed by Rear Admiral Ralph Earle, president of the Worcester Polytechnic Institute, and F. M. Feiker, executive secretary of the American Engineering Council, Washington, D. C. Rear Admiral Earle recalled his early days as a midshipman, before the day of the alternator, and mentioned briefly a few of his experiences as an early naval instructor in electrical subjects, and his World War service in the naval ordnance department where, he said, war demands contributed definitely to the ultimate perfection of the modern synchronous motor. Mr. Feiker outlined briefly the history of American Engineering Council, and emphasized its several important possibilities as the "Washington embassy of the engineering societies." National Secretary H. H. Henline responded briefly to the chairman's laudatory introduction. Prof. W. H. Timbie of Massachusetts Institute of Technology, the North Eastern District's vice-presidential nominee, spoke briefly of the Institute's long leadership in electrical matters, including education, and of the inspiration that can be derived by active and constructive participation in Institute affairs.

Future AIEE Meetings

Summer Convention,
Hot Springs, Va., June 25–29, 1934

Pacific Coast Convention,
Salt Lake City, Utah, Sept. 3–7, 1934

District Secretary-Treasurer A. C. Stevens presented the citations and prize awards for 1933 papers from the District:

1. Student Branch prize—Awarded jointly to H. L. Anderson and E. L. Angell for their paper "A Study of Mercury Switches."

2. District first-paper prize—to R. F. Edgar of Schenectady, N. Y., for his paper "Loss Characteristics of Silicon Steel."

3. District best-paper prize—Jointly to C. L. Dawes of Harvard University and P. H. Humphries, now of Tulane University, for their paper "The Electrical Characteristics of Impregnated Cable Papers."

4. Honorable mention—D. W. McLenegan of Schenectady, N. Y., for his paper "Energy Requirements of Various Types of Air Conditioning Apparatus."

5. Honorable mention—J. Allen Johnson, Buffalo, N. Y., for his paper "Operating Aspects of Reactive Power."

All of these papers were presented at the North Eastern District ninth annual meeting held at Schenectady, N. Y., May 10–12, 1933.

A special feature following the annual dinner Friday evening was an illustrated semi-popular lecture delivered most effectively by Dr. Robert J. Van De Graaff of Massachusetts Institute of Technology on the subject "High Voltage and Its Application to Atomic Disintegration." In his lecture Doctor Van De Graaff explained the essential features of the modern understanding of atomic structure and mentioned briefly the efforts currently being made to

carry researches in this subject further by means of the tremendously high impulse voltages now possible in the laboratory through the "static" type of generator originally devised by Doctor Van De Graaff. The speaker then described the principal features of this special device which in its original form was a classroom model capable of developing several thousand volts, and which now is being built on such a scale that it requires an airship hangar to accommodate it, and is capable of developing several million volts.

REGISTRATION

Attendance at all sessions was good. Analysis of final registration data showed:

Worcester Enrolled Students	63
Out-of-town Enrolled Students	79
Worcester Members and Guests	46
Out-of-town Members and Guests	130
Women Guests	19
Total	337

Registration personnel and facilities were provided through the coöperation of the publicity and convention bureau of the Worcester Chamber of Commerce.

Chemists' Medal to Be Presented Doctor Conant. The medal of The American Institute of Chemists, presented annually for outstanding service to chemistry in America, has been awarded this year to Dr. James Bryant Conant, president of Harvard University, in recognition of his many contributions to chemical science. Doctor Conant has done notable work in establishing the chemical structure of many complicated organic compounds, including, among others, haemoglobin of the blood substance, chlorophyll—the green coloring matter found in plant life, and a number of other coloring substances occurring in flowers and feathers. He has greatly extended the usefulness of electrometric methods, applying them to new problems, and has made many other fundamental researches. He has written 3 textbooks and many papers on subjects in organic chemistry. Doctor Conant became 25th president of Harvard University in May 1933, when he had just passed his 40th birthday. The presentation of the medal was made at the annual meeting of The American Institute of Chemists in New York, May 21, 1934.

A Few of Virginia's Many Natural Attractions Near Hot Springs

THOSE attending the Institute's fiftieth annual summer convention at Hot Springs by motor will have an excellent opportunity to see some of the underground caverns and other natural wonders for which the state of Virginia is noted. Above at the right is a view of the famous Natural Bridge a few miles southeast of Hot Springs. Hewn out of solid limestone by the waters of past ages this great natural arch stands more than 200 ft high and has a 90-ft span. Lee Highway (U.S. No. 11) passes over the top. At the right is a view of the "natural chimneys" near Mt. Solon, a few miles northeast of Hot Springs. Here 7 massive columns, 2 of which stand more than 100 ft high, have been eroded from the limestone cliff. Above is a typical view from the scenic highway (U.S. No. 60) along the James River between Lynchburg and Natural Bridge.

Institute Prize Awards Announced for 1933 Papers

FOUR national prizes for papers presented during the calendar year 1933 have been announced by the committee on award of Institute prizes, which consists of R. N. Conwell (A'15, F'31) *chairman*, F. M. Farmer (A'02, F'13), W. H. Harrison (A'20, F'31) and E. B. Meyer (A'05, F'27). These prizes in each case consist of a suitable certificate. Personal presentation of the prizes will take place at the opening session of the Institute's summer convention at Hot Springs, Va., June 25–29, 1934.

District prizes as announced by 3 Districts to date include 2 awards of $25 each, together with appropriate certificates. Where there is a joint authorship the cash awards are divided.

National Prizes

Best Papers

Prize for best paper in engineering practice was awarded to F. H. Gulliksen (A'29) for his paper "The Principle of Condenser Discharge Applied to Central Station Control Problems," presented at the winter Convention, New York, N. Y., January 23–27, 1933.

Honorable mention was made of the following paper: "Operating Aspects of Reactive Power" by J. Allen Johnson (A'07, F'27), presented at the North Eastern District meeting, Schenectady, N. Y., May 10–12, 1933.

Prize for best paper in theory and research awarded to Joseph Slepian (A'17, F'27) and L. R. Ludwig (A'28) for their paper "A New Method for Initiating the Cathode of an Arc," presented at the winter convention, New York, N. Y., January 23–27, 1933.

Honorable mention was made of the following papers: "Applications of Harmonic Commutation for Thyratron Inverters and Rectifiers" by C. H. Willis (A'22, M'28), presented at the winter convention, New York, N. Y., January 23–27, 1933; and "Carrier in Cable" by A. B. Clark (M'19, F'30) and B. W. Kendall (M'18, F'29), presented at the summer convention, Chicago, Ill., June 26–30, 1933.

No prize was awarded in the field of public relations and education.

Initial Paper

Prize for initial paper was awarded to K. S. Wyatt (A'32), E. W. Spring (A'26, M'32), and C. H. Fellows for their paper "A New Method of Investigating Cable Deterioration and Its Application to Service Aged Cable," presented at the summer convention, Chicago, Ill., June 26–30, 1933.

Honorable mention was made of the following paper: "Compensating Metering in Theory and Practice" by George B. Schleicher (A'20), presented at the summer convention, Chicago, Ill., June 26–30, 1933.

Branch Paper

Prize for branch paper awarded to Tom B. Wagner for his paper "A Universal Measuring Instrument for Communication Circuits," presented at a joint meeting of the Portland Section and Oregon State College Branch, May 20, 1933.

Honorable mention was made of the following paper: "The Measurement and Control of the Synchronous Machine Torque Angle" by A. E. Logan and S. W. Hannah, presented at a joint meeting of the Denver Section and University of Colorado Branch, April 28, 1933.

District Prizes

District No. 1

Prize for best paper awarded jointly to C. L. Dawes (A'12, M'15) and P. H. Humphries (A'26) for their paper "The Electrical Characteristics of Impregnated Cable Papers," presented at the North Eastern District meeting, Schenectady, N. Y., May 10–12, 1933.

Prize for initial paper awarded to R. F. Edgar for his paper "Loss Characteristics of Silicon Steel at 60 Cycles with D-C Excitation," presented at the North Eastern District meeting, Schenectady, N. Y., May 10–12, 1933.

Prize for branch paper awarded jointly to H. L. Anderson and E. L. Angell for their paper "A Study of Mercury Switches," presented at the North Eastern District Meeting, Schenectady, N. Y., May 10–12, 1933.

District No. 7

Prize for branch paper awarded to C. Forest Himes for his paper "Aviation Radio," presented at a meeting of the Oklahoma Arricultural and Mechanical College Branch on April 10, 1933.

District No. 10

Prize for best paper awarded to W. J. Moulton-Redwood (A'20) for his paper "Valuation and Depreciation," presented at a meeting of the Toronto Section, October 27, 1933.

Prize for initial paper awarded to George Morrison (A'19) for his paper "Electrically Operated Mine Hoists," presented at a meeting of the Toronto Section, October 13, 1933.

Names Requested for Washington Award

The commission of the Washington Award requests that members of the 4 national societies of civil, mechanical, mining and metallurgical, and electrical engineers suggest the names to this commission of persons to be put on the list of those eligible to receive the Washington Award.

The commission of the Washington Award was established in 1917 by Past-President Alvord of the Western Society of Engineers "to be presented annually to an engineer whose work in some special instance, or whose services in general, have been noteworthy for their merit in promoting the public good." The award is made annually by a committee composed of 9 representatives of the Western Society of Engineers and 2 each from the A.S.C.E., A.I.M.E., A.S.M.E., and the A.I.E.E.

Suggestions should be made directly to Edgar S. Nethercut, director of the Western Society of Engineers, Chicago, Ill.

Triennial Montefiore Prize Award Now Open

Constituting interest on 150,000 Belgian francs, distributed triennially in international competition for the best original work presented on scientific advancement and progress in technical application of electricity in every field, the Montefiore prize award now is open again to candidates.

To be eligible an achievement must have been made public at some time during the three years immediately preceding the period of award. Papers either signed or anonymous are acceptable in manuscript or reprint form; they must, however, have been edited in either French or English; also, all manuscripts must be typewritten.

By a $^4/_5$ vote of the board of examiners composed of 5 Belgian and 5 other electrical engineers, $^1/_3$ of the amount available may be designated as an unsecured loan to a person whose work does not fall completely within the ritual of the governing program but which demonstrates a new thought in connection with development of importance in the sphere of electricity.

A.S.M.E. to Hold Semi-Annual Meeting in June. The semi-annual meeting of The American Society of Mechanical Engineers will be held in Denver, Colo., June 25–28, 1934, with headquarters at the Cosmopolitan Hotel. Among the subjects which will be discussed are smoke problems, heat engineering, air conditioning, and recent developments in railroad trains. A series of lectures with motion pictures will be presented to give a very complete story of the remarkable work of Boulder Dam. An informal round-table discussion has been arranged by the management division on the subject of the decentralization of industry, with particular reference to its effect in the West. The N.R.A. also will come in for discussion. A semi-formal banquet is to be held on Tuesday evening, and a number of interesting inspection trips have been arranged.

A.S.T.M. To Hold Annual Meeting in June. The 37th annual meeting of the American Society for Testing Materials will be held at Atlantic City, N. J., June 25–29, 1934. At this meeting, some 46 reports on metals, cement and concrete, ceramics, masonry materials, standards, nomenclature and definitions, and miscellaneous subjects will be presented. Also, 46 technical papers are scheduled for presentation at this meeting. The annual address will be given by the president, T. R. Lawson, and the ninth Edgar Marburg lecture will be given by Sheppard T. Powell, consulting sanitary and chemical engineer of Baltimore. His subject will be "Water as an Engineering and Industrial Material."

American Physical Society Meetings. The 192nd regular meeting of the American Physical Society will be held in Berkeley, Calif., June 18–23, 1934, as a joint meeting with Section *B* of the American Association for the Advancement of Science. Tentative plans for the program consist of symposiums for Wednesday and Thursday, one dealing with nuclear physics and the other with the values of important physical constants. The sessions on Friday and Saturday are to be devoted to the usual program of 10-min contributed papers. Prof. R. W. Wood of The Johns Hopkins University, and vice-president of the Society, will deliver an address dealing with his device for using the grating in measuring the velocity of stars. The 193rd regular meeting of the American Physical Society will be held in Ann Arbor, Mich., June 29 and 30, 1934. The Society will be the guests of the Uni-

versity of Michigan. Tentative plans for the program consist of a special address by Prof. George Gamow of the Polytechnical Institute, Leningrad, Russia; a symposium on hyperfine structure, one-half day for the reading of 10-min contributed papers; an excursion to the Ford plant and to Ford's museum at Dearborn; and a picnic supper at a nearby lake.

Guggenheim Medal Awarded to Boeing. For "successful pioneering and achievement in aircraft manufacture and air transportation" the Daniel Guggenheim Medal was awarded to William E. Boeing of Seattle, Wash., chairman of the board of the United Aircraft and Transport Corporation, on May 3, 1934. Mr. Boeing is widely known for his development of airplanes for both commercial and military purposes. One of his first efforts was the construction of a flying boat which carried the first air mail transported on the American continent by a private contractor, and when the war emergency found the government in need of planes, the Boeing plant was ready to get into production promptly. Under Mr. Boeing's direction, his company has pioneered in many phases of aircraft development. The Guggenheim award is made annually, this year the award having been made by a board consisting of 8 members in the United States and 7 abroad.

Pioneer in Electrical Development Dies. George Huntington Barker, organizer of the West Side Lighting Company, which later developed into the Southern California Edison Company, died at Santa Monica, Calif., April 29, 1934. He was born in Brookfield, N. Y., and had been a state senator from Gloucester County, N. J., before moving to California in 1893. Mr. Barker was 77 years old.

Section and Branch Activities Summarized in Annual Report for 1933–34

FOLLOWING the plan established in 1933, of publishing the annual report on Section and Branch activities in ELECTRICAL ENGINEERING instead of in pamphlet form, the report for the fiscal year which ended April 30, 1934, is presented here. Similar information for the fiscal year which ended April 30, 1932, was published in ELECTRICAL ENGINEERING for October 1932, pages 738–40, and for the fiscal year ending April 30, 1933, in ELECTRICAL ENGINEERING for June 1933, pages 726–8.

The accompanying comprehensive summary constitutes a report upon the large and important division of Institute activities coming under the supervision of the Sections committee and the committee on Student Branches, the 2 committees being composed of the following personnel: Sections—I. M. Stein, *chairman*, L. A. Doggett, W. B. Kouwenhoven, Everett S. Lee, G. H. Quermann, J. J. Shoemaker, W. H. Timbie, and, *ex-officio*, the chairman of all Sections of the Institute. Student Branches L. A. Doggett, *chairman*, R. B. Bonney, F. O. McMillan, Charles F. Scott, W. H. Timbie, and, *ex-officio*, all Student Branch counselors.

SECTION ACTIVITIES

During the fiscal year which ended April 30, 1933, every Section of the Institute reported one or more meetings, and in virtually all cases the amount of activity was normal. The total number of meetings for the year was only slightly below that for the preceding year. All of the special features developed in recent years and found to be effective were retained.

President Whitehead visited many of the Sections during the fiscal year and visited several others in May. On account of the postponement of the Pacific Coast convention from 1933 to 1934, he visited all of the Sections which coöperated in the preparations for and the conduct of that convention.

Special efforts were made by the Section membership committees in coöperation with the national membership committee to induce individuals who had been forced during recent years to relinquish their membership to apply for reinstatement and excellent results have been reported by the national membership committee.

The New Orleans Section was organized in January with the entire state of Louisiana as its territory, and its members have taken up the Section activities with enthusiasm. This brought the total number of Sections to 61.

Many of the Sections enthusiastically accepted the suggestion of the fiftieth anniversary committee that each Section and each Branch hold a meeting during May 1934 for observing the fiftieth Anniversary of the organization of the Institute and made extensive plans for such meetings.

Detailed information on Section meetings during the past year is given in Table I, and Table II contains a brief summary of these meetings for the last 3 fiscal years.

BRANCH ACTIVITIES

Nearly all of the Branches carried on a normal amount of activity during the past fiscal year which was completed with a total number of meetings practically equal to that for the preceding year. The strong emphasis upon the importance of having talks by Students which has been pronounced during the past several years was retained with the result that the total number of talks by Students for the year which ended April 30, 1934, was slightly larger than that for the preceding year.

The counselor delegates attending the summer convention held in Chicago in June 1933, discussed a report presented by a subcommittee of the committee on Student Branches, and recommended that provisions be adopted for enrollment in the Institute of evening students in electrical engi-

Table I—Section Meetings Held During Year Ending April 30, 1934

Section	A.I.E.E. Members Aug. 1932	A.I.E.E. Members Aug. 1933	Meetings During Year Number	Meetings During Year Avg Attendance	Avg Attendance as Per Cent of Membership Aug 1933
Akron	84	63	7	60	95
Atlanta	86	65	1	25	38
Baltimore	197	157	8	121	77
Birmingham	30	19	3	848	446
Boston	456	377	8	133	35
Chicago	850	633	7	166	26
Power Group			3	79	
Cincinnati	162	146	10	201	138
Cleveland	257	193	8	242	125
Columbus	73	55	7	73	133
Connecticut	254	238	7	198	83
Dallas	103	78	9	93	119
Denver	134	130	9	112	86
Detroit-Ann Arbor	268	226	10	170	75
Erie	65	51	4	457	895
Florida	48	41	2	323	788
Fort Wayne	71	53	9	66	125
Houston	56	53	7	85	160
Indianapolis-Laf.	85	73	5	130	178
Iowa	58	55	5	38	69
Ithaca	42	41	2	43	105
Kansas City	165	138	9	101	73
Lehigh Valley	248	176	10	172	98
Los Angeles	413	349	9	140	40
Louisville	53	48	9	88	183
Lynn	122	104	13	554	533
Madison	60	59	6	52	88
Memphis	40	30	9	55	183
Mexico	74	51	9	50	82
Milwaukee	218	161	15	112	70
Minnesota	99	79	8	41	52
Montana	34	31	8	69	222
Nebraska	57	45	2	50	111
New Orleans*		32	2	31	97
New York	3,394	2,798	4	550	20
Communication Group			3	548	
Illumination Group			3	167	
Power Group			4	338	
Transportation Group			3	300	
Niagara Frontier	162	142	9	74	52
North Carolina	80	68	1	1,277	1,880
Oklahoma City	77	77	8	113	147
Philadelphia	678	529	7	165	31
Pittsburgh	572	409	7	134	33
Pittsfield	117	90	10	734	815
Portland	88	81	8	72	89
Providence	80	73	8	57	78
Rochester	87	64	10	111	173
St. Louis	227	195	7	182	93
San Antonio	54	40	8	36	90
San Francisco	435	379	8	130	34
Saskatchewan	36	31	7	20	65
Schenectady	424	335	11	192	57
Seattle	181	133	10	62	47
Sharon	75	50	9	119	238
Southern Virginia	79	72	3	116	161
Spokane	39	33	8	29	88
Springfield, Mass.	96	72	9	103	143
Syracuse	72	62	2	390	628
Toledo	83	61	11	109	179
Toronto	372	302	16	121	40
Urbana	38	34	4	101	297
Utah	53	44	9	42	95
Vancouver	85	77	9	50	65
Washington	181	155	8	122	79
Worcester	65	65	8	266	409
Total	61	12,892		10,531	

Total number of meetings 472
Total attendance 73,271

*Authorized by executive committee: December 8, 1933.

neering in institutions offering evening courses which are considered by the committee on Student Branches to meet the requirements outlined in the by-laws. They also recommended the adoption of provisions for the organization of such evening students for activities in connection with the corresponding Student Branches, each such case being subject to the approval of the committee on Student Branches.

These recommendations were approved in principle by the conference of officers, delegates, and members, and by the board of directors, with the understanding that further details would be developed by the appropriate committees. Later the by-laws were amended to include these provisions, and the committee on Student Branches has approved the enrolmentt of evening students of the following institutions: Polytechnic Institute of Brooklyn, University of Cincinnati, Cooper Union, George Washington University, College of the City of New York, and New York University.

The board of directors restored to the budget provisions for the allowance for traveling expenses for annual District conferences on Student activities in all Districts having committees on Student activities.

Of the 919 enrolled students whose terms expired April 30, 1934, nearly 50 per cent applied for admission as Associates.

New Branches were organized during the year at the South Dakota State College, Brookings, So. Dakota; and Villanova College, Villanova, Pa., bringing the total number of Branches to 113.

As reported above, the fiftieth anniversary Committee suggested that each Section and each Branch hold a meeting during the month of May, 1934, for observing the fiftieth anniversary of the organization of the Institute. Many of the Branches have planned to carry out this suggestion.

Much information on Branch activities during the past fiscal year is given in Tables III to VII.

Section and Branch Joint Meetings

As in past years an important feature of both Section and Branch activities was the coöperation between the 2 types of groups

Table II—Section Meetings Held During Last 3 Fiscal Years

	Fiscal Year Ending April 30		
	1932	1933	1934
Number of Sections	60	60	61
Number of meetings held	497	498	472
Average number of meetings	8.3	8.3	7.7
Total attendance	105,325	73,806	73,271
Average attendance per meeting	212	148	156

Table III—Branch Meetings Held During Year Ending April 30, 1934

Branch	Meetings During Year: Number	Meetings During Year: Avg Attendance	Approx. No. of Talks by Students
Akron, University of			
Alabama Polytechnic Institute	3	27	
Alabama, University of	10	58	9
Arizona, University of	22	11	22
Arkansas, University of	15	29	43
Armour Institute of Technology	10	42	1
British Columbia, Univ. of	11	15	15
Brooklyn, Polytechnic Inst. of	5	42	6
Bucknell University	6	33	4
California, Institute of Tech	10	67	6
California, University of	17	43	1
Carnegie Institute of Tech	5	63	9
Case School of Applied Science	17	58	28
Catholic University of America	4	20	4
Cincinnati, University of	7	60	
Clarkson College of Tech	1	34	
Clemson Agricultural College	8	34	13
Colorado State Agri. College	12	13	5
Colorado, University of	11	50	4
Cooper Union	9	37	8
Cornell University	3	47	
Denver, University of	10	30	2
Detroit, University of	6	33	
Drexel Institute	9	17	7
Duke University	9	18	17
Florida, University of	14	66	5
George Washington University	2	14	1
Georgia School of Tech	3	38	
Harvard University	3	32	2
Idaho, University of	7	34	5
Illinois, University of	8	64	
Iowa State College	8	97	1
Iowa, University of	24	38	30
Kansas State College	13	66	3
Kansas, University of	10	66	
Kentucky, University of	5	77	
Lafayette College			
Lehigh University	7	55	6
Lewis Institute	5	93	
Louisiana State University	4	23	3
Louisville, University of	11	24	12
Maine, University of	4	28	
Marquette University	6	52	
Massachusetts Inst. of Tech	6	73	
Michigan Col. of Min. & Tech	9	38	2
Michigan State College	10	18	5
Michigan, University of	7	54	
Milwaukee School of Engg	8	52	
Minnesota, University of	9	91	5
Mississippi State College	6	21	6
Missouri School of Mines & Met	3	41	2
Missouri, University of	10	30	8
Montana State College	30	59	86
Nebraska, University of	13	43	4
Nevada, University of	5	41	
Newark College of Engineering	8	26	12
New Hampshire, University of	23	36	39
New Mexico, University of	7	23	2
New York, Col. of the City of	12	26	7
New York University	11	22	43
North Carolina State College	14	68	18
North Carolina, University of	5	30	6
North Dakota State College	10	24	9
North Dakota, University of	15	18	19
Northeastern University	6	30	2
Notre Dame, University of	14	106	21
Ohio Northern University	10	17	8
Ohio State University	11	40	3
Ohio University	3	20	
Oklahoma A. & M. College	14	48	11
Oklahoma, University of	7	36	4
Oregon State College	8	55	2
Pennsylvania State College	10	61	17
Pennsylvania, University of	7	17	1
Pittsburgh, University of	26	77	24
Porto Rico, University of	7	39	2
Pratt Institute	19	41	26
Princeton University	3	58	
Purdue University	9	148	
Rensselaer Polytechnic Inst	5	191	5
Rhode Island State College	12	25	12
Rice Institute	9	47	3
Rose Polytechnic Institute	1	25	
Rutgers University	9	13	9
Santa Clara, University of	3	32	
So. Carolina, University of	13	34	13
South Dakota State College*	6	22	3
So. Dakota State School of Mines	6	44	8
South Dakota, University of	3	8	
Southern California, Univ. of	12	28	3
Southern Methodist University	4	19	
Stanford University	16	30	6
Stevens Institute of Tech			
Swarthmore College	1	3	
Syracuse University	22	15	34
Tennessee, University of	8	19	6
Texas A. & M. College	2	60	
Texas Technological College	11	21	7
Texas, University of	5	25	
Utah, University of	14	30	3
Vermont, University of	17	19	11
Villanova College†	4	24	4
Virginia Military Institute	5	20	
Virginia Polytechnic Institute	27	35	73
Virginia, University of	8	20	5
Washington, State College of	10	41	3
Washington, University of	12	39	7
Washington University	8	24	3
West Virginia University	18	33	121
Wisconsin, University of	3	39	
Worcester Polytechnic Inst	4	54	4
Wyoming, University of	8	22	
Yale University			
Total	113		1.004

Total number of meetings 1,015
Total attendance 41,772

Authorized by board of directors:
* May 22, 1933
† October 20, 1933

Table IV—Branch Meetings Held During Last 3 Fiscal Years

	Fiscal Year Ending April 30		
	1932	1933	1934
Number of Branches	109	111	113
Number of meetings held	1,135	1,026	1,015
Average number of meetings	10.4	9.3	9.0
Total attendance	54,197	59,439	41,772
Average attendance per meeting	48	58	41
Number of student talks	1,066	982	1,004

Table V—Comparison of Branch Activities by Districts

District	No. of Branches Jan. 1	Avg No. Meetings per Branch	Avg Attendance per Meeting	Approx. Avg No. Student Talks per Branch	No. Branches Reporting 9 or More Student Talks
1	13	8.2	45	8.4	4
2	20	7.5	34	11.9	6
3	9	8.9	27	12.0	4
4	17	9.0	36	10.9	7
5	16	8.6	62	4.1	2
6	10	9.4	27	5.4	3
7	14	8.4	38	6.1	3
8	7	12.2	36	5.4	1
9	6	13.5	43	17.7	1
10	1	11.0	15	15.0	1

Table VI—Conferences on Student Activities

District	Location	Date
1	Schenectady, N. Y. (North Eastern District Mtg.)	5/12/33
4	Raleigh, No. Carolina (No. Carolina State College)	1/12/34
6	Rapid City, So. Dakota (So. Dakota State School of Mines)	4/13/34

which is especially effective in giving the students knowledge of the types of work which they will do later, and also develops many helpful exchanges of experiences between the 2 groups. Some of the outstanding examples of such coöperation during the past year are listed in Table VIII.

Table VII—Student Conventions

Sponsored by District	Location	Date	No. of Student Papers
1	Schenectady, N. Y. (No. Eastern District Mtg.)	5/12/33	13
Mass. Inst. of Tech.	Cambridge, Mass.	12/9/33	3
4	No. Carolina State Col.	1/12/34	6
6	So. Dakota State School of Mines	4/13/34	6
New York Section	New York	4/18/34	4
Princeton University	Princeton, N. J.	4/30/34	7

Table VIII—Section or Joint Section and Branch Meetings With Active Student Participation

Sections	Schools	Date	Student Talks	Attendance
Cincinnati	Univ. of Cincinnati	5/11/33	8	70
Oklahoma City	Univ. of Oklahoma			
	Oklahoma A. & M. College	5/19/33	6	100
Portland	Oregon State College	5/20/33	2	57
Utah	Univ. of Utah	5/22/33	2	45
Pittsburgh	Carnegie Inst. of Tech.			
	Univ. of Pittsburgh			
	West Virginia Univ.	1/ 9/34	6	112
No. Carolina	No. Carolina State College	1/12/34	6	194
Vancouver	Univ. of British Columbia	3/ 5/34	4	52
Minnesota	Univ. of Minnesota	3/ 7/34	4	
Houston	Rice Institute			
	A. & M. College of Texas	3/24/34	2	72
Seattle	Univ. of Washington	4/17/34	3	70
Los Angeles	Calif. Inst. of Tech.			
	Univ. of Southern Calif.	4/17/34	6	127
Louisville	Univ. of Louisville	4/29/34	3	67
Denver	Univ. of Colorado			
	Univ. of Denver	4/20/34	2	58
San Francisco	Univ. of Calif.			
	Univ. of Santa Clara			
	Stanford Univ.	4/27/34	3	135
Spokane	Univ. of Idaho			
	Washington State College	4/27/34	2	70

American Engineering Council

Legislation and Administrative Policy Affecting Engineers

THE IMPORTANCE to engineers of events taking place in Washington, and the part which American Engineering Council takes in guiding legislation in logical channels, are indicated by the following excerpts from the report of American Engineering Council dated April 18, 1934. Although the status of some of the bills has changed since this report was issued, it reflects the activity of Council in Washington. The report follows:

Three Public Works Bills

Three public works bills have been introduced this month (April). The La-Follette and Brunner bills (S. 3348 and H.R. 9151) provide 10 and 12 billion, respectively, for the purpose of carrying forward the program of public works inaugurated under the provisions of the National Industrial Recovery Act. The Ellenbogen bill, H.R. 8979, provides an additional appropriation of 2 billion for the construction of public works projects and $400,000,000 for Federal grants to the several States for construction and extension of highways. Col. Frank M. Gunby (A'10, M'14) chairman of Council's committee on administration of public works has these bills under consideration.

It is probable that the Administration bill, not yet introduced, will coördinate some of the items named in the above bills for a total additional appropriation of approximately 2 billions of dollars.

Regulation of Communications

Of the 3 bills introduced in recent weeks seeking the establishment of a commission on communications, 2 are now being actively considered in Congress. The Dill bill, S. 3285 is pending before the Senate Committee on Interstate Commerce and will probably be reported on Friday or Saturday of this week. Additional hearings are to be held on the Rayburn bill, H.R. 8301, by the House Committee on Interstate and Foreign Commerce.

Council's committee on communications is making a thorough study of both the Dill and the Rayburn bills.

Engineers' Relation to the Securities Act

Three bills have been introduced looking to the modification of the Securities Act of 1933. They are S. 3125 and H.R. 8836, identical bills, introduced by Senator Thomas of Utah and Representative Scrugham of Nevada, and S. 3301, introduced by Senator Hastings.

A small committee of 3 has been appointed in the House of Representatives to study modification of the Securities Act with the idea of recommending remedial legislation. The committee is composed of the Honorable Abe Murdock of Utah, chairman, Honorable Harry L. Englebright of California, and Honorable Compton I. White of Idaho.

Council is coöperating with the American Institute of Consulting Engineers in an effort to have the severity of the penalties demanded in the civil liabilities clause materially reduced.

Restoration of Research Funds for Irrigation

When the bill making appropriations for the Department of Agriculture for fiscal year ending June 30, 1935, was first drafted, the Bureau of the Budget eliminated an appropriation of $87,933, for farm irrigation investigations. The elimination of this item meant the practical discontinuance of the division of irrigation in the bureau of agricultural engineering.

Council, upon the request of several sections of the American Society of Civil Engineers, wrote to the committee on appropriations of the House, asking the restoration of this appropriation to the bill.

When the bill became law a few days ago, it contained an appropriation of $350,318.00 for the bureau of agricultural engineering; $87,933, although not so earmarked, is for the continuance of the farm irrigation research work.

Uniform Administration of Public Lands

Council has supported over a period of years the principles contained in H.R. 6462, the Taylor bill, which seeks to prevent injury to the public grazing lands by preventing over grazing and soil deterioration, providing for their orderly use, improvement and development, and the stabilization of the livestock industry, which is dependent upon the public range.

This legislation has passed the House of Representatives and is now pending before the Senate committee on public lands. Senator Wagner plans to hold hearings before reporting the bill to the Senate.

"Following the Flags" at Washington

THE NEED and opportunity for a voice for organized engineers and engineering in the nation's capitol, is visualized in the accompanying reproduction of a retouched airplane photograph. The original appeared in the *United States News* and is reproduced with its permission. The location of the office of American Engineering Council, the "Washington Embassy" of American engineers and engineering, has been added to the original photograph with the idea of giving to engineers unacquainted with the city of Washington, not only a picture of the number and variety of the present government agencies, but to emphasize that through membership in their local and national societies, which Council represents, they have a representative in these many activities. That engineers individually as well as collectively are playing a part in the present program, is indicated by the fact that in Washington alone there are about 2,900 engineer-trained men in the administrative bureaus and agencies, about 1,000 of whom are newly resident.

WASHINGTON
AEC
EMBASSY
PSAC
ABC
CCC
DLB
FACA
FHC
CWA
ICC
BIR
BPR
SEC
USES
WHC
BIR
BPR
BIR
EHC
FAC
FCC
NRC
TEC
NEC
WHC
BIS
FRC
FDIC
FAC
FDIC
CWA
FRC
EHC
GAO
FPC
BHS
CSB
CBC
FRC
LAB
HOLC
FHLB
FCSB
AAA
BIR
MRA
BIR
FRC
BIR
FAC
BIR
FRC
BIR
EHC
FPC
BPR
BIR
BIR
BI

FIVE BILLS ON FLOOD CONTROL

Of the 30 or 40 bills which have been introduced during the 73rd Congress and referred to House committee on flood control, only 5 appear to be active. They are now under consideration by L. L. Hidinger, chairman of Council's committee on flood control.

Two of the bills, H.R. 5692 and H.R. 5910, introduced by Representative Wilson, chairman of the House committee on flood control, seek to amend the Flood Control Act of 1928; one, H.R. 6368, introduced by Mr. Marland, provides for the control of the flood waters of the Arkansas River. Of the 2 introduced by Mr. Disney, H.R. 7339 provides for flood control, irrigation, navigation, production of electric power, regulation of soil erosion, etc., in the areas drained by the Arkansas, Red and White Rivers; and H.R. 7548 provides for the control of flood waters in the State of Oklahoma in the watershed of the Arkansas and Red Rivers.

Council seeks, with the aid of its member-organizations, to protect the engineering soundness of flood control legislation enacted.

FINANCING PRIVATE DEVELOPMENT UNDER R.F.C.

There have been considerably over a hundred bills introduced in the House of Representatives alone, proposing amendments to and extensions of the authority of the Reconstruction Finance Corporation. Many of these bills seek to give aid to private industry. The committee on banking and currency has given considerable study to these bills but because of the pressure of other legislation pending before the committee has been unable to determine what action to take concerning them.

Council is watching the legislation closely in order to be ready to take action should any bills be reported of particular interest to engineering and to engineers.

Salaries for Engineers

Engineers quite properly have thought of their income as based upon professional qualifications and not on hourly or weekly rates. Because of the demand for some standard of pay for different classes of work brought about by widely published discrepancies between wages paid for skilled and unskilled labor, and compensation for knowledge and supervising ability, effort has constantly been made by American Engineering Council to provide information to government agencies, particularly C.W.A and P.W.A., as to proper compensation for engineers. A special report on salaries was compiled by the American Society of Civil Engineers at the request of the C.W.A. and this has had a far-reaching and salutary effect in providing a basis for local determination of salaries and lifting the consideration of engineering salaries out of the class of hourly rates into the class of compensation for technical services and supervision. Council has distributed this report, on request, to several of the government agencies and also recommended the American Society of Mechanical Engineers' report on the "Economic Status of Engineers," to many in the government.

Mapping and Surveying the United States

To put the former C.W.A. project, supervised by the Coast and Geodetic Survey, on a sound national basis for continuation, the executive secretary of American Engineering Council, acting under earlier policies established by the Council, prepared with the coöperation of the United States Geological Survey and Coast and Geodetic Survey a memorandum, outlining the needs, proposing a plan and recommending an appropriation of $20,000,000 to provide in 2 years what would normally take 10 to accomplish—a basic map of the United States. The proposal has been agressively pushed and at present has the support of high government officials, of local, state and national organizations and of many members of Congress. It is hoped that the funds will be provided from the Public Works' Administration Bill for additional funds for the national recovery program. Not the least value in this project is that it will provide employment for between 8 and 10 thousand men during the next 2 years on a constructive need, which underlies both public and private development.

Letters to the Editor

Slide Rule Calculation of Unbalanced 3-Phase Currents

To the Editor:

The author wishes to withdraw the solution for a-c circuits presented on p. 365 of the February 1934 issue of ELECTRICAL ENGINEERING, since it has been found upon subsequent investigation, that eq 4 is not applicable as a general solution for unbalanced a-c circuits.

Very truly yours,

E. F. SEAMAN
(Assistant Electrical Engineer, Bureau of Engineering, Navy Dept., Washington, D. C.)

Appreciation of the "Science Series"

To the Editor:

We have been appreciative readers of the "Science Series for Engineers," being published in current issues of ELECTRICAL ENGINEERING, and feel that articles of this nature are of considerable value in enabling practising electrical engineers to keep in touch with the advances of contemporary science.

We would suggest that consideration be given to the possibility of continuing this series indefinitely, rather than terminating it in January 1935, as mentioned in the February 1934 issue of ELECTRICAL ENGINEERING.

Very truly yours,

C. L. ROACH (A'24, M'30)
H. G. PALMER (A'30)
D. RHODES (A'30)
(Div. Toll and Trmn. Engr., Engg. Asst., and Div. Trmn. Engr., respectively, of The Bell Telephone Co. of Canada, Montreal, Quebec)

Building the Most Powerful Single-Shaft Generator

BUILDING the stator frame for the world's most powerful single-shaft generating set in the East Pittsburgh, Pa., shops of the Westinghouse Electric and Manufacturing Company. Being built for the Richmond Generating plant of the Philadelphia Electric Company on the Delaware river at Philadelphia, the set will consist of a 183,333-kva 13,800-volt 3-phase 60-cycle 90-per cent power-factor generator driven by an 1,800-rpm turbine. Fabricated of welded steel plate and cast iron end bells it will weigh 215 tons with punchings, the frame alone weighing 65 tons. Because of its size, it will be shipped in 3 sections and the laminations will be stacked at the Richmond station.

Personal Items

J. B. Whitehead (A'00, F'12, and president) dean of the engineering school of the Johns Hopkins University, Baltimore, Maryland, has been awarded a medallion by the Advertising Club of that city for the work he performed last year in dielectric and capable research, considering it the year's most important contribution to the advancement of science made by a citizen of Baltimore.

C. E. Skinner (A'99, F'12, and junior past-president) formerly assistant director of engineering for the Westinghouse Electric and Manufacturing Company at East Pittsburgh, Pa., and now retired, has been elected a vice-president of the American Association for the Advancement of Science and has been chosen chairman of its engineering section.

R. H. Barclay (A'14, F'28) has been made senior electrical engineer of the national power survey, which is a recently created branch of the Federal Power Commission. He will continue his connection for a while with McClelland Barclay Art Products, Inc., of which he has been president since 1931. Previously he had been with Stone and Webster.

O. M. Perry (A'14, M'25) manager, Windsor Hydro-Electric System, Windsor, Ont., Canada, was elected vice-president of the Association of Municipal Electrical Utilities, of Canada, at its recent convention at Toronto. He is also chairman of the convention committee for the year 1934 and a member of the rates committee.

W. P. Dobson (A'13, M'19) chief testing engineer, Hydro-Electric Power Commission of Ontario, Toronto, Ont., Canada, is a member of the papers committee of the Association of municipal Electrical Utilities, of Canada, serving for the year 1934. He is also a member of the regulations and standards committee.

E. R. Lawler (A'20) district electrical engineer for the Hydro-Electric Power Commission of Ontario was elected a member of the committee on accident prevention and health promotion of the Association of Municipal Electrical Utilities, of Canada, at its recent annual convention at Toronto.

T. C. James (A'18, M'18) district engineer for the Hydro-Electric Power Commission of Ontario was elected a member of the Committee on accident prevention and health promotion of the Association of Municipal Electrical Utilities, of Canada, at its recent annual convention at Toronto.

C. C. Curtis (A'23) has been selected as manager of the southwestern district of the Puget Sound Power and Light Company, at Olympia, Wash., succeeding A. M. Chitty (M'22). Mr. Curtis was division manager of the southern division at Olympia.

A. B. Cooper (A'16, F'33, and director) general manager and vice-president, Ferranti Electric Ltd., Mount Dennis, Toronto, Ont., Canada, has been appointed a member of the papers committee of the Association of Municipal Electrical Utilities, of Canada, to serve for the year 1934.

H. B. Dates (A'98, F'32) professor of electrical engineering at the Case School of Applied Science, Cleveland, Ohio, has been appointed administration member of the code authority for the vacuum cleaner manufacturing industry by the National Recovery Administration.

H. H. Weber (A'27, M'29) has been appointed assistant manager to C. W. Higbee, manager of tire sales, by the United States Rubber Products, Inc., New York, N. Y. Formerly he was director of low voltage engineering for the General Cable Corporation, New York City.

D. S. Jacobus (A'03) has been elected president of the American Welding Society. He has been associated with the Babcock and Wilcox Company since 1906 and at present is advisory engineer at the head of the engineering department. Doctor Jacobus devoted the earlier period of his life to teaching, joining the staff of the Stevens Institute of Technology after his graduation in 1884 and rising from the position of instructor in the department of experimental mechanics to that of professor of experimental mechanics and engineering physics. From 1900 to 1906 he was also in charge of the Carnegie Laboratory of Engineering. He is the author of

D. S. JACOBUS

numerous papers published in the transactions of various scientific and technical societies and engineering periodicals. He is a past-president of The American Society of Mechanical Engineers and of the American Society of Refrigerating Engineers, and a member of the American Institute of Mining Engineers, the Society for the Promotion of Engineering Education, and others.

R. W. Atkinson (A'09, F'28) director of high voltage research, General Cable Corporation, Perth Amboy, N. J., represents the Institute on the new sectional committee on electrical insulating materials of the American Standards Association, sponsored by the American Society for Testing Materials.

Wills Maclachlan (A'08, F'21) consulting engineer of Toronto, Canada, was elected to membership on the committee on accident prevention and health promotion of the Association of Municipal Electrical Utilities, of Canada, at its recent annual convention.

Dean Harvey (A'04, M'13) electrical engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., represents the National Electrical Manufacturers Association on the new A.S.A. sectional committee on electric insulating materials.

M. S. Sloan (A'07, F'30) formerly president of the Brooklyn Edison Company has been named chairman of the board of the Missouri-Kansas-Texas Railroad. He became a member of the board a year ago and has been a member of the executive committee since that time.

Edgar Kobak (A'21, M'22) has been appointed vice-president in charge of sales of the National Broadcasting Company, New York, N. Y. He was formerly vice-president and general sales manager of the McGraw-Hill Publishing Company, New York, N. Y.

L. W. Going (A'19) chief electrical inspector for the City of Portland, Ore., is working with a committee of the Northwestern Electric Company and Portland General Electric Company to formulate a new set of rules for electric services and meters.

C. B. Martin (A'07) transmission engineer, New York Central Railroad Company, was elected vice-chairman of the new sectional committee on electrical insulating materials of the A.S.A.; he is a representative of the American Railway Association.

W. B. Kouwenhoven (A'06, F'34) professor of electrical engineering and assistant dean, Johns Hopkins University, Baltimore, Md., represents the Institute on the new sectional committee on electrical insulating materials of the A.S.A.

J. E. Teckoe (M'29) manager, Hydro-Electric Commission of Niagara Falls, Niagara Falls, Ont., Canada, is a member of the rates committee, for the year 1934, of the Association of Municipal Electrical Utilities, of Canada.

F. D. Weber (A'09, M'30) chief electrical engineer, Oregon Insurance Rating Bureau, is working with a committee of the Northwestern Electric and Portland General Electric companies to formulate a new set of rules for electric services and meters.

W. R. Chawner (A'26) has resigned his position as power sales engineer of the Southern Sierras Power Company at Riverside, Calif., which he held for 14 years, to become general manager of the Temescal Water Company, Corona, Calif.

J. D. Ross (A'08, F'12) superintendent of lighting for the City of Seattle, Wash., has been called to Washington, D. C., on leave of absence, to assist in a nation-wide power survey which the Federal Trade Commission is conducting.

C. F. Schmid (A'20, M'34) is now test engineer for the Kerite Insulated Wire and Cable Company, Seymour, Conn. He was formerly an engineer in the cable engineering department of the Anaconda Wire and Cable Company at Hastings-on-Hudson, N. Y.

H. W. Hough (A'08, M'13) has been elected vice-president and general manager of the Cleveland Electric Illuminating Company, Cleveland, Ohio. He has been associated with the company for 24 years and previously was associate general manager.

R. H. Knowlton (A'12) vice-president of The Connecticut Light and Power Company of Hartford, Conn., will act as vice-chairman of the New York–New England Regional Gas Sales Conference to be held at New London, Conn., in June 1934.

J. B. McCarthy (A'23, F'27) has been appointed vice-president in charge of sales of the Eugene F. Philips Electrical Works, Ltd., Montreal, Que., Canada. Previously he had been engineer, and assistant to the president.

G. W. Henyam (A'20, M'26) commercial engineer, radio department, General Electric Company, Schenectady, N. Y., has been made chairman of a special section of radio applications of the National Electrical Manufacturers Association.

J. E. B. Phelps (M'29) manager and electrical engineer, Sarnia Hydro Electric System, Sarnia, Ont., Canada, is a member of the merchandising committee, for the year 1934, of the Association of Municipal Electrical Utilities, of Canada.

A. G. Oehler (A'18, F'28) editor of *Railway Electrical Engineer* and electrical department editor of *Railway Age*, New York, N. Y., has been elected to membership on the executive committee of the New York Section of the Institute.

M. F. Skinker (A'22, M'27) assistant director of research, Brooklyn Edison Company, Brooklyn, N. Y., is a representative of the electric light and power group of the A.S.A. on its new sectional committee on electrical insulating materials.

H. S. Vassar (A'06, M'18) laboratory engineer, Public Service Electric and Gas Company, Irvington, N. J., is a representative of the electric light and power group of the A.S.A. on its new sectional committee on electrical insulating materials.

Allan B. Campbell (A'20, M'24) engineer, Edison Electric Institute, New York, N. Y., serves as alternate representative of the electric light and power group of the A.S.A. on its new sectional committee on electrical insulating materials.

J. M. Wilson (A'18) electrical engineer, Bell Telephone Laboratories, Inc., represents the American Society for Testing Materials on its new sectional committee on electrical insulating materials.

H. A. Johnson (M'17) general manager of the Chicago Rapid Transit Company, Chicago, Ill., has been elected a director of the company.

Obituary

Edson Oliver Sessions (A'02, M'07, F'13) president of the E. O. Sessions Co., Ltd., died on April 15, 1934, at Chicago. He was born in Louisville, Ky., December 23, 1871. He obtained his technical education by private study and at the École de Polytechnic in Paris, of which he was a graduate. He also took a student course at the Thomson-Houston Electric Company at Lynn, Mass. In 1889 he became assistant to the state suprintendent of construction, associated with the United Edison Manufacturing Company, and was engaged in the installation of lighting systems at Herkimer, N. Y., and at other locations throughout the state. In 1892 he was made general superintendent and engineer for the Northern Electrical Manufacturing Company at Concord, N. H., taking charge of the installation of many small, complete plants, steam, water and electric, in New Hampshire, Vermont, and Canada. In 1893, as superintendent and electrical engineer for the Frank Jones manufacturing interests, he built a complete monocyclic plant at Portsmouth, N. H., 2 d-c plants there, and installed plants at Sorrento, Me., and at Boston, Mass. In 1895 he was appointed general superintendent and took charge of all of the Frank Jones investigations, installing power plants in various parts of the world. In 1899 he was erecting engineer for the General Electric Company. In 1901 he became consulting engineer to W. S. Stratton of Colorado Springs, Colo., designing a complete power house for electric traction and planning improvements in his entire traction system. In 1902 he entered the employ of the Stanley Electric Manufacturing Company, as engineer of construction, installing several plants and substations. He became resident engineer in New York City for the Stanley concern later. In 1904 he was made western sales engineer of the Stanley organization with headquarters in Chicago. Since 1905 he had been engaged in an extensive consulting practice, at one time as a member of the firm of Woodmanese, Davidson and Sessions and later, from 1920 to 1928, as president and consulting engineer for the Sessions Engineering Company. In 1919 he was district manager of the U.S. shipping board. In 1931 he spent several months in Russia making a detailed engineering analysis of several projected Soviet industrial plants.

George Herbert Condict (A'87, M'87) consulting electrical and mechanical engineer and inventor, of Plainfield, N. J., died April 9, 1934, at Orlando, Florida. He was born at Newark, N. J., in 1862. He graduated from the University of Pennsylvania. In 1882 he entered the employ of the Central Gas Light Company of San Francisco, and was connected with the building of gas plants in California and Oregon. In 1884 he became associated with the Pacific Coast Electric Construction Company of San Francisco, constructing dynamos and storage batteries. In 1885 he was the Pacific Coast agent for Van Depoele Electric Company of Chicago, erecting isolated arc and incandescent electric light plants in California. He visited Chicago and assisted Mr. Van Depoele in his electric railway and lighting experiments, installing his exhibition trolley line at the New Orleans Exposition in 1885. From 1887 to 1891 he was general manager of the Electric Car Company of America, at Philadelphia; 1892–93, chief engineer of the North American Storage Battery Company; 1893–96, sales engineer for the Electric Storage Battery Company of Philadelphia and San Francisco; 1896–97, general manager, Englewood and Chicago Railway; 1897–02, chief and consulting engineer, Electric Vehicle Company of New York and Hartford, Conn.; 1903–06, general manager, Electro-Dynamic Company of Philadelphia and New York; 1906–09, general manager, Box Electric Drill Company, New York; and 1909–12, manufacturers' sales engineer, New York and Jacksonville, Fla. From 1912 until his death he was engaged in an extensive consulting practice in the electrical and mechanical engineering fields. His inventions include the series parallel resistance controller, an improved storage battery for use as an auxiliary to provide for fluctuations of railway loads, and many other mechanical and electrical appliances and apparatus. During the War he was a member of the board of examiners for the Naval consulting board and from 1919 to 1920 he was on the technical advisory commission of the war claims board. He was a member of the Franklin Institute, the New York Electrical Society and the American Association for the Advancement of Science.

James Lyman (A'94, M'01, F'13, and Life Member) consulting engineer, retired, died from a heart attack on March 28, 1934, at Del Monte, Calif. He was born September 1, 1862, at Middlefield, Conn. He graduated from the Sheffield Scientific School of Yale University in 1883 with the degree of Ph.B. and from Cornell University in 1884 with the degree of M.E. In the latter year he became construction electrician for the Edison Construction Company and assisted in the installation of a number of lighting plants in Pennsylvania and one at Piqua, Ohio. From 1885 to 1886 he was assistant superintendent of

the Marr Construction Company which was organized to take over the construction work for the Edison company. He had entire charge of the installation of plants for the lighting companies at Johnstown, Wayne, Tamaqua, and DuBois, Pa., and also gave exhibitions of incandescent lighting. In 1886 he resigned his position with the Marr Construction Company to superintend the private interests of his family in the Metropolitan Manufacturing Company. In 1895 he received the degree M.M.E. from Cornell University and entered the employ of the General Electric Company as an assistant to Dr. C. P. Steinmetz. He conducted special experimental testing and designed various electric apparatus. About 3 years later he was transferred to the power and mining department. In 1899 he was appointed assistant engineer of the Chicago branch of the General Electric Company, and in 1911 was made district engineer for Chicago. From 1911 until his death he was associated with the firm of Sargent and Lundy, Inc., of Chicago, as electrical engineer, member, vice-president (1926–30), and as consultant retired, since 1930. He was a member of The American Society of Mechanical Engineers, American Electrochemical Society, Western Society of Engineers and the British Institution of Electrical Engineers.

George Johnson Newton (A'10, M'15) consulting engineer and specialist in designing and laying underground conduit and cable-systems, died on March 26, 1934, at Sunland, Calif. He was born February 28, 1867, at Gloversville, N. Y. He attended the public schools of Tarrytown, N. Y., and obtained his technical education through his own efforts, studying and reading. For about 20 years he worked for various telephone companies, including the Westchester Telephone Company, Nyack, N. Y.; Metropolitan Telephone Company, New York City; New York and New Jersey Telephone Company; American Telephone and Telegraph Company at Syracuse; and Newark Telephone Company, Citizens Telephone Company, Kenosha, Wis. In 1904 he was engineer in charge of construction for the State Line Telephone Company, New York City. He was designing engineer with G. M. Gest in New York City from 1906 to 1916 when he established a consulting practice. From 1919 to 1922 he was designing engineer for the Connecticut Light and Power Company at Waterbury and in 1923 he was with the Philadelphia Electric Company. He resumed his practice as a consultant in 1924. He was one of the first engineers to realize the advantages of the 3-phase 4-wire system which he designed and installed at Dallas, Texas, Canton, Ohio, and at Denver, Colo. He designed similar systems for the British Columbia Electric Railway Company of Vancouver and for the American Gas and Electric Company at Atlantic City, which were installed later. He also designed and installed the 33,000-volt underground transmission system for the electrification of the Staten Island Rapid Transit. He served the Institute as a member of the transmission and distribution committee from 1916 to 1917 and from 1921 to 1924.

Herbert Eugene Kaighn (A'12, M'31) electrical engineer of Wilmington, Del., died on March 18, 1934. He was born August 19, 1875, at Washington, D. C. He secured his technical training through practice in and around the Navy Yard at Washington during his school day vacations and later through tutoring in electrical and mechanical engineering. He engaged in various branches of ordnance work. In 1898 he was an instructor in ordnance at the Naval Training Station, Newport, R. I. In 1899 he was in charge of electrical equipment, marine district, for the New York, New Haven and Hartford Railroad. From 1900 to 1904 he was ballistic engineer at the Naval Torpedo Station, Newport, R. I., and the following 2 years was inspector of ordnance and powder at the Philadelphia Navy Yard. In 1907 he entered the employ of the E. I. du Pont Company of Wilmington as ballisitic and experimental engineer in charge of installations, testing, designing and constructing electrical and physical apparatus for explosives tests. He left the E. I. du Pont Company in 1917 and established a consulting practice, specializing in designing and wiring hospital and institution systems until 1926, when he began specializing in radio and acoustic and amplifying systems. He was consultant for the American Car and Foundry Company on marine installations. He was a member of The American Society of Mechanical Engineers and the United States Naval Institute.

Guy Köchling Mitchell (A'06, M'14) engineer and appraiser and formerly president and proprietor of the Standard Electric Machinery Company of Baltimore, Md., died on January 15, 1934. He was born in Baltimore, July 5, 1877, and was educated at Baltimore Polytechnic Institute and through his own efforts. He worked for a year as draftsman and in the electrical shop of the United Electric Light and Power Company of Baltimore. In 1902, after a short period of work on the installation of a steam plant and transmission line for the Embree Iron Company of Embreeville, Tenn., he returned to Baltimore to do estimating and layout work in the distribution department of the United Electric Light and Power Company. In 1906 he went with Crook Horner Company as manager of the electrical department. When the firm dissolved in 1907 he purchased the electrical and elevator departments, and established the Standard Electric and Elevator Company, operating it as a manufacturing and contracting concern. Later it became the Standard Electric Machinery Company. He was the head of the company and in charge of all the engineering work for many years. During the war period he devised an automatic system for reconnection and rerating motors and generators of all makes and types, which filled a great many Government emergencies. He was a member of The American Society of Mechanical Engineers.

Charles Wilson Price (A'94, and member for life) who for many years was editor and owner of electrical publications, died in New York, N. Y., May 11, 1934. He was born at Barnesville, Ohio, in 1857. After learning the printing trade he became the editor of the *Barnesville Enterprise*. Going to Topeka, Kan., he was one of the founders in 1879, and for several years one of the editors of the *Topeka Daily Capital*. He later became interested in electrical science and in 1885 joined the staff of the *Electrical Review*, New York, of which he was for 37 years associate editor and editor-in-chief, and president of the Electrical Review Publishing Company. He purchased the *Western Electrician* in 1908, and *Electrocraft* in 1912, consolidating these with the *Electrical Review*. For a number of years preceding his death he was president of the Publishers Sales Company, Inc., and was a director in the Columbia Casualty Company, Commercial Union Fire Insurance Company, both of New York, N. Y., and was interested in Magazines, Inc., of Chicago. Mr. Price was a frequent contributor to newspapers and magazines on electrical subjects. He was a past-president of the Kansas Society of New York, and a member of the Ohio Society of New York, a past vice-president of the Lotus Club, and a member of the Press, Advertising, and Travel Clubs, all of New York. He was for several years secretary and treasurer of the International League Press Clubs.

Membership

Recommended for Transfer

The board of examiners, at its meeting held May 23, 1934, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

MacKavanagh, Thomas J., prof. of elec. engg., (Patent Attorney) The Catholic University of America, Washington, D. C.
Pilliod, James J., engr., long lines dept., American Tel. & Tel. Co., New York.
Vickers, Herbert, prof. and head of dept. of elec. & mech. engg., Univ. of British Columbia, Vancouver, B. C., Canada.

To Grade of Member

Belknap, J. Harrison, control engr., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Clement, Andrew E., member of technical staff, Bell Telephone Labs., Inc., New York.
Cogan, Charles M., secy. of the codes and standards committee, National Electrical Manufacturers Association, New York.
Cogswell, Burnham, field engr., General Electric Co., Buffalo, N. Y.
Cruikshank, James S., supt., elec. meter & installation Dept., Consolidated Gas Elec. Lt. & Pwr. Co., Baltimore, Md.
Dickinson, A. G., elec. engr., Consolidated Mining and Smelting Co., Trail, B. C., Canada.
Dunlop, Robert P., tests engr., Hong Kong Elec. Co., Ltd., North Point, Hong Kong, China.
Fetsch, Joseph T., Jr., asst. engr., radio, head of vacuum tube section at Naval Research Laboratory, Bellevue, D. C.
Gardner, John H., Jr., captain, signal corps, U.S. Army, Signal Corps Laboratories, Fort Monmouth, Oceanport, N. J.
Mathes, John A., foreman, test laboratory, United Elec. Lt. & Pwr. Co., New York.
Reed, Henry R., associate prof. of elec. engg., Michigan College of Mining and Technology, Houghton, Mich.
Russell, Chester, Jr., asst. prof. of elec. engg., University of New Mexico, Albuquerque, New Mexico.
Schramm, Frederic B., patent attorney, General Elec. Co., Schenectady, N. Y.
Smith, Edward F., asst. prof. of elec. engg., University of Florida, Gainesville, Fla.
Taylor, Paul B., 2123 California St., Washington, D. C.
Walker, Harry N., asst. prof. of elec. engg., New York University, New York.
White, Allen O., sales engr., General Elec. Co., Washington, D. C.
Wolff, Frank A., chief telephone section, Bureau of Standards, Washington, D. C.
Zubair, S. Mohammed, elec. engr., Buffalo, Niagara & Eastern Power Corp., Buffalo, N. Y.

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before June 30, 1934, or August 31, 1934, if the applicant resides outside of the United States or Canada.

Albright, C. L. (Member), Univ. of Richmond, Va.
Audry, P. L., Jr., Shell Petroleum Corp., Noreo, La.
Antofili, V., Nat. Dist. Tel. Co., Astoria, L. I., N. Y.
Baroco, J. F., Baroco Elec. Co., Pensacola, Fla.
Bethea, H. F., Graybar Elec. Co., Jacksonville, Fla.
Bialek, A. J., Duquesne Lt. Co., Pittsburgh, Pa.
Brown, W. R., Niagara Lockport & Ontario Pwr. Co., Olean, N. Y.
Callander, M. B., B. C. Elec. Ry. Co., Vancouver, B. C., Can.
Chinn, G. I., 1642 North Monroe St., Baltimore, Md.
Cook, R. K., Western Union Tel. Co., Phila., Pa.
Dadahian, M., Cornell Univ., Ithaca, N. Y.
Diehl, F. V., Okla. Gas & Elec. Co., Oklahoma City.
Elmore, D. R., Gibbs & Hill, Inc., N. Y. City.
Evans, O., 556 N. Getty St., Uvalde, Texas.
Ferguson, J. D., Ranier Natl. Park Co., Longmire, Wash.
Gehrmann, W. E., Am. Elevator & Machine Corp., N. Y. City.
Holder, DeW. H., Jr. (Member), Louisiana Pwr. & Lt. Co., Algiers.
Hollis, M. O., Jr., Raybro Elec. Supplies, Inc., Tampa, Fla.
Hoover, W. G., Stanford Univ., Stanford Univ., Calif.
Hutchinson, M. C., 128 E. 44 St., N. Y. City.
Johnson, E. W., Canada Wire & Cable Co., Ltd., Vancouver, B. C.
Kukutschka, E. (Member), AEG Cia. Mexicana de Electricidad S. A. Mexico, D. F., Mex.
Larsen, T., Bklyn. Edison Co., Inc., Bklyn., N. Y.
Lightbody, D. C., Hartford Steam Boiler Inspection & Ins. Co., Phila., Pa.
Martin, B. J., Bennett-Watts-Haywood Co., Chicago, Ill.
McGinity, J. V., Am. Steel & Wire Co., Tulsa, Okla.
McKnight, C. H., 1625 Vine St., Scranton, Pa.
Miller, H. B., Utilities Serv. Co., Allentown, Pa.
Milligan, H. F., Mountain States Tel. & Tel. Co., Santa Fe, New Mexico.
Morrison, W. G., Inland Engg. Co., Dallas, Texas.
Patton, G. M., P. McCuaig Ltd., Montreal, Que., Can.
Platt, A. B., Scranton Elec. Const. Co., Pa.
Poti, W. M., N. Y. & Queens Elec. Pwr. & Lt. Co., Flushing, N. Y.
Reisener, H. E., Westinghouse X-ray Co., Inc., Toledo, O.
Schweitzer, W. J., Jr., Detroit, Mich.
Smith, K. B., Carolina Pwr. & Lt. Co., Pee Dee, N. C.
Sparolini, J. A., Jr., Gen. Petroleum Corp., Monterey, Calif.
Wolfe, A. K., Allen Bradley Co., Milwaukee, Wis.

38 Domestic

Foreign

Chhabra, S. R., P. O. Kamabia, Distt. Lyallpur, Punjab, India.
Ewart, W. L. (Member), Lago Oil & Transport Co., Ltd., Aruba, Dutch West Indies.
Ghafoor, M. A., School for Electricians, Ludhiana, Punjab, India.
Green, R., Demerara Electric Co., Ltd., Demerara, British Guiana, S. A.
Pennell, E. R., Hewittic Elec. Co., Ltd., Thames, Eng.
Singh, G., Ganga Sugar Corp., Ltd., Saharanpur, U. P., India.

6 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Bonell, R. K., 45 Clifton St., Newark, N. J.
Brayman, Chas. E., c/o J. J. Murphy & Son, 38 Ford St., Hartford, Conn.
Chilberg, Ernest R., Gen. Elec. Co., 230 S. Clark St., Chicago, Ill.
Carvey, C. J. A., 4144 Cottage Grove, Chicago, Ill.
Cilliam, Charles T., Power Cost Engg. Co., 742 Milam Bldg., San Antonio, Texas.
Coulding, Harold, 404 W. 116th St., New York, N. Y.
Gray, L. Tenney, Jr., 6452 Hillegas Ave., Oakland, Calif.
Hammond, William M., Idaho Springs, Colo.
MacDonald, Robert, 6 Rue Nicolas Charlet, Paris, France.
McNitt, Donald P., 1009 First Natl. Life Bldg., St. Louis, Mo.
Miller, Frank D., Box 34, Yatesboro, Pa.
Nemkowski, B., 104–25 115th St., Richmond Hill, N. Y.
O'Handley, Joseph A. E., 579—61st St., Bklyn., N. Y.
Patton, Edgar P., Standish Arms, 169 Columbia Heights, Bklyn., N. Y.
Tamburello, G., 307 West 20th St., N. Y. City.
Valier, Chas. E., Jr., 1804 Tel. Bldg., St. Louis, Mo.

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

BASILY INTERPOLATED TRIGONOMETRIC TABLES with NON-INTERPOLATING LOGS, COLOGS and ANTILOGS. By F. W. Johnson. San Francisco, Simplified Series Pub. Co., 1933. Tables, 10x7 in., cloth, $3.50. Aims to provide logarithmic tables sufficiently accurate for ordinary calculations without any interpolation, and a set of trigonometric tables which can be interpolated more easily than others. The book contains both four-place and five-place tables of logarithms, cologarithms and antilogarithms, five-place tables of natural and logarithmic trigonometric functions, and various other tables, with instructions.

(The) ELECTROMAGNETIC FIELD. By H. F. Biggs. Oxford (England), Clarendon Press; N. Y., Oxford Univ. Press, 1934. 158 p., illus., 9x6 in., cloth, $3.50. Presents the classical theory of the electromagnetic field, for students of physics. Static fields, electrodynamics, Maxwell's equations, energy, momentum, and special relativity and the electromagnetic field are considered.

Great Britain. Dept. of Scientific and Industrial Research. REPORT for the Year 1932–1933. London, His Majesty's Stationery Office, 1934. 189 p., tables, 10x6 in., paper, 3s. (Obtainable from British Library of Information, N. Y., $0.88.) The work done by all the governmental research institutions and the licensed research associations is reviewed in this report, with lists of the publications that describe the results more fully.

HIGHER MATHEMATICS for ENGINEERS and PHYSICISTS. By I. S. and B. S. Sokolnikoff. N. Y. and Lond., McGraw-Hill Book Co., 1934. 482 p., illus., 9x6 in., cloth, $4.00. Aims to give students of engineering and other applied sciences a bird's-eye view of those topics of mathematics indispensable in the study of physical sciences, and thus to serve as a stepping-stone to advanced mathematical treatises.

INDUSTRIAL RADIOGRAPHY. By A. St. John and H. R. Isenburger. N. Y., John Wiley & Sons, 1934. 232 p., illus., tables, 9x6 in., cloth, $3.50. The general principles that govern the production and use of X rays and gamma rays are set forth clearly, together with the special technique suitable for important classes of materials. The equipment required and the methods of using it, and the radiography of large castings and forgings, of welded structures, and of small objects are discussed in practical fashion. Costs are considered briefly. There is a bibliography.

PRINCIPLES of RADIO. By K. Henney. 2 ed. N. Y., John Wiley & Sons, 1934. 491 p., illus., 8x5 in., cloth, $3.50. A practical presentation of the subject, which avoids the use of higher mathematics. The principles are presented simply, and their application to practical problems discussed. The book is well adapted to home study. This edition has been rewritten.

Der KONDENSATOR in der STARKSTROMTECHNIK. By F. Bauer. Berlin, Julius Springer, 1934. 314 p., illus., 10x6 in., cloth, 18.50 rm. This work is chiefly concerned with questions relating to the use of condensers in factories and transmission systems. The general laws are presented briefly in an introductory chapter, and the greater portion of the book is devoted to the special technical and economic problems which arise in practice. A chapter upon design and construction is included.

Das LÄRMFREIE WOHNHAUS, herausgegeben von Fachausschuss für Lärmminderung beim Verein deutscher Ingenieure. Berlin, VDI-Verlag, 1934. 90 p., illus., 8x6 in., paper, 2.50 rm. Discusses the prevention and suppression of noise from the point of view of the builder and owner. The effect of noise upon human beings, methods of measurement, and practical methods for constructing soundproof buildings are described with sufficient detail. Issued by the noise prevention section of the Society of German Engineers.

LIMITATIONS of SCIENCE. By J. W. N. Sullivan. N. Y., Viking Press, 1933. 307 p., 9x6 in., cloth, $2.75. Only one chapter of this interesting work is concerned with the "limitations" of science. The remainder is concerned with its achievements and future objectives. Affords a picture of the whole field of scientific thought, adapted to the needs of laymen.

SCIENCE MUSEUM, SOUTH KENSINGTON. HANDBOOK of the COLLECTIONS ILLUSTRATING ELECTRICAL ENGINEERING. Part 2. Descriptive Catalogue. London, His Majesty's Stationery Office, 1933. 96 p., illus., 10x6 in., paper, 2s. (Obtainable from British Library of Information, N. Y., $0.61.) Contains the substance of the descriptive labels attached to the exhibits in the valuable electric power collections of the Science Museum. Over 300 exhibits are described, with photographs of many of the most interesting ones. The pamphlet supplements the historical handbook.

(The) VALUATION and REGULATION of PUBLIC UTILITIES. By J. H. Gray and J. Levin. N. Y. and Lond., Harper & Bros., Publishers, 1933. 143 p., 8x5 in., paper, $0.75; cloth, $1.00. The reader who wishes to become acquainted with the general features of the problem of utility regulation should find this book a clear, concise outline of the subject. The history of regulation is briefly traced and the attempt at regulation by commissions is analyzed. The reasons why present methods have failed to meet public needs are discussed.

VDI 71. HAUPTVERSAMMLUNG, Friedrichshafen/Konstanz, 1933. VORTRÄGE und AUSSPRACHEN. Berlin, VDI-Verlag, 1933. 157 p., illus., 12x8 in., paper, 3 rm. The papers presented at the 1933 meeting of the Society of German Engineers are presented here in a single volume. These papers are grouped under several headings: food and housing, welding, flow, light construction, civil engineering, steam boilers, textiles, and technology and economics.

BUILDING an ENGINEERING CAREER. By C. C. Williams. N. Y. & Lond., McGraw-Hill Book Co., 1934. 247 p., illus., 8x6 in., cloth, $2.00. Based upon the orientation and motivation courses given at the State University of Iowa. Aims to give the student a preview of the character of the profession and of its relation to social organization, to assist him to adopt efficient methods of study, to indicate the nature of the engineer's mode of thinking, to afford a historical background, and to indicate future possibilities.

Engineering Societies Library

29 West 39th Street, New York, N.Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

Electrical Features of Ford Exhibit at Chicago Fair.—One hundred miles of electric wiring, more than 225 electric motors, a lighting display which includes a battery of 9,000 concealed floodlights, an amplifying system containing more than 750 loudspeakers—this is only part of the electrical installation for the Ford Exposition Building at the 1934 World's Fair in Chicago. The huge Ford project, covering over 11 acres, will require a load of 6,000 kilowatts, or more than a third of the total electric capacity of the entire Fair in 1933. The exhibits will show in actual operation practically all of the steps required in Ford manufacturing, from the raw materials to the finished parts of cars.

Inventions Service for Manufacturers.—A new service for the manufacturer, to keep him advised month by month of the progress and availability of new inventions in his field, has been announced by Inventions Digest, Inc., 310 South Michigan Ave., Chicago. This service collects descriptions of recent inventions from patent attorneys and reports news of these inventions to manufacturers. Subsequent negotiations for sale or licensing are handled direct between the manufacturer and the inventor's attorney.

New Power Connectors.—A complete line of outdoor, full-bolted electric power connectors has been announced by the General Electric Co., enabling power connections to be made between electric conductors, or between conductors and terminal parts with minimum time and expense. The outstanding feature of these connectors is the line pressure contact obtained by means of a series of thread like cuts on the serrated surface. These pressure contact lines also serve to bite into the conductor and assure a tighter joint. The connectors, of high conductivity copper alloy, have the same current carrying ratings as extra-heavy, iron-pipe-size copper tubing of 98% conductivity.

Trade Literature

Motor Generator Sets.—Bulletin 1155, 24 pp. A comprehensive treatment of this type of equipment; illustrated. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Surge Proof Transformers.—Bulletin D.M.F. 8323, 8 pp. Describes new, surge proof, distribution transformers. Westinghouse Electric & Mfg. Co., East Pittsburgh.

Distribution Cutouts.—Bulletin GEA-1673, 52 pp. Describes enclosed, open, and oil type cutouts and fuse links. General Electric Co., Schenectady, N. Y.

Motors.—Bulletin 167, Part 8, 4 pp. Describes type RD direct-current, compound-wound motors. Wagner Electric Corp., 6400 Plymouth Ave., St. Louis, Mo.

Weatherproof Wires and Cables.—Bulletin 8 pp. Describes URC weatherproof wires and cables. General Cable Corp., 420 Lexington Ave., New York.

Diesel Electric Locomotives.—Catalog 1994, 80 pp. Describes Westinghouse Diesel engines and 15 standard sizes of Diesel electric locomotives. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Mining Cable.—Bulletin GEA-1920, 12 pp. Describes tellurium-compound mining cable for various mine services, including machinery, gathering-reel locomotives, power distribution, telephone circuits, etc. General Electric Co., Schenectady, N. Y.

Network Cable.—Bulletin, 4 pp. Describes a non-metallic sheathed, rubber insulated, braided network cable, extremely resistant to the penetration of oil, moisture, acids, etc. General Cable Corp., 420 Lexington Ave., New York.

Expulsion Protective Gaps.—Bulletin GEA-1858A, 12 pp. Describes expulsion protective gaps for the protection of transmission-line insulation against lightning flashovers and resultant line outages. General Electric Co., Schenectady, N. Y.

Control Equipment.—Catalog, 40 pp. Describes practically all control products manufactured in both the Switch and Panel Division in Detroit and Industrial Controller Division in Milwaukee. Includes prices. Square D Co., Detroit, Mich.

Luminous Fountains.—Bulletin C-1982, 16 pp. Describes 3 standard types of illuminated fountains for estate gardens, public parks, etc. A number of fountain installations are illustrated in color. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Alsimag and Lava Insulators.—Bulletin 34, 28 pp. Describes composition ceramic materials of high dielectric and mechanical strength, widely applicable in the electrical industry and available at moderate costs. American Lava Corp., Chattanooga, Tenn.

Electric Heating Units.—Bulletin GEA-1520B, 52 pp. Describes immersion heaters, cartridge units, strip heaters, calrod units, gluepots, air heaters, soldering irons, control equipment, etc. General Electric Co., Schenectady, N. Y.

Wood Conduit.—Booklet, entitled "The Trend toward Wood Conduit," relates the history of this equipment from 1619 and emphasizes a conduit that has been developed and is capable of carrying lines with 33,000 volts. Installations are illustrated. Southern Wood Preserving Co., Dollar's Savings and Trust Bldg., Pittsburgh, Pa.

Network Protectors.—Catalog 35-500, 12 pp. Describes type CM-2 heavy duty network protectors. The latest refinements in all types of this equipment for heavy duty service, including submersible and open-type units, transformer-mounting units and a compact unit for temporary use on new construction, are illustrated. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Truck and Trailer State Regulations.—Handbook, 56 pp. Outlines the regulations and laws of each state, giving the size and weight restrictions of trucks and trailers. The interpretations of the laws are arranged in tabular form and are approved by a responsible public official of each state, whose signature appears below the interpretation. The Four Wheel Drive Auto Co., Clintonville, Wis.

Instrument and Control Switches. Catalog 9, 8 pp. Describes a new line of instrument and control switches, designated type "R Rotary." The instrument switches are used in connection with electrical measuring instruments and the control switches are employed for establishing proper connections to air and oil circuit breakers and similar equipment. The new line has been worked out to provide a switch for practically every known requirement. Roller-Smith Co., 233 Broadway, New York.

Megger Instruments.—Bulletin 1375. Describes the Megger capacity meter, a portable, direct-reading, multi-range, microfarad or capacity meter, which includes for the first time in an instrument of this character a self-contained source of test current.—Midget Megger Circuit Testing Ohmmeters.—Bulletin 1380. Describes midget Megger circuit testing ohmmeters for quick measurements of resistance from as low as a fraction of an ohm to as high as 200,000 ohms. James G. Biddle Co., 1211 Arch St., Philadelphia, Pa.

Field Intensity Meter.—Bulletin 40, 8 pp. Describes a new radio field intensity meter, Type TMV-75-B. The instrument, complete in two carrying cases, consists essentially of an extremely sensitive loop receiver of the superheterodyne type, incorporating a self-calibrating oscillator. The frequency range is from 25 kc to 20,000 kc. The field intensity range is from 20 micro-volts per meter to 6 volts per meter; readings are direct. The instrument is of value in radio transmission surveys and interference location. RCA Victor Co., Inc., Camden, N. J.

Capacitors.—Bulletin GEA-77F, 28 pp. Describes Pyranol-treated capacitors for power-factor improvement. These are applicable over a wide range of service conditions and are of 4 general types: box-type, small rack-type, small outdoor, and large rack-type capacitors for either indoor or outdoor installations. These capacitors are treated and filled with Pyranol. This new liquid is an outstanding dielectric material for capacitors because its extraordinary insulating and dielectric properties permit an unusually small capacitor for a given rating; also because it is nonflammable. General Electric Co., Schenectady, N. Y.

Published Monthly by

American Institute of Electrical Engineers

(Founded May 13, 1884)

Electrical Engineering

Registered U. S. Patent Office

July 1934
Volume 53
No. 7

The Official Monthly Journal and Transactions of the A.I.E.E.

J. B. Whitehead, President
H. H. Henline, National Secretary

Publication Committee
E. B. Meyer, Chairman
R. N. Conwell **H. H. Henline**
W. S. Gorsuch **H. R. Woodrow**

Publication Staff
G. Ross Henninger, Editor
C. A. Graef, Advertising Manager

PUBLICATION OFFICE, 20th and Northampton Streets, Easton, Pa.

EDITORIAL AND ADVERTISING OFFICES, 33 West 39th Street, New York, N. Y.

ENTERED as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918.

SUBSCRIPTION RATES—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii and the Philippine Islands, Central America, South America, Haiti, Spain and Spanish Colonies; $13 to Canada; $14 to all other countries. Single copy $1.50.

CHANGE OF ADDRESS—requests must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered due to incorrect address cannot be replaced without charge. Be sure to specify both old and new addresses and any change in business affiliation.

ADVERTISING COPY—changes must be received by the fifteenth of the month to be effective for the issue of the month succeeding.

STATEMENTS and opinions given in articles appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters.

REPUBLICATION from "Electrical Engineering" of any Institute article or paper (unless otherwise specifically stated) is hereby authorized provided full credit be given.

COPYRIGHT 1934 by the American Institute of Electrical Engineers.

ELECTRICAL ENGINEERING is indexed in Industrial Arts Index and Engineering Index.

Printed in the United States of America. Number of copies this issue—

17,700

This Month—

Front Cover

"Sunset Lays a Path of Gold Across Great Salt Lake"—a scene near Salt Lake City, location of the Institute's Pacific Coast Convention, Sept. 3–7, 1934

Educational Series—No. 7

Electron Emission 1054
By SAUL DUSHMAN

Special Features

The Institute's National Officers Newly Elected for the Year 1934–35 . . 1038

An Insight Into the Workings of the Institute 1039
By J. ALLEN JOHNSON

Report of the Board of Directors . . 1095

A.I.E.E. Papers

Resonant Lines in Radio Circuits . . . 1046
By FREDERICK EMMONS TERMAN

Insulator Arcover in Air. 1062
By F. W. MAXSTADT

A Glow Discharge Anemometer . . 1068
By F. C. LINDVALL

Distance Relay Action During Oscillations 1073
By E. H. BANCKER and E. M. HUNTER

Reignition of an Arc at Low Pressures. . 1081
By S. S. MACKEOWN, J. D. COBINE, and F. W. BOWDEN

A Survey of Hydroelectric Developments—II 1086
An A.I.E.E. Committee Report

The Expulsion Oil Circuit Breaker . . . 1108
By A. C. SCHWAGER

Counterpoise Tests at Trafford 1116
By C. L. FORTESCUE and F. D. FIELDER

Field Tests on Conductor Vibration . 1123
By E. M. WRIGHT and J. MINI, Jr.

News of Institute and Related Activities 1128

Plan Your Vacation to Include the Pacific Coast Convention . . 1128

An Address on "Human Engineering Problems" 1130

Student Conference Held by North Central District . . . 1132

Letters to the Editor 1133

Membership 1138

Engineering Literature. 1139

Industrial Notes 1140

Employment Notes (See Advertising Section)

Officers and Committees (For complete listing see p. 658–81, September 1933 issue of ELECTRICAL ENGINEERING)

CORRECTION: The title of Prof. D. C. Jackson's contribution to the May 1934 50th anniversary issue of ELECTRICAL ENGINEERING should have read "The Evolution of Electrical Engineering Education" instead of "The Evolution of Electrical Engineering" as appears on p. 770 of that issue.

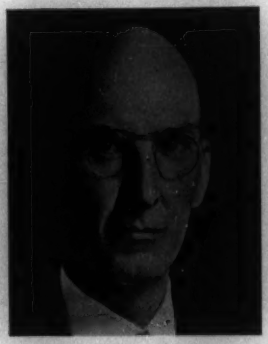
The Institute's National Officers Newly Elected for the Year 1934–35

W. H. TIMBIE
Vice President
Professor of Electrical Engineering and Industrial Practice, Massachusetts Institute of Technology, Cambridge Mass.

G. G. POST
Vice President
Vice President, Milwaukee Electric Railway and Light Company, Milwaukee, Wis.

R. H. TAPSCOTT
Vice President
Vice President, New York Edison Company, New York, N. Y.

F. J. MEYER
Vice President
Vice President in Charge of Operation, Oklahoma Gas and Electric Company, Oklahoma City, Okla.



J. ALLEN JOHNSON
President
Chief Electrical Engineer, Buffalo, Niagara and Eastern Power Corp., Buffalo, N. Y.

F. O. McMILLAN
Vice President
Research Professor of Electrical Engineering, Oregon State College, Corvallis, Ore.

H. B. GEAR
Director
Assistant to the Vice President, Commonwealth Edison Company, Chicago, Ill.

N. E. FUNK
Director
Vice President in Charge of Engineering, Philadelphia Electric Company, Philadelphia, Pa.

F. M. FARMER
Director
Vice President and Chief Engineer, Electrical Testing Laboratories, New York, N. Y.

An Insight Into the Workings of the Institute

By J. ALLEN JOHNSON, Vice President A.I.E.E.

The keynote behind the success of the Institute is the spirit of mutual helpfulness to other members and of disinterested service to humanity. That such a spirit motivates the large number of individuals who coöperate actively in the affairs of the Institute is brought out in the following discussion by President-Elect J. Allen Johnson. To the many members of the Institute who are not intimately familiar with its "workings" this article should be interesting and helpful.

THE "workings" of the Institute involve many types of activity, and to many members who are not familiar with all of these activities, the administration of the Institute by its officers, committee members, staff, and others, appears as something complicated and difficult to understand. Of course, nothing could be further from the truth, and it is hoped that this discussion may serve to dispel any such impression.

Now it appears that the Institute works the way it does because of what it is and consequently that consideration should first be given to what the Institute is before proceeding to a discussion of how it works.

What the Institute is is defined by its objects and its membership. According to its constitution its objects are "The Advancement of the theory and practice of Electrical Engineering and of the allied Arts and Sciences and the maintenance of a high professional standing among its members." Its membership comprises electrical engineers by profession, professors and other teachers of electrical engineering and electrical subjects, persons who have done notable original work in electrical science, and others engaged in electrical or closely allied work. The membership is classified into Honorary Members, Fellows, Members, and Associates. The requirements for admission to the several membership grades are specified in the constitution, and it may be assumed that all members are familiar with them.

Objects

Now as to the objects of the Institute, there are a number of points to which attention should be directed. The first point is that the objects, as stated, proceed from broad unselfish motives rather than from narrow selfish ones. They are directed toward general social progress rather than mere class advancement. To the extent that these objects are directed toward advancement of the Institute's membership they are directed toward their professional rather than their economic advancement. They are based upon the principle that engineering is a profession and thus proclaim their origin in the principle of "noblesse oblige" which acknowledges the obligation of the professional man unselfishly to devote to the good of the social order some part of the advantages which that social order has enabled him to obtain. This principle, it seems to me, must be firmly maintained as the guiding principle of a professional life.

This does not mean that the Institute may not concern itself at all with the economic status of its members. It may and it does, but it does seem clear that such concern must be secondary to the primary concern of "maintaining their high *professional* standing." The primary concern of a professional engineering society must be to make better engineers. Better engineers will result in better engineering; better engineering should result in a better world and a better world must necessarily result in a better and happier life for all, including of course the engineers themselves. Thus the Institute's stated objects seem to require that whatever the Institute may do to promote the economic advancement of its membership it must do in the spirit that such action will be for the benefit, rather than at the expense, of other social groups and society as a whole.

Membership

Now as to the membership, the first point to which attention should be called is that the Institute is a society of individual engineers. Engineering work is peculiarly individual work because it is very largely the product of imagination, which is inherently an individual characteristic. The Institute is composed therefore of peculiarly individual individuals.

As a second point regarding the Institute's membership, suppose we take a look at engineers and see what kind of people they are. In general, it appears, engineers become engineers because they are interested in the forces of nature and enjoy the ability which the study of engineering gives them to direct those forces "for the use and convenience of man." That is, to the extent that they share the normal human desire for power and influence, they satisfy that desire by exercising that power and influence over the physical forces of nature rather than over their fellow men. Furthermore, I believe that the desire for wealth is not a typical characteristic of the engineer. He expects his work to be properly evaluated and compensated in proportion to its worth, but he is, in general, a sane and modest chap and has no delusions of grandeur or exaggerated idea of his importance in the social scheme. Possibly he is unduly modest and underrates his value but if so he gets his compensation in the pleasure he derives

Essentially full text of an address presented at the A.I.E.E. North Eastern District meeting, Worcester, Mass., May 16–18, 1934. *Not published in pamphlet form.*

from his work, and he is fortunate in having a kind of work to do in which he can take pleasure. That fact is one good reason why he owes something to the social order which has made it possible for him to acquire the knowledge which enables him to do interesting and pleasurable work. In that respect, at least, he has the advantage over the great majority of human beings. It is possible that when engineers, as they occasionally do, become unduly concerned in regard to their economic status as compared to other working groups, they forget this great advantage that they possess over most of those with whom they compare themselves. If so, they should remind themselves of it.

It is true, of course, that in times of economic stress, many engineers, in common with many workers in less attractive fields, are forced out of employment. Under such circumstances it is the duty of other engineers more fortunately situated to rally to their assistance. The engineer whom you help in time of trouble may be the very one who, in better days, provided you with an idea or an inspiration by way of the free exchange which takes place through the Institute, which enabled you to gain or hold the job which you have. Through your mere continued membership in the Institute, whether you know it or not, you have been of help to many unemployed engineers hard pressed during the recent depression, by enabling the Institute to be more lenient in the matter of delinquent dues.

Well, what has all this to do, you say, with the workings of the Institute? It has this to do. There are certain things the Institute can consistently do because it is what it is and because its members are what they are. There are certain other things the Institute cannot consistently do because it is not what it is not. It is not a labor union. It is not an organization of class conscious workers for the purpose of promoting their own economic self-interest. It cannot call a strike of its members in order to force an increase in their compensation. Probably no Institute member ever thought of such a thing, but nevertheless the Institute has been criticized on the ground that it hasn't done enough for the economic advantage of its members. The answer of course is that that is not what the Institute is for.

The prime function of the Institute, so far as its members are concerned is and always must be that of promoting their technical, professional, intellectual, cultural, and social advancement. It cannot consistently concern itself primarily with their economic condition as a class.

There is still another reason why a specialized engineering society like the A.I.E.E. cannot make the economic status of its members its primary concern. Engineering is *one* profession, not *many*. Its members may, and indeed must, specialize, to which fact the number of engineering societies amply testifies, but specialists though they be, they are engineers first and specialists afterward. When, therefore, such a specialized engineering group as the A.I.E.E. finds that it *must* act in the interest of the economic status of its members, the solidarity of the engineering profession requires that it do so through some joint agency with other engineering societies. As a matter of fact, the Institute does engage in certain activities of this character, which will be mentioned later on.

It was stated at the beginning that the Institute works the way it does because of what it is and an attempt has been made in the foregoing to give an interpretation of what the Institute is and why. We may now proceed to a discussion of "its workings."

Institute Management

In the first place, since the Institute is an organization of individuals, it must of course be and it is, a democratic institution. Every corporate member of the Institute, of whatever grade, has an equal right to vote. Its method of nominating and electing its officers is also thoroughly representative and democratic. Let us see how this is so.

The management of the Institute, as you know, is vested in a board of directors. This board consists of a president, 2 junior past-presidents, 10 vice presidents, 12 directors, and a treasurer. The national secretary also serves as secretary to the board but is not a member of it. The 10 vice presidents represent, respectively, the 10 geographic Districts and the nomination and election procedure is such that each District vice president is nominated by his own district. The president serves for 1 year, vice presidents serve for 2 years. The 12 directors are chosen at large, 3 being nominated and elected each year and they serve for 4 years.

Nomination of Officers

The nominating procedure is thoroughly democratic. Each Section chooses its own officers. Section chairmen and secretaries constitute the District executive committees. The national nominating committee consists of one representative from each geographic District, elected by its executive committee, and other members, not exceeding in number the number of geographic Districts, chosen by and from the board of directors. As a matter of fact, the board of directors has voluntarily limited its representation on the nominating committee to $^1/_2$ the number of geographic Districts so that as a matter of practice the nominating committee is dominated by the representatives of the geographic Districts and not at all by the board of directors. It is thus quite impossible for the board of directors to perpetuate itself or to "hand pick" the nominees even if it wanted to do so. The national nominating committee has nothing whatever to say about the nominations for vice presidents (of which 5 are elected each year) unless some District fails to nominate a candidate within the time provided by the by-laws, in which event the national nominating committee is empowered to act. The national nominating committee itself nominates only a candidate for president, 3 candidates for directors, and 1 candidate for national treasurer. The constitution provides that independent nominations may be made by the petition of 25 or more members sent to the national secretary, and that such petitions for the

nomination of a vice president shall be signed only by members within the District concerned. Thus, if any group of 25 or more members is dissatisfied with the candidates nominated by the District executive committee, or by the national nominating committee, they are entirely free to nominate independent candidates. The fact, however, that this is so seldom done is in itself an acknowledgment of the fairness and truly representative character of the nominating and election procedure as it now exists.

Summarizing, the national nominating committee of 15 includes only 5 members selected by the board of directors and this committee nominates only $^1/_2$ of the officers to be elected each year. Under these circumstances it seems quite clear that no small group can possibly control the nominations. The men who from year to year are chosen to the board of directors by this procedure, are of high caliber, and serve with unselfish devotion. They take their jobs seriously and render to the Institute a quality of service which does not in any degree suffer from the fact that it is rendered without pay.

Joint Activities of the Institute

The activities in which the Institute engages are many and various. These activities may be considered to be divided roughly into 2 classifications; first, internal activities primarily for the benefit of its own membership; second, joint and coöperative activities primarily for the benefit of the engineering profession, the country, and the world at large. The second group will be first briefly outlined and discussed. This group includes the following:

1. United Engineering Trustees, Inc., including Engineering Foundation and Engineering Societies Library
2. American Standards Association, including the Electrical Standards Committee, and the United States national committee of the International Electrotechnical Commission
3. Engineering Societies Employment Service
4. The American Engineering Council
5. The Engineers' Council for Professional Development

United Engineering Trustees, Inc.

The United Engineering Society, now known as United Engineering Trustees, Inc., was created in 1904 by the American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, and the American Institute of Electrical Engineers, to hold and administer for them jointly real estate and funds, "to advance the engineering arts and sciences in all their branches, and to maintain a free public engineering library." The American Society of Civil Engineers became a member of the group in 1916. Each society has 3 representatives on the board of trustees.

The United Engineering Trustees, Inc., holds the United Engineering Societies Building at 29–33 West 39th Street, New York City, and each founder society is assessed by the U.E.T., Inc., for building operation and maintenance in proportion to the amount of space occupied and pays additional amounts for actual use of the auditorium, other meeting rooms, public address system, etc. The present Institute budget contains an allowance of $3,000 for the building assessment. For the year which ended September 30, 1931, the actual payments amounted to $5,713.66.

The United Engineering Trustees, Inc., also holds the principal of the gifts of Doctor Swasey and others to the Engineering Foundation for safe-keeping and administration, but the net incomes are administered by the Engineering Foundation board.

Engineering Foundation

The Engineering Foundation is a joint agency of the founder societies "for the furtherance of research in engineering or for the advancement in any other manner of the profession of engineering and the good of mankind." It devotes its research to human as well as technical aspects of engineering problems of wide interest. The Foundation's aid to the advancement of the profession extends to activities aimed at both understanding and application of natural laws fundamental to both physics and ethics. Coöperation and effectiveness are keynotes of the Foundation's policies. They are personal traits of its founder, Dr. Ambrose Swasey, of Cleveland, Ohio.

The Institute makes no financial contributions to the Foundation's work; on the contrary, the Foundation furnishes assistance in connection with researches recommended by the Institute and other societies. During the past several years, it has supplied substantial financial assistance for 2 researches sponsored by our committee on electric welding, one at Massachusetts Institute of Technology and the other at Lehigh University. The former has been completed, and the latter is being continued.

The Engineering Foundation board, which administers the net incomes of funds set aside for its use, is composed of 16 members, including 2 representatives of each of the founder societies, 4 representatives of the United Engineering Trustees, Inc., 3 members at large, and the president of U.E.T., Inc., *ex-officio.*

Engineering Societies Library

The Engineering Societies Library, to the extent that it is not self-supporting, is supported by contributions from the 4 founder societies on the basis of an equal contribution from each plus an additional contribution from each society based upon its membership. The library board consists of 21 members: 4 appointed representatives of each society, the secretary of each society, and the director of the library.

American Standards Association

The American Standards Association, formerly known as the American Engineering Standards Committee, was organized in 1918 by the A.I.E.E. and 4 other societies. The American Standards Association is now composed of about 200 member

bodies. The Institute has representatives on many of the Association's committees and is sponsor or joint sponsor under the A.S.A. for a large number of standardization projects.

Under the A.S.A. procedure, all proposed electrical standards are referred to the association's Electrical Standards Committee on which the Institute is directly represented by 3 members with an alternate. There are many other individual members of the Institute on the Electrical Standards Committee as representative of various other groups, such as the electric light and power group and the National Electrical Manufacturers' Association.

The Electrical Standards Committee on which the Institute is thus largely represented also serves, with the addition of representatives from the American Society of Mechanical Engineers and a number of members at large (most of whom are also members of the Institute), as the U.S. national committee of the International Electrotechnical Commission, which is the agency through which international standardization projects in the electrical field are coordinated with American standards and practices.

Engineering Societies Employment Service

The Institute coöperates with the national societies of civil, mining, and mechanical engineers in the operation of the Engineering Societies Employment service with its main office in the Engineering Societies Building, New York. Offices are operated in Chicago and San Francisco also. In addition to the societies named, others coöperate in certain of the offices as follows: New York, Society of Naval Architects and Marine Engineers; Chicago, Western Society of Engineers; San Francisco, California Section of the American Chemical Society, and the Engineers' Club of San Francisco.

The New York office has been coöperating closely with the Professional Engineers Committee on Unemployment which was organized in the fall of 1931 by the local Sections of the A.S.C.E., A.I.M.E., A.S.M.E., and A.I.E.E.

The service is supported by the joint contributions of the societies and their individual members who are benefited. As in the past, it consists principally in acting as a medium for bringing together the employer and the employee. In addition to the publication of the employment service announcement monthly in Electrical Engineering, weekly subscription bulletins are issued for those seeking positions.

In 1929, the service was on a practically self-supporting basis, but as the number of positions available declined, and as a smaller percentage of the members placed were able to make the expected contributions toward the operating costs, it became necessary for the societies to increase their appropriations, as well as to reduce the costs of operation of the service.

The appropriations of the societies have for years been adjusted according to the numbers of placements among their respective members.

For the year ending September 30, 1931, the Institute expended for this service $1,226.22, and for the present budget year it has appropriated $4,000. The service is supervised by a committee composed of the secretaries of the 4 societies.

Prior to the establishment of the joint employment service, the staff of each society furnished assistance to its members who were seeking positions. Many members expect their society to make special efforts to secure positions for them, and the joint service has been more economical and satisfactory than the previous arrangement. It is certain that if the joint service were not available members of the Institute headquarters staff would find it necessary to spend far more time on employment matters.

(For an analysis of recent accomplishments of the Engineering Societies' Employment Service, see Table XI of the report of the Institute's board of directors for the fiscal year ending April 30, 1934, p. 1095–1107, this issue.)

American Engineering Council

The "object" of the American Engineering Council, as stated in its consitution, is "to further the public welfare wherever technical and engineering knowledge and experience are involved, and to consider and act upon matters of common concern to the engineering and allied technical professions."

The Council includes in its membership about 20 national, state, and local engineering societies and maintains it headquarters at Washington, D. C. Under the plan of reorganization recently adopted for the purpose of making further drastic reductions in the operating expenses of the Council, the assembly and the administrative board were combined, and the numbers of representatives reduced. The A.S.C.E., A.S.M.E., and the Institute now have 5 representatives each, 2 other societies have one each, and there are 6 regional representatives for state and local societies. In addition, past-presidents of Council serve for 6 years after the expiration of their terms as president without being accredited to any member organization.

It is interesting to note that 2 former members of the Institute board of directors were elected officers of the Council for 1934: C. O. Bickelhaupt, vice-president, and C. E. Stephens, treasurer. Our Past-President William McClellan is chairman of the finance committee, and hence is a member of the executive committee which is composed of the elected officers and the chairman of the finance committee.

Some of the subjects considered by the assembly-administrative board in January are:

Transfer of coast and geodetic survey to Navy Department

Employment conditions for engineers imposed by the Federal Government

Federal public works policy, governmental competition

Securities Act of 1933

Telephone directory classification of engineers

The wide variety of types of activities in which the Council engages is illustrated by the titles of the special committees which have been continued for 1934, as follows:

Administration of public works

Air transport service in foreign commerce

Communications

Competition of governmental agencies with engineers in private practice

Engineers' water power policy

Flood control

Naval towing tank

Patents

Relation of consumption, production, and distribution

State engineering councils

Telephone directory classification of engineers

Water resources

Committee to appear before coördination committee of founder societies

In his annual report, presented in January, L. W. Wallace, who resigned at that time as executive secretary, stated that in no like period in the Council's history had its assistance been sought as much as during 1933, and specifically after March 4. A large number of the Federal agencies called upon it for advice and for recommendations of engineers for many types of work. The Council has endeavored in so far as possible to protect the well-being of the engineering profession by encouraging any desirable developments and opposing those which were considered to be against the public welfare.

F. M. Feiker, who succeeded Mr. Wallace as executive secretary, in January, is anxious to have the Council become known as the "Washington Embassy" for engineers and engineering, and is intensively seeking ways in which it can most effectively serve the engineering profession and through it the public welfare.

Engineers' Council for Professional Development

This activity is undoubtedly the most important and far reaching movement for the advancement of the professional standing of engineers which has ever taken place. The following discussion of it is taken largely from the Council's first annual report, published Dec. 4, 1933.

The Engineers' Council for Professional Development, a new agency of the engineering profession, was brought into being in October 1932, by joint authorization of the American Society of Civil Engineers, the American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, the American Institute of Electrical Engineers, the American Institute of Chemical Engineers, the Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners.

The Council consists of 21 members, 3 from each of the participating bodies, from whom a chairman is elected, and a secretary, who need not be one of the representatives. Its purpose is the enhancement of the professional status of the engineer. To this end, it aims to coördinate and promote efforts and aspirations directed toward the higher professional standards of education and practice, greater solidarity of the profession, and greater effectiveness in dealing with technical, social, and economic problems. Its immediate objective is the development of a system whereby the progress of the young engineer toward professional standing can be recognized by the public, by the profession, and by the man himself through the development of technical and other qualifications which will enable him to meet minimum professional standards.

E.C.P.D. functions by studying questions within the range of its objectives, and making recommendations from time to time to the governing boards of the participating societies as to procedures that are considered of value in promoting such objectives. It will administer only such procedures as have been approved by the boards of the participating societies and assigned to it.

During its first year, the Engineers' Council for Professional Development perfected its organization and made far-reaching recommendations including (1) a program for accrediting engineering schools, (2) a minimum definition of the engineer, and (3) a suggested scheme looking to greater uniformity in the grades of membership in the professional societies. The Council has 4 standing committees.

The function of the committee on student selection and guidance is to report to E.C.P.D. schemes for the educational and vocational orientation of young men with respect to the characteristics of an engineering education and the responsibilities and opportunities of engineers in order that only those who have the high qualities, aptitude, and capacity required to obtain intellectual satisfaction therefrom may seek entrance to such courses.

The duties of the committee on engineering schools are to report to E.C.P.D. means for bringing about coöperation between the engineering profession and the engineering schools. As a first step in its activity, the committee has the duty of reporting to the Council criteria for colleges of engineering which will insure to their graduates a sound educational foundation for the practice of engineering. The Council voted to approve the recommendations of this committee and to recommend to the participating bodies that E.C.P.D. be set up as an accrediting agency for schools of engineering.

The duties of the committee on professional training are to report to E.C.P.D. plans for the further personal and professional development of young engineering graduates and young men entering the profession without formal scholastic training.

The committee on professional recognition is charged with the duty of reporting to E.C.P.D. methods whereby engineers who have met suitable standards may receive corresponding professional recognition. Upon recommendation of the committee, E.C.P.D. approved a definite policy as a guide in fulfilling the committee's purpose. This policy was outlined in an article "E.C.P.D. Committee on Professional Recognition Commented Upon by C. N. Lauer and Dean Barker," appearing in Electrical Engineering for January 1934, p. 224–5. This program involves selection of proper material, its supervised education, intimate contact with the profession during the apprenticeship stage, and the

attainment of definite specified educational requirements with concurrent recognition by professional societies, educational institutions, and state laws. The committee also has formulated a definition of an "engineer" which was approved by E.C.P.D., which voted to transmit it to the participating bodies for their discussion and approval. These minimum qualifications for an engineer also were given in the previously mentioned article in the January issue. At a recent meeting this committee adopted and recommended for approval "a practical program of certification covering the transition period, with progressive adjustment of requirements and successive tightening of standards, always keeping in view, as a goal, the early complete effectuation of the E.C.P.D. standards and program of individual certification as applied to new members of the profession."

It should be clearly understood that this program of E.C.P.D. is still in the formative stage and has not as yet been approved for adoption by the several sponsoring organizations. It cannot be adopted until it has the approval of the governing boards of all of those organizations. The proposals are receiving most careful and thorough consideration by the Institute's board of directors, but it would, of course, be premature to predict at this time what action the board will take. However, faced as we are, in many States, with licensing legislation, a uniform definition of an "engineer" and uniform procedures for certifying their eligibility appear highly desirable if a condition of chaos is to be avoided, and the professional standing of qualified engineers is to be uniformly recognized.

The problem of financing these activities has still to be worked out, but it is thought that they can be made self-supporting and at a social cost much less than would result from the alternative chaotic situation. It is not anticipated that the program will involve any direct expense to the Institute.

Internal Activities of the Institute

A lengthy discussion of Institute activities with which members are all familiar, such as its meetings, its publications, and its geographical District, Section, and Branch activities, is not included here. There are however 2 internal activities with which the membership at large have comparatively little direct contact, but whose personnel carry heavy responsibilities in promoting the effectiveness of the Institute in its service to its members. These are the Institute's committees and its headquarters staff.

There are 2 groups of standing committees.

General Committees

The general committees include the executive and finance committees and the board of examiners provided by the constitution, and 15 other committees dealing with the following subjects: technical programs, publications, coördination of Institute Activities, Sections, constitution and by-laws, Institute policy, headquarters, membership, standards, Edison medal, Lamme medal, award of Institute prizes, safety codes, code of principles of professional conduct, and Student Branches. In addition to these standing committees, special committees are appointed from time to time to consider matters not within the scope of the standing committees.

Technical Committees

There are 18 technical committees on the following subjects: automatic stations, communication, education, electrical machinery, electric welding, electrochemistry and electrometallurgy, electrophysics, instruments and measurements, applications to iron and steel production, production and application of light, applications to marine work, power generation, power transmission and distribution, protective devices, research, and transportation.

Any attempt to visualize the tremendous mass of work performed by these committees must be left to the reader's imagination. Some of course are more active than others, but many of them hold several meetings a year, and many of them have subcommittees which also hold independent meetings. Much work is done also by correspondence. The personnel of the general committees comprises about 200 men and the technical committees about 375. There are some duplications in these numbers but on the other hand there are probably many others working on subcommittees who do not appear in the published lists. It is probably safe to say that from 500 to 600 Institute members are actively engaged in committee work.

We should all bear in mind that these 500 or 600 men who are giving of their knowledge, experience, and energy for the benefit of the entire membership, are just members like ourselves. They pay no less in dues than other members and they receive no monetary compensation whatever for their committee work; in fact, in many cases it causes them additional expense. In spite of these facts however, these 500 or 600 members who give their time and energy to committee work are the ones who are getting the most out of their Institute membership. This, however, does not alter the fact that the Institute and its members owe them a debt of gratitude. Without their contribution to its work the Institute could hardly function at all.

Of all the Institute committees, the one which has probably faced the most difficult task during the last 4 years has been the finance committee of which E. B. Meyer is chairman. The finance committee has the task of fitting the Institute's expenses to its income, and with the reduction which this income has undergone, this committee has had most difficult problems to solve. How some of these problems have been met Mr. Meyer has told in his article "The Story of the Institute Budget" in the March 1934 issue of Electrical Engineering, p. 375–81. Every member who has not already done so should read and study Mr. Meyer's article. Every member of the Institute should understand its financial problems and how they are dealt with and especially so if he ever feels inclined to criticize the distribution of its income.

It is true that in the past the opportunities for participation in technical committee work have been somewhat limited. However, under the leadership of I. Melville Stein of Philadelphia, chairman of the Institute Sections committee, a definite plan for Section participation in technical committee work has been proposed and is scheduled for discussion at the conference of officers and delegates at the coming midsummer convention. The plan is outlined in the April 1934 issue of ELECTRICAL ENGINEERING, p. 631. The plan provides an opportunity for every Section member desiring to do so to participate in technical committee work, and is worthy of careful consideration by every member of the Institute.

THE HEADQUARTERS STAFF AND ITS DUTIES

On May 1, 1902, 18 years after its organization, the Institute had a membership of only 1,549, and was the smallest of the 4 societies of civil, electrical, mechanical, and mining engineers. The very rapid increase in membership, after the establishment in that year of the provisions for Sections and Branches, made it the largest of the 4 societies less than 5 years later (4,000 members). (It retained that distinction until 1915.) The rapid increase in membership, which continued at varying rates for many years and the accompanying expansions of the activities required the building up of a staff which would be able to render effectively all of the many types of services demanded of the headquarters of such a society.

With a membership of 3,027 in 1904 (May 1), the Institute had a staff of 10 persons. By 1917, the membership had increased to 8,710 (May 1) and the staff to 17. The membership of more than 18,000 which was maintained from the early part of 1926 until reductions were caused by the depression, and some further expansions in the activities, caused the total number of staff members to reach 36 in 1929.

On account of the decreased income, the acting national secretary and the office manager recommended some reductions in staff at the end of 1932, and did not fill a vacancy which occurred in 1933. These changes reduced the staff to a total number of 26. The reductions were made despite the fact that the revised publication plan required more persons in the editorial department than in 1929, and the fact that other essential parts of the work have been made materially heavier by the depression, notably correspondence regarding inability to pay dues, and the answering of many inquiries which result directly from the large amount of time many individuals have available.

Since 1904, the numbers of Sections and Branches have increased from 16 and 11, respectively, to 61 and 113. The number of committees has likewise been greatly increased, and the activities in general have been expanded in many directions.

Members of the staff carrying the principal responsibilities are:

H. H. Henline, national secretary

F. A. Norris, office manager

G. Ross Henninger, editor

H. E. Farrer, secretary, board of examiners
secretary, standards committee

C. A. Graef, advertising manager

C. S. Rich, secretary, technical program committee

Of these, it is worthy of note that Messrs. Henline and Henninger are Members and Messrs. Farrer and Rich Associates of the Institute.

In addition, there are 4 editorial workers, 3 of whom are Associates; 3 junior clerks who perform a wide variety of duties, including addressograph, mimeograph, mailing, stock, and messenger services; and 13 other persons who are engaged in the entire range of work required of the staff.

The duties of the staff embrace a mass of detail work in connection with ELECTRICAL ENGINEERING and the TRANSACTIONS, advertising, the Year Book, the 61 Sections and 113 Branches, general administration, joint activities, secretarial and other work for committees, etc. These duties include editing and proof-reading, correspondence, record keeping, billing, indexing, preparation of annual and other reports, mailing, interviewing, arranging for meetings and conventions, accounting, filing, shipping, assistance in preparation of budget, and others too numerous to mention. A mere catalog of the specific services required of the staff comprises over 4 typewritten pages.

It always has been the practice to keep the staff at the minimum number of persons required for performing the necessary duties. Accounting, members' records, correspondence, and all other parts of the work have been kept on the simplest possible basis. The variety of duties required of the limited staff makes it essential that the assignments be arranged on a flexible basis. No member of the staff is limited entirely to one particular type of work, except in editorial and advertising, but each has been thoroughly trained in other duties, and practically all have had years of experience in Institute methods. Consequently, the distribution of duties can readily be shifted from day to day, and the services can be maintained with a minimum payroll cost per member of the Institute.

That the Institute is not overstaffed is indicated by a recent comparison of the staffs of the 4 large national engineering societies, which shows the following:

	A.I.E.E.	A.S.C.E.	A.I.M.E.	A.S.M.E.
Total number of employees	26	52	23	63

SECTIONS AND BRANCHES

Before concluding, a few statements should be made regarding the relationship of the Sections and Student Branches to the Institute. Student enrollment in the Institute was initiated in order that the young men training to become engineers might be kept informed as to the latest developments in the various fields of electrical engineering, so that their transition from student life to professional life might be made gradually rather than abruptly. It was felt that, by this means, these young men would be greatly assisted in "finding themselves"

in the professional field, thereby not only accelerating their individual professional progress but also enhancing the standing of the profession as a whole. That this purpose is being accomplished will be readily admitted by any one who has attended a Student session at any of our meetings. The provision of student meetings conducted on a professional basis by the Branches can add tremendously to the effectiveness of this development. The very moderate fees paid by Enrolled Students obviously do not cover the entire cost of this service, which includes sending ELECTRICAL ENGINEERING to each Enrolled Student, but the Institute has faith that the bread so cast upon the waters will return again after many days in the form of an enthusiastic membership imbued with the professional spirit. I think there is no service which the Institute renders that is more worth while.

Now as to the Sections; they were organized in order that a larger proportion of the Institute membership might have the opportunity, by meeting together, to promote the objectives of the Institute. These objectives imply, as already pointed out, an attitude of unselfish service to the profession, to the nation, and to the world. Now not all members of the Institute are fortunate enough to be able to participate in Section activities. Only about $^2/_3$ of the membership even resides in Section territory. Section members and officers might do well to remember this fact when they feel inclined to be dissatisfied with the degree of financial support accorded their activities, by the Institute. I am sure they would not want to feel that they were promoting their own local interests at the expense of other members unable to enjoy like privileges.

Now of course there are many Section activities which do, directly or indirectly benefit the Institute as a whole. Surely no one will deny the value to the Institute of the splendid work of the Section membership committees, and occasional social activities which assist in obtaining desirable members are, without doubt, of benefit to the Institute as a whole as well as to the individual Sections. No hard and fast rules can be laid down. The important thing is that members fortunate enough to be able to enjoy participation in Section activities might well bear in mind that after all, the principal functions and activities of the Institute must be carried out on a national, or perhaps I should say continental basis, and that in the long run the Section members will benefit most by so planning and conducting their Section affairs *as to contribute to*, as well as enjoy the benefits of these broader activities. They owe this much to that $^1/_3$ of the membership who help to pay their cost without being able to participate in them.

To sum up the whole matter, an insight into the "workings" of the Institute seems to reveal that its aims and activities are rooted in a spirit of mutual helpfulness to each other and disinterested service to humanity. Its officers, its headquarters staff and those who work on its committees all share in that spirit. The principal obligation of membership, it seems, is to cultivate that spirit, the possession of which, after all is said and done, yields the most lasting satisfactions of the professional life.

Resonant Lines in Radio Circuits

Resonant transmission lines may be used as circuit elements in the ultra-short wave range as a means of obtaining high impedance with low loss. The lines may be of either concentric tubes or 2 wires, and are sufficiently small that they may be placed within the apparatus. These circuits can be made highly selective, and when used to control oscillator frequency will give stability comparable to that of a crystal. The mathematical relations governing their operation and several applications are discussed in this paper.

By
FREDERICK EMMONS TERMAN
ASSOCIATE A.I.E.E. Stanford Univ., California

AT THE HIGHER frequencies now used in radio communication and, in particular, at frequencies above 30 megacycles it is possible and sometimes highly desirable to replace the usual circuit elements by resonant transmission lines. At these high frequencies the wave length is so small that resonant lines are of reasonable physical dimensions and, when properly built, have low losses and a large circulating voltampere capacity.

The principal uses that thus far have been made of resonant transmission lines are with high frequency oscillators. Engineers of the Radio Corporation of America have used long resonant lines to replace the oscillator tank circuit, and equipment embodying this principle is being used in the telephone system connecting the Hawaiian Islands.[1] Mouromtseff and Noble have designed a water cooled tube in such a way that the grid and plate structures are part of a half wave length resonant line which is used as the tank circuit of the oscillator. With this arrangement it is possible to obtain frequencies about twice as high as can be realized with the same tube in a conventional circuit.[2]

It is the purpose of the present paper to present the fundamental properties of resonant lines when used as substitutes for the circuit elements commonly employed at high frequencies. In particular,

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. Pacific Coast convention, Salt Lake City, Utah, Sept. 3–7, 1934. Manuscript submitted April 30, 1934; released for publication May 16, 1934. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

the possibilities of resonant lines as a means of developing high impedances, highly selective circuits, low loss inductances and capacitances, and high voltage step-up ratios will be investigated, and the best proportions for each purpose determined.

Fundamental Relations

Resonant lines may be either open- or short-circuited at the receiver. The voltage and current distributions that result for these cases are shown in Fig. 1. These curves are discussed in many textbooks and so need not be considered in detail here. It is sufficient to call attention to the fact that with an open circuited receiver the voltage is low at points that are an odd number of quarter wave lengths distant from the receiver, and high at points at an even number of quarter wave lengths. For the short-circuited receiver the relations are the opposite; the voltage is low at points of high voltage for the open-circuited receiver, and *vice versa*. The current distribution for the open-circuited receiver is exactly the same as the voltage distribution for the short-circuited receiver; conversely the current distribution for the short-circuited receiver follows the same law as the voltage distribution for the open-circuited receiver. In dealing with resonance phenomena in transmission lines, the receiving end of the line always is chosen as the reference point. This is because the resonances arise as a result of reflections at the receiver and the maxima and minima in the standing wave patterns are hence always an exact multiple of a quarter wave length from the receiver.

The impedance of the line looking toward the receiver follows the voltage distribution in a general way, being high or low depending upon whether the voltage is at a maximum or minimum. The curves of impedance and power factor also are given in Fig. 1. It will be observed that the power factor passes through unity whenever either the voltage or current is at a minimum, but is very nearly 90 deg leading or lagging for other conditions.

The formulas giving the properties of resonant lines are to be found in all books on transmission line theory and are

For open circuit at receiver

$$E_s = E_r \cosh(\alpha + j\beta)\, l$$
$$I_s = \frac{E_r}{Z_0} \sinh(\alpha + j\beta)\, l \qquad (1a)$$
$$Z_s = \frac{E_s}{I_s} = \frac{Z_0}{\tanh(\alpha + j\beta)\, l}$$

For short circuit at receiver

$$E_s = I_r Z_0 \sinh(\alpha + j\beta)\, l$$
$$I_s = I_r \cosh(\alpha + j\beta)\, l \qquad (1b)$$
$$Z_s = \frac{E_s}{I_s} = Z_0 \tanh(\alpha + j\beta)\, l$$

where

E_s = sending end voltage
E_r = receiving end voltage
I_s = sending end current
I_r = receiving end current
Z_s = impedance at sending end looking toward receiver
Z_0 = characteristic impedance of line
$\alpha + j\beta$ = propagation constant of line
l = line length

At high frequencies, such as are of interest here, the propagation constant $(\alpha + j\beta)$ takes the following simplified form:[3]

$$\alpha + j\beta = \frac{R}{2Z_0} + \frac{GZ_0}{2} + j\frac{2\pi}{\lambda} \qquad (2)$$

where

R = resistance in ohms per unit length
Z_0 = characteristic impedance in ohms
G = leakage conductance in mhos per unit length
λ = length corresponding to one wave length

At radio frequencies the characteristic impedance is almost exactly a pure resistance having a value $Z_0 = \sqrt{L/C}$, and the wave length with air insulation corresponds extremely closely to the wave length calculated on the basis of the velocity of light, *i. e.*, λ = (velocity of light)/frequency.

As a result of the fact that the characteristic impedance is real, the only imaginary term in the right-hand side of eq 2 is the last term, so that

$$\beta = \frac{2\pi}{\lambda} = \frac{2\pi f}{c} \qquad (3)$$

where c is the velocity of light and f is the frequency. Likewise, if the leakage conductance is assumed to be zero, which is always the case in well constructed radio frequency transmission lines, the attenuation constant α is given by the first term on the right-hand side of eq 2 and so becomes

$$\alpha = \frac{R}{2Z_0} \qquad (4)$$

The characteristic impedance Z_0 for concentric tube and 2-wire transmission lines is readily calculated by the usual formulas:

$$\left.\begin{array}{l}\text{Characteristic impedance for}\\ \text{concentric tube line}\end{array}\right\} = 138 \log_{10}\frac{b}{a} \qquad (5a)$$

$$\left.\begin{array}{l}\text{Characteristic impedance for}\\ \text{2-wire line}\end{array}\right\} = 276 \log_{10}\frac{b}{a} \qquad (5b)$$

where

b = inner radius of outer conductor in concentric tube line or the spacing between wire centers with a 2-wire line
a = outer radius of inner conductor in a concentric tube line, or the conductor radius in a 2-wire line

The resistance R that appears in eqs 2 and 4 can be readily calculated at radio frequencies for the usual types of lines because the skin effect is so great at these frequencies that the skin depth is very small. In general, when the skin depth is small compared with the radius of curvature of the conductor surface, the resistance of the conductor is equal to the resistance of a surface layer having a depth which for copper is $6.62/\sqrt{f}$ cm. With a concentric tube transmission line this results in a resistance per unit line given by the following formula

$$R = 41.6\sqrt{f}\left(\frac{1}{a} + \frac{1}{b}\right) \times 10^{-9} \text{ ohms per cm} \qquad (6)$$

where

b = inner radius of outer conductor in centimeters
a = outer radius of inner conductor in centimeters
f = frequency in cycles

In the case of a 2-wire transmission line with large conductor spacing, the resistance, taking into ac-

count skin effect, is twice the resistance of a single wire considered as an isolated conductor and so becomes

$$R = 83.2 \frac{\sqrt{f}}{a} \times 10^{-9} \text{ ohms per cm} \tag{7}$$

The notation is the same as in eq 5 except that a is now the radius of the conductor, in centimeters. When the 2 wires are reasonably close together, the actual resistance is somewhat higher than given by eq 7 because of the proximity effect which results in each of the wires inducing eddy currents in the other wire. The proximity factor can be taken into account by multiplying the resistance calculated from eq 7 by the factor given in Fig. 2.[4]

All of the fundamental factors required to obtain an analysis of the properties of resonant transmission lines at high frequencies now have been considered. Equations 1a and 1b give the voltage, current, and impedance relations existing on the line in terms of the line length, frequency, and line constants. Equations 3 and 4 give the wave length constant and the attenuation factor while eqs 6 and 7 give the resistance of the line at high frequencies. These fundamentals now will be applied to the solution of various problems involving resonant transmission lines.

Resonant Transmission Lines as High Impedance Devices

Resonant transmission lines can be used as interstage coupling devices for vacuum tube amplifiers

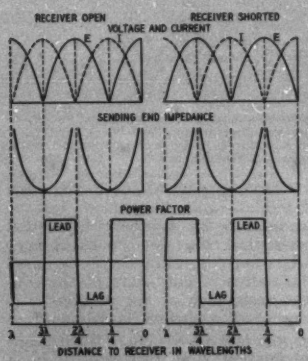


Fig. 1. Voltage, current, sending end impedance, and sending end power factor of resonant transmission lines as functions of distance from receiver

in place of the parallel resonant circuit normally employed. At high frequencies resonant lines have the advantage of giving greater impedance and greater selectivity than are obtainable with a parallel tuned circuit, and appear to have real possibilities in the receiver art.

A resonant transmission line developing a high impedance may consist either of a line an odd number of quarter wave lengths long and short-circuited at the receiver or an even number of quarter wave lengths long and open-circuited at the receiver, as is apparent from Fig. 1. In Appendix I it is shown that by a manipulation of eqs 1 and 2 the sending end impedance for both cases is

$$Z_s = \frac{8Z_0 f}{Rnc} \tag{8}$$

where

Z_s = sending end impedance of the line
Z_0 = characteristic impedance of the line
f = frequency
R = line resistance per unit length
n = number of quarter wave lengths in the line
c = velocity of light

This is the general expression for the sending end impedance when the line is of such a length as to give a high impedance.

In the particular case of a concentric tube line it is advantageous to rearrange eq 8 by making use of eqs 5a and 6. As shown in Appendix I this gives

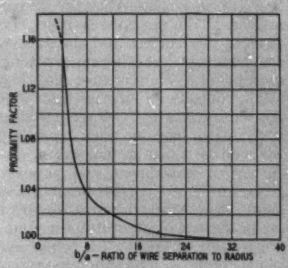
$$Z_s = \frac{122.2\sqrt{f}\,b}{n}\left[\frac{(\log_{10} b/a)^2}{1 + b/a}\right] \tag{9}$$

where

b = inner radius of outer conductor in cm
a = outer radius of inner conductor in cm

Examination of this equation yields some very interesting and important results. In the first place,

Fig. 2. Proximity effect factor for 2-wire line with wires spaced closely



it may be noted that the sending end impedance obtainable is inversely proportional to the number of quarter wave lengths involved in the line, is directly proportional to the diameter of the outer conductor, is proportional to $\sqrt{f}$, and is a function of the line proportions (b/a). For any given outer diameter there is a best diameter for the inner conductor. This best proportion is $b/a = 9.2$, but is not particularly critical with respect to line proportions as can be seen from Fig. 3. One now may rewrite eq 8 in a very convenient form:

$$Z_s = \frac{11.11\sqrt{f}\,b}{n} F \tag{9a}$$

where F is the factor given by Fig. 3, and with optimum line proportions will be equal to 1.

Substituting reasonable numerical values in eq 9a shows that extremely high impedances are readily obtainable at high frequencies. Thus for $b = 1$ cm, $f = 60 \times 10^6$ cycles, $n = 1$, and $F = 1$ (optimum proportions), it is found that $Z_s = 86{,}000$. It may

be noted that this line is so small that it can be coiled up and used in a radio receiver or portable transmitter. If the line diameter is enlarged to 10 cm, the sending impedance is 860,000 ohms, a truly enormous impedance at a frequency of 60×10^6 cycles per second.

Equation 8 indicates that the sending end impedance increases proportionally to $\sqrt{f}$. This behavior is the opposite of that of ordinary circuits and is correspondingly important. It comes about because, although the resistance per unit length increases with frequency, the increase is proportional to $\sqrt{f}$, whereas the length of the conductor involved is inversely proportional to frequency.

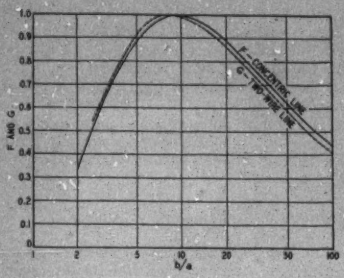
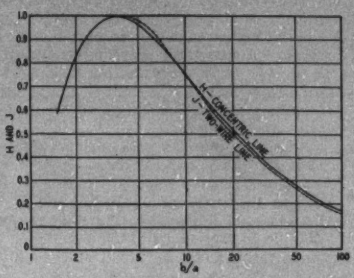


Fig. 3 (left). Factors F and G as functions of b/a, giving the relative impedance of a resonant line

Fig. 4 (right). Factors H and J as functions of b/a, giving the relative selectivity factor of a resonant line



A 2-wire transmission line exhibits exactly the same type of behavior as the concentric tube line although the formula differs slightly. It is shown in Appendix I that for this case

$$Z_s = \frac{23.95\sqrt{f}\,b}{n}\,G \tag{9b}$$

where G is a factor given in Fig. 3, and b is the wire spacing in centimeters. The optimum proportions here are $b/a = 8.0$, but are not critical.

The impedance possibilities of resonant lines at frequencies such as 10 megacycles and higher can be summarized as follows: An impedance in the order of 100,000 ohms or more is readily obtainable with reasonable proportions. The sending end impedance obtainable is greater the higher the frequency and is also directly proportional to the outside dimension of the line. The highest impedance is obtained when the line is a quarter wave length long short-circuited at the receiver, and for highest impedance there is an optimum proportion.

High Impedance Resonant Lines as Selective Circuits

The selectivity of a high impedance such as obtained by a quarter wave length resonant line can be thought of as a measure of the extent to which the impedance varies with frequency in the region around exact resonance. This variation of impedance with frequency is a property more or less independent of the magnitude of the impedance obtained and so must be considered separately. In particular, the conditions that give maximum selectivity are not the same as those that give maximum impedance.

It is shown in Appendix II that as frequency is varied slightly about resonance the impedance of a line varies according to exactly the same law as does the impedance of an ordinary parallel resonant circuit. The selectivity around the resonant frequency is hence expressible in terms of an equivalent selectivity factor, Q, just as is the selectivity of ordinary resonant circuits.[6] The value of Q that results is derived in Appendix II, and is

$$Q = \frac{2\pi Z_0 f}{Rc} \tag{10}$$

In the particular case of concentric lines the formula may be made more usable by substituting for Z_0 and R from eqs 5 and 6. This yields

$$Q = 0.694\sqrt{f}\,b\left(\frac{\log_{10} b/a}{1 + b/a}\right) \tag{11}$$

$$= 0.0839\sqrt{f}\,b\,H \tag{11a}$$

where the notation is the same as previously used with concentric lines with the addition that H is a factor given in Fig. 4. As may be seen, Q is proportional to $\sqrt{f}$, is proportional to the diameter b of the outer conductor, is a function of the line proportions (b/a), and is independent of the number of quarter wave lengths involved in the line. It is particularly interesting to note that, unlike ordinary circuits, the selectivity factor, Q, tends to become larger the greater the frequency.

The value of Q will be greatest when the line proportions make Z_0/R in eq 10 a maximum. Inspection of eq 4 shows that this is also the requirement for minimum attenuation factor, α, which already is known to occur when $b/a = 3.6$ for concentric lines.[4]

A 2-wire line exhibits exactly the same selectivity characteristics as a concentric tube line, although the numerical coefficients differ. It is shown in Appendix II that the equation for the 2-wire line corresponding to eq 11a is

$$Q = 0.0887\sqrt{f}\,bJ \tag{12}$$

where J is a factor given in Fig. 4. The line proportions are optimum when $b/a = 2.72$ if the prox-

imity effect is neglected, or when the ratio is between 3 and 4 if the proximity effect is included.

Substitution of reasonable numerical values in eqs 11 and 12 shows that the value of Q obtainable with resonant lines is surprisingly large at frequencies in the short wave and ultra-short wave range. For example, a quarter wave length concentric line 1 cm in outer diameter, of optimum proportions, and operating at 60 megacycles, has an equivalent selectivity factor, Q, of 650, and if the diameter is increased to 10 cm Q becomes 6,500. These values are much higher than can be obtained with ordinary resonant circuits, and are comparable to or exceed the effective selectivity of quartz crystal vibrators. It thus appears that resonant lines are as effective as a quartz crystal for stabilizing the frequency of a short wave oscillator.

In ordinary parallel resonant circuits the resonant impedance can be expressed as $Q\omega L$, where ωL is the reactance of the inductive branch of the circuit and Q is the ratio of ωL to the circuit resistance. An analogous expression can be obtained for a resonant transmission line by combining eqs 8 and 10 with the interesting and useful result

$$Z_s = \left(\frac{4Z_0}{\pi n}\right) Q \tag{13}$$

In summarizing the selectivity properties of resonant lines the most noteworthy points to consider are the differences in requirements for maximum selectivity as against maximum impedance. In general the best proportions are distinctly different, a lower characteristic impedance being preferable for maximum selectivity. The selectivity is also independent of the number of quarter wave lengths involved in the line whereas the impedance is inversely proportional to the number of quarter wave lengths. However, the selectivity and impedance both vary with frequency and dimension b in the same way.

Resonant Lines as Voltage Step-Up Devices

An important use of an ordinary resonant circuit is as a voltage step-up device employing the well-known resonance rise of voltage existing in a series circuit. A transmission line can be used for the same purpose. The idea is to use an open-circuited receiver and a line an odd number of quarter wave lengths long, in which case the resonance rise of voltage is from the sending end to the receiving end, or else to employ a short-circuited receiver and a line that is an even number of quarter wave lengths long, in which case the resonant rise of voltage is from the sending end to a point an odd quarter of a wave length from the sending end.

The voltage step-up properties of such lines can be determined by making use of the fundamental equations of the line, and reducing them to a form that will permit ready interpretation for this special case. This is done in Appendix III and yields the following result:

$$\text{Ratio of voltage step-up} = \frac{8Z_0 f}{Rnc} \tag{14}$$

Likewise it is shown in the same appendix that the voltage step-up ratio in the vicinity of resonance has exactly the same type of selectivity characteristic as the voltage step-up in an ordinary resonant circuit, so that the voltage rise effect may be said to have an effective selectivity factor that can be expressed by the following equation

$$Q = \frac{2\pi Z_0 f}{Rc} \tag{15}$$

It may be observed that Q is exactly the same here as for the same line when used as a high impedance device. A comparison of eqs 14 and 15 shows that the step-up obtainable is $(4/\pi n)Q$. It should be noted that the step-up ratio is greatest when the line is only a quarter wave length long and is not Q as in a simple series circuit. Inasmuch as the selectivity of resonant lines can be made high, the voltage step-up obtainable is correspondingly large and, unlike ordinary circuits, tends to increase as the frequency is increased.

Resonant Lines as Low Loss Reactances

When a line that is either open- or short-circuited at the receiver is not an exact multiple of a quarter wave length long the sending end impedance is primarily reactive with a low power factor. The impedance is inductive in a short-circuited receiver when the line is shorter than an odd number of quarter wave lengths and longer than an even number. With an open-circuited receiver an inductive reactance is obtained with the line longer than an odd number of quarter wave lengths, and shorter than an even number. This is shown in Fig. 1. The important practical case is for inductive rather than capacitive reactance, because low loss capacitive reactances can be obtained readily by conventional methods, whereas low loss inductive reactances are difficult to achieve at high frequencies. The inductive case is also important because in a circuit where a resonant line is used to develop a high impedance in association with a vacuum tube, the tube electrode capacitance requires that the line have an inductive reactance in order that the combination of line and tube may give resonance.

The nature of the reactances obtainable can be ascertained by rearranging the general equation for sending end impedance and neglecting terms that are important only at or very near resonance. This has been done in Appendix IV and gives:

For a short-circuited receiver:

$$Z_s = \frac{Rc\,\frac{l}{\lambda}}{2f\cos^2 2\pi\left(\frac{l}{\lambda}\right)} + jZ_0 \tan\left(2\pi\,\frac{l}{\lambda}\right) \tag{16a}$$

For an open-circuited receiver:

$$Z_s = \frac{Rc\,\frac{l}{\lambda}}{2f\sin^2 2\pi\left(\frac{l}{\lambda}\right)} - j\,\frac{Z_0}{\tan\left(2\pi\,\frac{l}{\lambda}\right)} \tag{16b}$$

The notation is the same that already has been used with the addition that (l/λ) is the line length measured in wave lengths. The equation does not hold of course when (l/λ) approaches an integral multiple

of a quarter wave length. It may be noted that the reactive component of the impedance is proportional to the characteristic impedance Z_0, and varies cyclically with line length. The reactance can be controlled either by varying Z_0 or the length, and may be varied from perhaps $^1/_{10}$ to 10 times the characteristic impedance.

The ratio of reactance to resistance components of the sending end impedance can be called the selectivity factor of the reactance, and for both terminations is

$$Q = \frac{Z_0 f}{Rc} \frac{\sin\left(4\pi \frac{l}{\lambda}\right)}{\frac{l}{\lambda}} \tag{17}$$

Comparison of eqs 10 and 17 shows that Q varies with line proportions and frequency according to the same law for both the impedance of the resonant

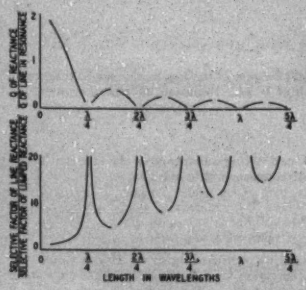


Fig. 5. Effect of line length on selective characteristics of reactances of lines

line and the reactance of the line when not in resonance. The value of Q now varies cyclically with length, however, with a general lower trend as length increases. This is shown in Fig. 5, which gives values of Q for the reactance of a line not in resonance divided by values of Q for a resonant line of the same construction, and at the same frequency. It is apparent that the "Q" of the reactance compares favorably with that of resonant lines. Also, the lowest loss inductive reactance is obtained when a short-circuited line less than a quarter wave length long is used, and the lowest loss capacitive reactance when an open line less than a quarter wave length long is used. Longer lines than these can be arranged to give the same reactance, but will have greater losses.

The reactances obtained from lines can be used in the same way as those of ordinary coils and condensers, and as far as everything except selectivity is concerned the equations and laws for lumped circuits hold without change. When lumped coils and condensers are associated with the line, it is necessary to include the losses in these elements in the calculations; and these extra losses are commonly more than the line losses unless unusual precautions are taken. In particular, when a line is combined with the tube capacitance to give resonance, the losses in the tube leads will dominate the situation unless the tube is properly constructed.

Improved Selectivity Characteristics

The selectivity characteristics of circuits involving reactances derived from lines are not the same as when ordinary lumped reactances are used, however. This is because the reactance obtained from lines varies more rapidly with frequency than does the reactance of an ordinary condenser or coil. *As a result, a reactance having a certain magnitude and "Q" has greater effective selectivity than does a lumped reactance having the same magnitude and "Q".* The magnitude of this effect is computed in Appendix V, and is

$$\frac{\text{Selective factor of line reactance}}{\text{Selective factor of lumped reactance}} = \frac{4\pi \frac{l}{\lambda}}{\sin\left(4\pi \frac{l}{\lambda}\right)} \tag{18}$$

If the line length is very small this factor becomes unity as might be expected, but otherwise the factor is greater than unity and tends to become very great when the line is long. Equation 18 is plotted in Fig. 5.

The use of eq 18 can be illustrated by a specific example. Assume $l/\lambda = 0.2$; then the factor is 4.25. If the line reactance now is tuned to resonance by a lossless condenser the effective selectivity factor of the circuit will be $(4.25 + 1)/2 = 2.62$ times as great as it would be if the line were replaced by a coil having the same ratio of reactance to resistance.

The real merit of a line reactance from the point of view of selectivity is the ratio of rate of change of reactance to the effective resistance. This can be shown to vary cyclically, repeating every even multiple of a quarter wave length. Thus a line 0.7 wave length long has as good selectivity characteristics as a reactance obtained from a line of 0.2 wave length, although in the latter Q as given from eq 17 is greater and the resonant impedance and resonant step-up effects likewise are greater.

Suggested Applications

It has been demonstrated that resonant lines can be used to replace ordinary circuit elements and tuned circuits, and that the performance of resonant lines at the higher frequencies used in radio communication is vastly superior to that of any ordinary type of circuit or circuit element. At wave lengths in the order of 10 m it is a simple matter to obtain resonant impedance in excess of 100,000 ohms and to obtain resonant impedances, resonant step-up effects, and either inductive or capacitive reactances that have an effective circuit selectivity factor Q ranging from 500 to perhaps 5,000. Unlike ordinary circuit elements, the resonant lines perform better the higher the frequency. The full possibilities of resonant lines can be obtained only when they are designed properly. There is a best proportion that gives the highest values of Q, and there is also a different proportion that gives the highest impedance.

Possible applications of resonant lines to ultra-

short wave radio technique appear to be almost without limit, since at these high frequencies resonant lines can out-perform any circuit employing lumped elements, and at the same time are so compact as to be usable even in small receivers by the expedient of using a coiled concentric line.

A few of the possible applications that immediately suggest themselves are shown in Fig. 6. In

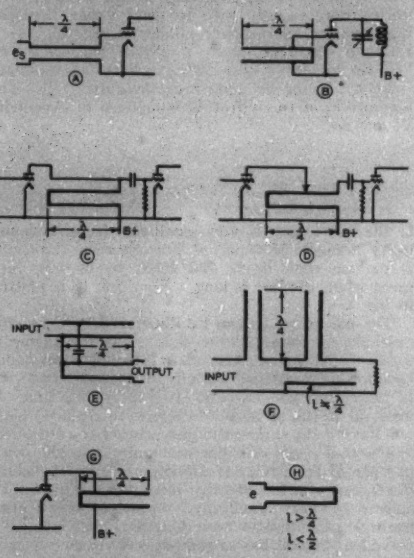


Fig. 6. Applications for resonant lines

A. Line as step-up circuit
B. Line as oscillator frequency control
C and D. Line as interstage coupling device
E and F. Line as band pass filter
G. Line as power amplifier tank circuit
H. Line as condenser that will pass direct current

the case of the oscillator frequency control arrangement (*b*) it is possible, by coupling the oscillator near the shorted end of the line so that only a small effect is reflected into the resonant line, to obtain frequency stability comparable to or better than that given by a crystal. Temperature effects can be made practically nil by using a construction and mounting such that the line length cannot change with temperature. At (e) in Fig. 6 are shown 2 resonant lines loosely coupled together to serve as a band pass filter such as commonly is used in radio receivers; and at (f) is shown a simple band pass filter of the type commonly used in telephone carrier work, with the 2 quarter wave lines acting as series resonant circuits, and the shunt line serving as a capacitance or inductance as desired. At (h) is indicated a line arranged to function as a capacitive reactance and *yet pass direct current*, a common need in many tube circuits.

Appendix I—Derivation of Equations for Impedance of Resonant Lines

For an open-circuited receiver the sending end impedance is

$$Z_s = \frac{Z_0}{\tanh(\alpha l + j\beta l)} \tag{19}$$

But βl is an exact multiple of π, so that this can be rewritten as

$$Z_s = \frac{Z_0}{\tanh \alpha l} \tag{20}$$

For the short-circuited case the sending end impedance is

$$Z_s = Z_0 \tanh(\alpha l + j\beta l) \tag{19a}$$

However, here βl is an odd multiple of $\pi/2$, so eq 19a can be written as

$$Z_s = \frac{Z_0}{\tanh \alpha l} \tag{20a}$$

This is the same as eq 20, so the 2 cases can be treated alike from now on.

Now αl is always small because of the low line losses, so that for all practical purposes $\tanh \alpha l = \alpha l$. Equation 20 hence becomes:

$$Z_s = \frac{Z_0}{\alpha l}$$

By making use of eq 4, and taking advantage of the fact that l is an exact multiple of a quarter wave length, one has

$$Z_s = \frac{Z_0}{\alpha l} = \frac{2Z_0^2}{Rl} = \frac{8Z_0^2}{Rn\lambda} = \frac{8Z_0^2 f}{Rnc} \tag{21}$$

This is the same as eq 8.

Equation 9 is obtained by substituting in eq 21 the value of R given by eq 6 and the expression for Z_0 from eq 5a. The right-hand side of eq 9 is maximum when $b/a = 9.2$, and eq 9a represents eq 9 for this optimum b/a multiplied by the factor F, which is the ratio of the impedance with the actual b/a to the impedance with optimum b/a.

Equation 10 is obtained from eq 8 in the same way that eqs 9 and 9a are, except that the expressions for R and for Z_0 now are given by eqs 7 and 5b, respectively, and the resistance must be multiplied by the proximity factor given in Fig. 2. The resulting equation becomes

$$Z_s = \frac{244.4\sqrt{f}\,b}{n}\left[\frac{\log b/a^2}{\frac{b}{a}P}\right] \tag{22}$$

where P is the proximity factor and is a function of b/a. The right-hand side is a maximum when $b/a = 8.0$, and eq 10 merely represents the impedance with this optimum b/a multiplied by the factor G which is the ratio of the impedance for any desired b/a to the impedance with the optimum b/a, b being constant.

Appendix II—Selectivity Equations for Resonant Lines

The selectivity of resonant lines is determined by the variation of impedance as the frequency is varied about resonance. Consider, for example, eqs. 1a and 1b. These can be written

$$Z_s = \frac{Z_0}{\tanh(\alpha l + j\beta l)} = \frac{Z_0}{\tanh(\alpha l + j2\pi fl/c)}$$

and (23)

$$Z_s = Z_0 \tanh(\alpha l + j\beta l) = Z_0 \tanh(\alpha l + j2\pi fl/c)$$

If f and l are such that the line is in exact resonance, then βl is an exact multiple of $\pi/2$ and both equations become $Z_s = Z_0/\tanh \alpha l$. Assume now that the frequency is off resonance by an amount δf. In this case

$$\beta l = \frac{n\pi}{2} + j2\pi l\delta f/c$$

or

$$Z_s = \frac{Z_0}{\tanh\left(\alpha l + j\frac{2\pi l}{c}\delta f\right)} \tag{24}$$

But as δf and αl are small, one can write

$$Z_s = \frac{Z_0}{\alpha l + j\frac{2\pi l}{c}\delta f} \tag{25}$$

This expression for impedance is of exactly the same form as the impedance of an ordinary parallel circuit about resonance. Thus the usual rule for determining Q may be applied, which is that when δf is such that the real and imaginary terms of the denominator are equal,

$$\delta f = \frac{\text{Resonant frequency}}{2Q}$$

Hence

$$Q = \frac{f}{2\delta f} = \frac{f}{2\alpha l/(2\pi l/c)} = \frac{\pi f}{\alpha c} \tag{26}$$

Substituting from eq 4 for α gives

$$Q = \frac{2\pi f Z_0}{Rc} \tag{27}$$

For a concentric line eq 27 can be simplified by introducing eqs 6 and 5a for R and Z_0, respectively, with the result given in eq 11. The line proportion that makes Q in eq 11 maximum is $b/a = 3.6$, and eq 11a merely gives the Q for this optimum proportion multiplied by the factor H which is the ratio of Q for any value of b/a to the Q for optimum b/a.

For a 2-wire line eq 27 can be simplified by following the same procedure as for the concentric tube. Here the optimum proportions are for b/a between 3 and 4. Equation 12 is the result, where J is the factor corresponding to H, but on the assumption that the reference condition is $b/a = 4$.

Appendix III—Voltage Step-Up Equations of Resonant Lines

When the receiver is open and the line is an odd number of quarter wave lengths long (n odd):

$$\frac{E_s}{E_r} = \cosh(\alpha l + j\beta l) = \cosh\left(\alpha l + jn\frac{\pi}{2}\right) \tag{28}$$

$$= j\sinh \alpha l$$

since αl is small we have

$$\text{Step-up ratio} = \left|\frac{E_r}{E_s}\right| = \frac{1}{\alpha l} = \frac{8Z_0 f}{Rnc} \tag{29}$$

If the receiver is short-circuited, $E_s = I_r Z_0 \sinh(\alpha l + j\beta l)$ and the voltage at a voltage loop is $I_r Z_0 \sinh\left[\alpha l + j\beta l - \frac{\pi}{2}\right) = -jI_r Z_0 \cosh(\alpha l + j\beta l)$

$$\text{Step-up ratio} = \frac{\cosh \alpha l}{\sinh \alpha l} = \frac{1}{\alpha l} = \frac{8Z_0 f}{Rnc} \tag{30}$$

The effective Q can be determined for this case as was done in Appendix II. We note in both open- and short-circuited receivers that as the frequency is brought off resonance by an amount δf the result is the same as in eq 25, and Q, hence, follows the same law for voltage step up as for lines operated to give high impedance.

Appendix IV—Equations for Reactance Developed by Lines

For short-circuited receiver eq 1 gives

$$Z_s = Z_0 \tanh(\alpha l + j\beta l) = Z_0 \frac{\sinh 2\alpha l + j\sin 2\beta l}{\cosh 2\alpha l + \cos 2\beta l} \tag{31}$$

but as αl is small, $\cosh 2\alpha l = 1$, and $\sinh 2\alpha l = 2\alpha l$. Hence

$$Z_s = Z_0 \frac{2\alpha l + j\sin 2\beta l}{1 + \cos 2\beta l} = Z_0\left[\frac{\alpha l}{\cos^2 \beta l} + j\tan \beta l\right]$$

$$= \frac{Rc\left(\frac{l}{\lambda}\right)}{2f\cos^2 2\pi\left(\frac{l}{\lambda}\right)} + jZ_0 \tan\left(2\pi\frac{l}{\lambda}\right) \tag{32}$$

In the case of an open circuit at the receiver the derivation follows the same steps, but starts with the general equation of sending end impedance for an open receiver.

Appendix V—Selectivity Characteristics of Reactances Developed by Resonant Lines

In the case of ordinary reactances the change of reactance Δx produced by a fraction change of frequency $\Delta f/f$ is

$$\Delta x = X\frac{\Delta f}{f} \tag{33}$$

In the case of lines this simple relation no longer holds. Thus for the short-circuited receiver case of eq 16a

$$X = Z_0 \tan 2\pi\left(\frac{l}{\lambda}\right) = Z_0 \tan\left(\frac{2\pi f l}{c}\right) \tag{34}$$

$$\frac{dx}{df} = Z_0 \frac{2\pi\, l/c}{\cos^2 2\pi f l/c} = \frac{Z_0\left(2\pi\frac{l}{\lambda}\right)}{f\cos^2 2\pi\left(\frac{l}{\lambda}\right)} \tag{35}$$

Hence

$$dx = \frac{2\pi l/\lambda}{\cos^2(2\pi l/\lambda)} Z_0 \frac{\delta f}{f} \tag{36}$$

Multiplying both numerator and denominator by $\tan\left(2\pi\frac{l}{\lambda}\right)$ and reducing gives

$$dx = \frac{4\pi\frac{l}{\lambda}}{\sin\left(4\pi\frac{l}{\lambda}\right)} X \tag{37}$$

Comparison of eqs 33 and 37 immediately yields eq 18. The same result also will be obtained when this same procedure is applied to eq 16b.

References

1. New Methods of Frequency Control Employing Long Lines, Conklin, Finch, and Hansell. *Proc.* I.R.E., v. 10, Nov. 1931, p. 1918.
2. A New Type of Ultra Short Wave Oscillator, J. E. Mouromtseff and H. V. Noble. *Proc.* I.R.E., v. 20, Aug. 1932, p. 1328.
3. The Propagation of Electrical Currents, J. A. Fleming.
4. Wave Propagation Over Parallel Tubular Conductors, S. Pero Meade. *Bell System Tech. Jl.*, v. 4, April 1925, p. 327.
5. Radio Engineering, F. E. Terman. McGraw-Hill Book Company, 1932.
6. Transmission Lines for Short Wave Radio Systems, Sterba and Feldman. *Proc.* I.R.E., v. 20, July 1932, p. 1163.

Electron Emission

By SAUL DUSHMAN
ASSOCIATE A.I.E.E.

General Elec. Co.,
Schenectady, N. Y

Edison's observation of the discharge of negative electricity from the carbon filament of an incandescent lamp to an auxiliary electrode in the bulb, commonly known as the "Edison effect," remained unexplained until the beginning of the 20th century. Since that time, an entire new industry—radio—has grown up as a result of continued research in the emission of electrons from hot cathodes. This article, seventh of a series prepared under the sponsorship of the A.I.E.E. committee on education, reviews some of the more important observations and conclusions obtained from investigations in this field.

THE OBSERVATION made by Edison on the discharge of negative electricity from the carbon filament of an incandescent lamp to an auxiliary anode in the bulb (Edison effect) remained unexplained until O. W. Richardson started his investigations at the beginning of this century. While Richardson and other English investigators used metals (such as platinum and sodium) and carbon as emitters, A. Wehnelt showed (in 1905) that metallic oxides, such as those of barium (BaO), calcium (CaO), and strontium (SrO), also emit electrons at high temperatures, and Jentzsch (1908) made similar observations on the oxides of a great many elements. Between these dates and 1913 several workers in this field reached the conclusion that the observed emission is caused in all cases, by chemical effects of residual traces of gases, and that under better vacuum conditions the emission phenomenon would disappear. Furthermore, there appeared to be some valid experimental evidence for this point of view. However, with the publication (1913–14) by I. Langmuir of the results of his investigations on the electron emission from tungsten in high vacuum and his evidence of space charge effects under these conditions, the subject of thermionics entered a new stage of development of extreme importance both theoretically and practically.

The past 2 decades have seen a veritable revolution in many industrial operations, produced by the application of electronic devices of the most varied types. A whole new industry—that of radio—has grown up as a result of the investigations on the emission of electrons from hot cathodes and on the various methods by which these electrons may be controlled.

Equations for Electron Emission

In his 1903 paper, Richardson developed an equation expressing the variation in electron emission with temperature. Assuming that at any temperature only those electrons are able to escape through the surface that have an energy in excess of a certain critical value, E, and, furthermore, assuming that the distribution of kinetic energies of the electrons in the metal is of the Maxwell Boltzmann type, Richardson derived the following emission equation:

$$N = n\sqrt{\frac{kT}{2\pi m}}\, \epsilon^{-E/kT} \tag{1a}$$

where

N = number of electrons per unit area per unit time
n = number of electrons per unit volume in the metal
k = Boltzmann gas constant
= 1.371×10^{-16} ergs per degree
T = absolute temperature on Centigrade scale (degrees K)
m = mass of an electron
= 9.0×10^{-28} g
ϵ = base of natural system of logarithms

Since n is assumed to be a constant for any metal, independent of T, eq 1 may be written in the form

$$I = a\sqrt{T}\,\epsilon^{-b/T} \tag{1b}$$

where I is the electron current per unit area, and a and b are *constants* for any given emitting surface. This is the form in which Richardson's equation usually is stated. It should be observed that the constant b corresponds to E/k in eq 1a. Now E can be expressed in terms of the voltage drop, ϕ, through which an electron would have to be accelerated in order to acquire the kinetic energy, E, by the relation

$$E = bk = \phi e$$

where

e = electric charge on an electron
= 4.770×10^{-10} electrostatic units (e.s.u.)
= 1.591×10^{-19} coulombs

Hence

$$\phi = \left(\frac{k}{e}\right) b$$

$$= \left(\frac{1.371 \times 10^{-16} \times 300}{4.770 \times 10^{-10}}\right) b \text{ (volts)}$$

$$= 8.62 \times 10^{-4}\, b \text{ (volts)}$$

where the factor 300 is used to convert to the customary volts and b evidently is expressed in degrees K. The quantity ϕ, expressed in volts, is known as the "work function" for electron emission.

While Richardson had pointed out that an equation of the form

$$I = AT^2\,\epsilon^{-b/T} \tag{2a}$$

would be just as valid theoretically and would be in satisfactory agreement with observed data, it was shown subsequently by M. v. Laue (1918) and by the author (1922) independently that on the basis of the third law of thermodynamics and Planck's theory of energy quanta, an equation of the latter type must apply, in which A is a universal constant defined by the relation

$$A = \frac{2\pi emk^2}{h^3} \tag{3}$$

where

h = Planck's constant = 6.547×10^{-27} erg sec

e, m, k have the same significance as in the previous equations

The numerical value of the constant is

$A = 60.2$ amp/cm² deg²

More recently, it has been shown that this value of A ought to be multiplied by the factor 2 to take into account the fact, deduced from observations on atomic spectra, that the electron possesses a spin momentum. However, the actual emission data for certain special surfaces are in much better agreement, as is mentioned later, with the value 60.2 than with this theoretical value 120.4.

Equations 1b and 2a may be written in a form that is much more convenient for the actual calculation of the constants a and b or A and b_0. From these equations, it follows that in terms of ordinary logarithms

$$\log I - \frac{1}{2}\log T = \log a - \frac{b}{2.303T} \tag{1c}$$

and

$$\log I - 2\log T = \log A - \frac{b_0}{2.303T} \tag{2b}$$

Thus if $\log (I/\sqrt{T})$ or $\log (I/T^2)$ is plotted against $1/T$, the value of b or b_0 is determined from the slope of the straight line thus obtained, while that of a or A is determined from the intercept on the ordinate axis for $1/T = 0$.

As an illustration of the method of applying eq 1c and 2b, Table I gives emission data actually obtained for a pure tungsten filament under excellent vacuum conditions. From a plot of these data, the following values of the emission constants were derived:

$A = 55.6$ amp/cm² deg²

$b_0 = 52{,}570$ degrees

Table I—Emission Data for a Pure Tungsten Filament in a Vacuum

T	$10^3/T$	$\log I + 6$	$\log(I/T^2) + 14$	b_0
1477	0.6770	0.6065	0.2677	52,760
1543	0.6482	1.3432	0.9666	53,630
1640	0.6098	2.2850	1.8554	52,570
1761	0.5679	3.3158	2.8248	52,520
1897	0.5371	4.2696	3.7434	52,690
2065	0.4842	5.3043	4.6743	52,790
2239	0.4467	6.2659	5.5659	52,640
				Avg 52,660

The last column in Table I gives values of b_0 calculated for each temperature by assuming $A = 60.2$ amp/cm² deg².

It is of interest to point out in this connection that on the basis of the new electron theory of conduction developed by A. Sommerfeld (1928) an equation for electron emission is derived identical with eq 2a with the modified value $2A$ as mentioned already. However, from actual emission data it has been found that: (1) in no case is the observed value of the constant in agreement with this theoretically derived value; (2) for several pure metals, A has a value approximately equal to 60.2; and (3) for composite surfaces, such as thoriated tungsten and oxide coated cathodes, the observed values of A differ considerably even in order of magnitude from the theoretical value. It has been suggested, therefore, that this difference might be ascribed to the existence of a reflection coefficient, r, for the electrons. This would lead to a constant of the form $2A(1 - r)$ in which $r = 0.5$. In a recent paper, J. A. Becker and W. H. Brattain have pointed out that the value of r is probably very small; they suggest that the discrepancy is attributable to the existence of a temperature coefficient for the work function. Thus further investigation still is required to determine the reasons for the fact that factor A as observed from emission data is different from the theoretical value $2A = 120.4$ amp/cm² deg².

Requirements for Accurate Emission Data

During the first decade of the investigations by Richardson, Wehnelt, and others on thermionic emission, considerable doubt was expressed by several other investigators regarding the existence of this phenomenon in such a good vacuum that the effect could not be ascribed to traces of residual gases. This theory that electron emission results from chemical reactions between the metal and residual gases was held very widely, and it was only the epoch-making investigations of Langmuir that finally led to indisputable evidence for the existence of a thermionic emission *per ipse*. In this work, Langmuir developed a technique of producing and maintaining an extremely good vacuum (of the order of 10^{-9} atmosphere) and also demonstrated that if care were taken to obtain a *clean* surface, absolutely reproducible emission data were obtained which could be represented satisfactorily by Richardson's equation. In the case of tungsten, which has an extremely high melting point (3,655 deg K) and a very low rate of evaporation even at 2,400 deg K, ideal experimental conditions could be obtained both as regards extremely low pressures and clean surfaces.

Under these conditions, Langmuir found (1913) that the electron current passing from a filamentary cathode to an adjacent anode (which, of course, was heated to a high temperature in a vacuum, in order to remove occluded gases and oxides) is limited by either of 2 factors: (a) voltage on the anode, or (b) temperature of the cathode. With the cathode at a definite and constant temperature, the electron current to the anode increases at first as the voltage is increased according to the "three halves power law," that is

$$i_e = cV^{3/2} \tag{4}$$

However, this increase in electron current with V continues only until a certain limiting value, i_T, is reached which depends only upon the temperature. This is the *saturation electron emission which is a function of the temperature and of cathode area only.* It is this saturation current that obeys the Richard-

son equation. As has been shown by Langmuir, the electron current is limited at the lower anode voltages by a *space charge effect* resulting from the repulsive forces between electrons in the space between the electrodes, and on the basis of Coulomb's law, he was able to derive the conclusion that the relation between space charge limited current and anode voltage should be of the form stated in eq 4 where the exact value of c is determined by the relative configuration and shapes of the electrodes.

Thus for 2 infinite parallel planes separated by a distance x (in centimeters) the maximum current density i_s (in amperes per square centimeter) is given by

$$i_s = 2.33 \times 10^{-6}\ V^{3/2}/x^2$$

where V is the potential difference in volts.

Similarly, for a filamentary cathode of radius a placed in the axis of a cylinder of radius r, the maximum electron current per unit length of time is given by

$$i_s = 14.65 \times 10^{-6}\ V^{3/2}/r$$

for the case where r is more than 10 times greater than a.

From these considerations, it is evident that for any given temperature of the cathode, the temperature limited emission, i_T, may be observed only if the anode voltage is greater than the value defined by the relation

$$V = (i_T/c)^{2/3}$$

corresponding to space charge limitation.

As the anode voltage is increased beyond this value, there is observed a further slight increase in emission because of the increase of field strength at the cathode. A theoretical explanation of this phenomenon was suggested first by Schottky (1914) and hence it is known as the *Schottky effect*. According to this theory, the emission, i_T, at any field strength, E, is related to the emission, i_0, at zero field strength (which is the value to which the emission equations apply) by the relation

$$i_T = i_{0e}^{4.39\sqrt{E/T}} \qquad (5)$$

Since for any given arrangement of electrodes E is proportional to V, eq 5 leads to the conclusion that at anode voltages in excess of those required to overcome space charge, log i_T should increase linearly with $\sqrt{V}/T$. For tungsten and similar pure metallic thermionic sources, it has been shown that eq 5 is valid over the range of voltages used in making observations on electron emission. Therefore, the emission at zero field strength, that is, the value to be used in eqs 1 and 2, is obtained from the straight line plot of log i_T versus $\sqrt{V}$ by extrapolating to $V = 0$.

In the actual technique for obtaining accurate emission data, it is necessary to take care of the 2 very important factors that influence the magnitude of the emission. The first factor involves precautions regarding the removal of adsorbed and occluded gases from the emitting surface, and the maintenance of as nearly perfect vacuum conditions as possible. The second factor is the need of an accurate temperature scale for the surface under investigation. A further point in connection with the accurate determination of the temperature is that regarding corrections for end-losses where filaments are supported by leads. Information on these topics is now available in several publications.

Table II—Emission Data for Homogeneous Metallic Emitters

Metal	A	$b_0 \times 10^{-4}$	ϕ_0	I_T	T
Cs	162	2.10	1.81	2.8×10^{-11}	800
Mo	60.2	5.09	4.38	2.34×10^{-8}	2,000
Pt	1.7×10^4	7.25	6.27	9.2×10^{-10}	1,600
Ta	60.2	4.72	4.07	1.38×10^{-8}	2,000
W	60.2	5.24	4.52	1×10^{-8}	2,000
Th	60.2	3.89	3.36	4.3×10^{-9}	1,600
Zr	330	4.79	4.13	8.5×10^{-8}	1,600

Table II gives electron emission constants for some of the metals for which accurate values are available. Only values of A and b_0 are given, not those of a and b since nearly all investigators now use eq 2. The second last column gives the value of emission in amperes per square centimeter at the absolute temperature, T, given in the last column.

Thoriated Tungsten Cathodes

In 1913 Langmuir and W. Rogers discovered that by proper thermal treatment of a tungsten wire containing 1 to 2 per cent of thoria (ThO_2) a very much higher electron emissivity could be obtained than that observed from filaments of pure tungsten. As was shown by Langmuir, this increased activity is due to the presence of a layer of thorium atoms adsorbed on the surface of the tungsten. The procedure finally adopted for obtaining thorium emission is as follows:

1. By flashing the filament for a minute or 2 at temperatures higher than 2,700 deg K, some of the thoria is reduced to thorium. Because of the high temperature any thorium atoms that diffuse to the surfaces are immediately evaporated there, so that the emission is substantially that of tungsten.

2. If now the temperature is decreased to 2,000–2,200 deg K, the rate of diffusion is still quite high, but the rate of evaporation is decreased to such an extent that thorium atoms can accumulate on the surface as an adsorbed layer.

In order to observe the rate at which the surface becomes covered with thorium atoms at these temperatures, the temperature is lowered at frequent intervals during the activation process to such a value (1,600 deg K or less) that the rate of diffusion also becomes negligibly small. In this manner a plot is obtained of emission at a given testing temperature as a function of the time at the activating temperature. Evidently such a curve should make it possible to calculate the rate at which thorium atoms diffuse to the surface at any temperature; similarly by means of a deactivation curve at temperatures between 2,200 and 2,700 deg K it should be possible, from a knowledge of rates of diffusion to the surface (as extrapolated from the values obtained at lower temperatures), to derive rates of evaporation of thorium atoms at different temperatures.

The foregoing involves as a preliminary and

very essential step the derivation of a relation between the observed emission (which shall be indicated by i) and the fraction of the surface covered with thorium atoms (θ). Langmuir assumed a linear relation between log i and θ and that $\theta = 1$ for maximum emission. On this basis he derived relations for the diffusion constant and rate of evaporation as a function of the temperature, T. However, as has been shown by the recent work of Brattain and Becker (1933) and confirmed by Langmuir (in a paper recently published in *Physical Review*), the assumption made by the latter in his 1923 paper is not justifiable. It seems highly probable that the maximum emission (i_m) is obtained for $\theta = 0.7$ approximately. In view of the present uncertainty in the exact value of θ for $i = i_m$, the method of interpretation suggested by Becker is very useful. According to the latter, the amount of thorium on a tungsten surface is defined by a quantity, f, and it is found empirically that if f is assumed to be 1 for $i = i_m$ at any temperature, then the emission for any surface for which f lies between 0 and 0.8 or 0.9 is given by an empirical relation of the form

$$\frac{\log i - \log i_W}{\log i_m - \log i_W} = 1.13\,(1 - \epsilon^{-2.32f})$$

where

i_W = emission from pure tungsten
i_m = maximum emission from tungsten covered with thorium

both measured at the same temperature.

According to Brattain and Becker, the emission from thoriated tungsten as a function of f and T is given by the relation

$$\log (i/i_W)_T = 0.54k(1 - \epsilon^{-2.32f})$$

where

$$k = 1 - 1.42 \times 10^3 \left(\frac{1}{1{,}274} - \frac{1}{T}\right)$$

The values thus obtained agree satisfactorily with those obtained previously by the author and Mrs. J. W. Ewald and lead to the values of A and b_0 in eq 2a for different values of f shown in Table III. The fourth column gives the emission in amperes per square centimeter at $T = 1{,}274$, and the last column the logarithm of the ratio between the emission for thorium covered and pure tungsten at $T = 1{,}274$, for each value of f. While these values are based upon emission data taken with an applied potential of 100 volts, observations by Brattain and Becker indicate that both A and b_0 increase with decrease in applied potential, the relative magnitude of this decrease being least for $f = 1$ (where there is practically no change in A and only a slight increase in b between 100 and 10 volts) and greatest at $f = 0.6$ and $f = 0.3$.

Table III—Emission Constants for Thoriated Tungsten Filaments

f	$b_0 \times 10^{-4}$	A	$10 + \log I_{1,274}$	$\log(I/I_W)_{1,274}$
0.0	5.20	69	0.32	0.00
0.1	4.75	48	1.71	1.39
0.2	4.39	36	2.80	2.48
0.3	4.11	29	3.66	3.34
0.4	3.89	24	4.34	4.02
0.5	3.71	21	4.88	4.56
0.6	3.55	19	5.30	4.98
0.7	3.46	17	5.65	5.33
0.8	3.39	16	5.86	5.54
0.9	3.34	15.8	6.02	5.70
1.0	3.32	15.5	6.08	5.76
1.2	3.43	20	5.87	5.55
1.4	3.61	37	5.46	5.14
1.6	3.74	53	5.20	4.88
1.8	3.79	61	5.11	4.79
2.0	3.80	65	5.07	4.75

It may be observed that for $f = 1$, at $T = 1{,}274$, the maximum emission from thoriated tungsten is $10^{6.76} = 5.75 \times 10^6$ times that of pure tungsten. At higher temperatures this ratio is lower, because of the difference in values of b_0.

With regard to the mechanism of diffusion of thorium, Langmuir points out in his most recent paper that "It seems reasonable to assume (on the basis of the results obtained by a number of investigators) that a large fraction of the thorium which arrives at the surface travels from the interior along grain boundaries, and then spreads out over the surface." That is, at lower temperatures the coefficient of diffusion along the surface of grains is considerably greater than that of diffusion from within the grains themselves. It is only at 2,300 to 2,400 deg K and higher temperatures that the latter becomes of importance in governing rates of deactivation. Langmuir finds that the coefficient of surface diffusion and rate of evaporation of thorium from the surface are, in each case, functions of both f and T. Hence the conclusions given in the 1923 paper regarding the values of diffusion constants (which at that time were calculated on the assumption that diffusion occurs only in the solid lattice of tungsten atoms) and values of rates of evaporation must be disregarded in view of the more recent work.

It should be noted in this connection that other rare earth oxides (such as those of cerium, lanthanum, yttrium, uranium, and zirconium) added to tungsten and molybdenum show characteristics similar to those exhibited by thorium on tungsten, but in none of these cases is the emission at any given temperature as great. The emission phenomena for films of thorium on molybdenum are also quite similar; and while the emission per watt input is approximately the same at lower temperatures as for thorium on tungsten, it is not possible to obtain as high emission at temperatures higher than 1,700 deg K on account of the extremely high rates of diffusion and of evaporation.

The data given by Brattain and Becker show that for $f = 2$, the emission is approximately $^1/_{10}$ of that observed for $f = 1$ and approaches very closely that obtained by Zwikker (1926) for solid thorium.

Oxide Coated Cathodes

The oxide coated type of cathode, while of greatest importance from the technical point of view, presents the most complex problems from the purely scientific point of view. As has been mentioned previously, the emission from oxides of the alkaline earth metals (CaO, SrO, and BaO) was observed first by Wehnelt (1904). The high value for the emission per watt input together with the high absolute magnitude of the emission obtainable at temperatures at which

the life is very long, led to the adoption of this type of cathode in the various types of electronic devices useful in industrial applications.

Various methods have been used for the preparation of filaments coated with the oxides mentioned in the preceding paragraph and these are described in detail in technical literature (see bibliography at end of article). The present practice consists in general in the use of nickel, nickel alloy, tungsten, or molybdenum as core metal upon which a coating of either mixed oxides or oxide of barium is put in the form of carbonates or nitrates or a mixture of these. The water used in forming the coating, as well as some of the carbon dioxide and oxides of nitrogen are driven off by a preliminary heating in air; after the filament is introduced into the tube, the latter is exhausted well, following which the filament is subjected to a final activation process. During this treatment, combined carbon dioxide and oxides of nitrogen as well as residual water are driven off first so that the pure oxides are left. Then either the filaments are heated to a high temperature, which presumably causes a reduction of some portion of the oxides to their respective metals, or an electron current is drawn from the cathode by applying a rather high positive potential gradient. During this process the emission increases greatly and the treatment is continued until the maximum emission is obtained. As will be pointed out later, there are good reasons for assuming that during this treatment with anode voltage the oxides are decomposed electrolytically with formation of their respective metals at the surface of the core and subsequent diffusion of the metal atoms to the surface of the oxide. Often a combination of the thermal and electrical methods of activation is used.

Before discussing the various views held regarding the exact nature of the emission phenomena and of the mechanism of activation, some of the actual emission data obtained with cathodes of the oxide coated type will be presented briefly.

The behavior of these cathodes is so different from that of filaments of pure metals that it has been found very difficult to obtain precise data on emission constants comparable with those obtained for pure metals or even thorium on tungsten. The emission from oxide coated cathodes increases very rapidly with voltage, especially at higher temperatures, even when it is considerably below the limit set by space charge effects. Furthermore, the emission is likely to change with time, and there are pronounced fatigue effects. Also the composition and mode of application of the materials used and subsequent activation treatment affect profoundly the maximum emission obtainable at any temperature. In general, it may be stated that increased technical experience gradually has produced much more active filaments than those available at an earlier period. Thus, according to data published by H. D. Arnold (1920) the emission from a mixture of barium and strontium oxides at a temperature of 1,000 deg K is about 10×10^{-3} amp per square centimeter, while according to C. Davisson (1928) the emission from the same composition at the same temperature is about 100×10^{-3} amp per square centimeter. Rothe (1926) has published values of emission as high as 800×10^{-3} amp per square centimeter obtained at this temperature. Table IV gives a few of the more recent values of emission constants for oxide coated cathodes. As shown there, the work function for oxide coated cathodes is about 1 volt or even lower, while the values of A range from 0.24 to 10^{-4}.

Figure 1 shows a curve of log I/T^2 versus $1/T$ for an oxide coated cathode calculated on the basis of the constants given by Davisson (1928). In the same figure are shown also similar curves for other emitting surfaces (including caesium on tungsten discussed in the subsequent section of this article). The upper limit of each plot (lowest value of $1/T$) as is shown corresponds to the melting point in the case of pure metals or to the temperature at which the rate of evaporation of surface films becomes very high.

From a practical point of view, the *efficiency of emission* (milliamperes per watt) as a function of power input (watts per square centimeter) is of very great importance. Figure 2 shows (on specially designed cross section paper) the emission as a function of power input for different oxide coated cathodes (curves A to D) and for thorium on tungsten and pure tungsten. Curve A corresponds to data obtained with the best of oxide coated cathodes in 1923 and is taken from a paper published by R. W. King, of the Western Electric Company, while curve B corresponds to the data given by Davisson for oxide coated cathodes produced by the same company in 1928. The data used in plotting curves C and D were kindly furnished by G. R. Shaw, of the R.C.A. Radiotron Company, and correspond to the values for the emission observed on 2 different commercial types of radio tubes as made at the present time.

Operating points in each case in Fig. 2 are indicated by circles. Thus thoriated tungsten cathodes are operated at about 25 ma per watt, while in the case of curves A and B the efficiencies obtained were about 50 ma per watt. The higher emission efficiencies shown in curves C and D are probably to a large extent the result of improved tube design which makes it possible to operate the filaments at a given temperature with a very much lower power input. Thus with an oxide coated filament an increase in temperature of about 300 deg C would cause approximately a hundredfold increase in emission; therefore the higher emission observed on curves C and D

Table IV—Emission Constants for Mixture of Barium and Strontium Oxides and Emission at 1,000 Deg K

Year	Source	A	$b_0 \times 10^{-4}$	ϕ_0	I (Milliamperes Per Square Centimeter)
1925	Koller	1.07×10^{-3}	1.21	1.05	6.6
1926	German tube	9.6×10^{-4}	0.953	0.82	60
	German tube	8.7×10^{-4}	0.849	0.73	118
	German tube	9.8×10^{-3}	0.627	0.54	185
	German tube	1.6×10^{-3}	1.180	1.02	110
	Dutch tube	0.24	1.324	1.14	430
1927		2.97×10^{-3}	1.58	1.36	4.1
1928	Davisson	1.0×10^{-3}	1.16	1.00	92

could be accounted for by an increased temperature of operation at the *same power input*, as compared with previous tubes.

In this connection it should be pointed out that the effect of plate voltage on the emission is much greater for composite filaments than can be accounted for on the basis of Schottky's equation. As has been shown in recent papers by Langmuir and J. B. Taylor for caesiated tungsten, and by C. G. Found for oxide coated nickel cathodes, the zero-field emission for such cathodes is probably as small as 10 per cent of the value obtained at zero field by an extrapolation, on the basis of Schottky's equation from data obtained at higher voltages. For this reason it is impossible to give values of emission constants for thoriated tungsten and oxide coated cathodes that are quite comparable with those obtained for pure metal surfaces.

The different views that have been advanced in order to interpret the activation and emission phenomena exhibited by oxide coated filaments will be considered next. Contributions toward the elucida-

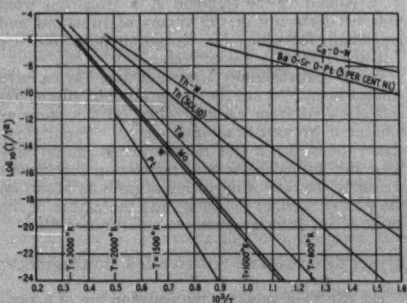
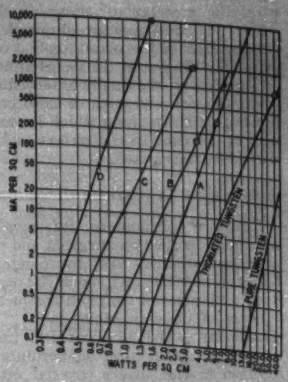


Fig. 1. Comparison of emission from coated filaments with that from pure metals

tion of these phenomena have been made by many investigators whose views are not always in agreement. However, since the most thorough investigations in this field have been carried out by J. A. Becker and his associates his conclusions will be summarized briefly in the following paragraphs.

The emission is ascribed to "an active layer at the outer oxide surface." This active material consists of metallic barium produced either by electrolysis of the oxide at the high temperature of activation or by chemical reaction between the oxide and the core material. The barium diffuses to the surface and forms there an adsorbed layer of ionized barium atoms (adions). These adions lower the work function for emission of electrons "which come from the underlying oxide." On this basis: "One might reasonably expect the activity to increase at a rate which is much more than proportional to the concentration of adsorbed barium, and that it might reasonably reach an optimum value for a monatomic layer before it decreases to its value characteristic of solid barium. Of course, eventually as the concentration of barium increases, the electrons must originate in the barium." The activity thus depends upon both the concentration of barium on the surface and upon the amount of barium or other metal (such as nickel) dispersed through the oxide. Ac-

Fig. 2. Emission from coated filaments as a function of power input



cording to Becker there is no valid reason for assuming that the electrons are emitted by a layer of barium adsorbed on the core and that these electrons then must pass through the oxide layer (thousands of atoms in thickness) in order to reach the outer surface. In support of this theory is the fact that oxygen decreases the activity of a coated filament, as well as the observations on the conduction phenomena in the oxide as determined by the quantity of electricity sent through it and by the temperature.

The foregoing view accounts for the observed increase in emission with relatively high anode voltages (this causes the deposition of barium at the core by electrolysis and the metal diffuses subsequently to the surface) and also for the decrease in work function during activation. At higher temperatures the barium evaporates from the emitting surface and leads to a deactivation of the latter. Furthermore, as shown by some recent work in the research laboratory of the General Electric Company by L. R. Koller, the barium may be sputtered off and made to deposit on an adjacent tungsten filament by positive ion bombardment.

A great deal of stress has been laid by some investigators, notably by Lowry, on the rôle of core material. The latter has observed that oxide coated filaments having cores made of "konel" (an alloy consisting of nickel, cobalt, iron, and titanium) behave quite differently from filaments with other cores. There is considerable evidence for the conclusion that in this case the barium is obtained by chemical reaction between the barium oxide and reducing metals in the alloy. According to Becker the differences in behavior of this cathode may be accounted for wholly by differences in rates of pro-

duction and diffusion of barium to the outer surface. For a similar reason, a core consisting of nickel to which a slight amount of metallic barium has been added also affects the rate of activation.

From the foregoing it is evident that the oxide coated cathode resembles the thoriated tungsten type in many respects. In each case, increased activity, as compared with the core or pure tungsten, results from the presence of adions on the outer surface. These adsorbed ions are obtained primarily by decomposition of the corresponding oxide and secondarily by diffusion of the metal atoms to the surface. In both cases, the finally observed emission depends upon the concentration of adsorbed atoms or ions present on the surface, which in turn is governed by rate of diffusion to the surface and rate of evaporation from the surface.

Caesium on Tungsten and Oxidized Tungsten

Emission phenomena for monatomic films of caesium adsorbed on tungsten and oxidized tungsten were investigated first by Langmuir and K. H. Kington in 1923. At about 700 deg K, the emission from a filament of tungsten completely covered with a layer of caesium atoms is 10^{-4} amp per square centimeter, which is about 10^{20} times that of pure tungsten at the same temperature. Denoting the fraction of the surface covered with caesium by θ, the value $\theta = 1$ is obtained in a bulb containing caesium at room temperature (0.10 mm vapor pressure) for temperatures of the tungsten filament as high as 800 deg K. At higher temperatures the value of θ decreases because of evaporation of caesium atoms, and the actual value obtained varies with both the temperature of the filament and the pressure of the caesium vapor (that is, the bulb temperature).

The following remarks on the emission phenomena exhibited by caesium films on tungsten are taken from a discussion by Langmuir (*Industrial and Engineering Chemistry*, v. 22, 1930, p. 390):

"This remarkable case of adsorption has been found to be due to the tendency of caesium atoms to lose their valence electrons to the tungsten. The work necessary to remove an electron from a caesium atom is measured by the ionizing potential, 3.9 volts. The affinity of a pure tungsten surface or electrons is measured by the heat of evaporation, 4.52 volts. Therefore, when a caesium atom comes into contact with a tungsten surface, the tungsten captures the valence electron and leaves the caesium as an ion, which is then held to the tungsten surface because of the negative charge which it induces (electric image force). This is confirmed by the fact that these adsorbed films are not formed if caesium is brought into contact with thoriated tungsten having an electron affinity of only 2.9 volts.

"If the filament temperature is high enough, the caesium ions evaporate from the filament as fast as the atoms strike the surface, but these ions are not formed if a fully thoriated surface is used. Thus with pure tungsten (or any material with electron affinity greater than about 4 volts, such as carbon, nickel, molybdenum, or platinum) the positive ion current that can be drawn with voltages great enough to overcome space charge is strictly independent of filament material or temperature (above a certain lower limit) or the electrode voltage, but is accurately proportional to caesium vapor pressure, p, being in fact given by

$$I = ep\,(2\pi mkT)^{-1/2}$$

where I is the current density, e the charge of an electron, m the mass of the caesium atom, and k is the Boltzman gas constant.

"The 2 curves marked 'Cs-W' in Fig. 3 [of this article] give the electron emission of pure tungsten filaments in presence of caesium vapor saturated at 20 deg and at 80 deg C. The falling off of emission as the temperature is raised above 700 or 800 deg K is due to the evaporation of caesium so that θ progressively decreases.

"When the current of caesium in the surface film is greater than corresponds to about $\theta = 0.20$, the electron affinity of the surface is less than 3.9 volts, so the caesium evaporates as atoms. Only at temperatures above about 1,200 deg K, when θ has fallen to 0.2, do all the atoms leave the filament as ions."

In Fig. 3 is shown also the variation with bulb temperature and filament temperature of the emission from a film of caesium on a tungsten filament that has been treated previously in oxygen to form an adsorbed layer of oxygen atoms. The latter stabilize, as it were, the caesium atoms on the surface and it is therefore possible to obtain higher emission from caesium on oxidized tungsten (Cs-O-W) than from caesium on tungsten (Cs-W) films. According to Kingdon the values of the emission constants for a completely covered surface of caesium on oxidized tungsten are: $A = 0.001$ amp/cm^2 deg^2; $b_0 = 8{,}300$; $\phi_0 = 0.695$ volts.

The *emission of positive ions* by the impact of caesium atoms on tungsten and other surfaces having a work function greater than 4 volts is an important effect. Similar observations have been made by T. J. Killian on the emission of positive ions from tungsten filaments in the vapors of rubidium and potassium, for which the ionization potentials are 4.16 and 4.32 volts, respectively.

Becker and especially Langmuir and Taylor have studied in great detail the evaporation of atoms, ion and electrons from caesium films on tungsten, as influenced by variations in θ and T. From these observations the 2 last named investigators have been able to deduce several interesting conclusions regarding the rate of migration of caesium atoms on the surface (surface diffusion) and the nature of the forces acting between atoms in an adsorbed film.

Effect of Gases and Positive Ion Bombardment

The effects of gases on the emission are of a twofold nature: Firstly, they may form *adsorbed monomolecular* or *monatomic* films on the surface of the cathode. Secondly, and especially with anode voltages in excess of a certain critical value (which varies

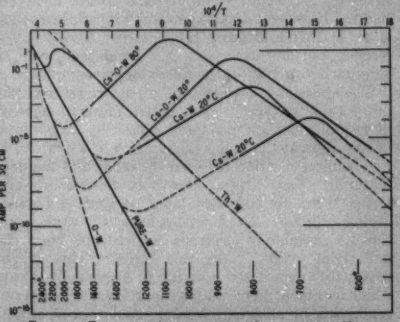


Fig. 3. Emission characteristics of monatomic films on tungsten

with the nature of the gas), positive ions are formed which sputter atoms off the surface of the emitter and thus may decrease the emission considerably. The first type of effect is illustrated by the observations on the enormously decreased emission from tungsten, thoriated tungsten, and other metals in a low pressure of oxygen, while the second type occurs, for instance, when an oxide coated or, thoriated tungsten cathode is operated with an anode voltage in excess of about 30 volts in a low pressure of a rare gas such as helium, neon, or argon.

In a review such as this it is possible to refer briefly to only a few of the gas effects that have been observed, although the number of investigations dealing with this topic is quite extensive. (A summary of this work has been published by K. Becker in *Physikalische Zeitschrift*, v. 32, 1931, p. 489–507).

Oxygen on tungsten forms adsorbed layers which are quite stable up to temperatures of 1,800 deg K, and decreases the emission to about 10^{-4} of its value for the pure tungsten surface. This gas also decreases the emission from monatomic films of thorium and barium (as in oxide coated filaments) by forming adsorbed layers which are extremely difficult to remove. The work functions for such adsorbed films are very much higher than for the uncontaminated surfaces, increasing in the case of oxygen on tungsten to 9.26 volts, and in the case of oxygen on barium to 3.1 volts.

Carbon monoxide and carbon dioxide behave quite similarly to oxygen. The emission from tungsten is unaffected by nitrogen if low anode voltages are used, but is decreased by the use of higher voltages because, as shown recently by Langmuir, active nitrogen is formed which liberates oxygen from oxides on the leads and filaments. However, Kingdon has shown that in case of thoriated tungsten, nitrogen at a pressure of 0.0001 to 0.005 mm causes approximately a fivefold increase in emission.

In the case of metals that form nitrides and oxides (tantalum, zirconium, and hafnium) adsorbed films of oxygen and nitrogen decrease the emission, and it is therefore necessary to heat these metals to as high a temperature as possible for a long period in order to obtain the lowest values of work function (and highest emission). In all these cases it has been observed that the value of the constant A also decreases during degassing. In fact, as has been pointed out by L. Du Bridge, there seems to exist a linear relation between b_0 (or ϕ_0) and log A. However, the decrease in A is negligible in its effect on the observed emission as compared with the increase in emission due to decrease in b_0.

The effect of hydrogen on the emission from platinum was investigated first by Richardson in his earliest work, and has been studied more recently by Du Bridge. This metal *absorbs* hydrogen very readily, and at 1,033 deg C, 100 g may contain as much as 0.021 mg of hydrogen. As the gas is eliminated by continued heating, the electron emission *decreases* continuously and ϕ_0 increases from 4.7 volts to 6.27 volts for a well degassed sample. Tantalum shows similar behavior to platinum, in respect to both absorption capacity for hydrogen and the effect of the gas on the emission.

Iodine, phosphorus vapor, and similar electronegative gases decrease the emission from metals because of formation of adsorbed films of high work function. On the other hand, as mentioned already, vapors of the alkali metals increase the emission from metals of high work function by forming adsorbed layers having lower work functions.

The effects of bombardment by positive ions vary with the nature of the gas and that of the surface. In the case of pure metals, such as tungsten, molybdenum, and others, bombardment by positive ions of rare gases has no effect on the emission, but causes, of course, a mechanical disintegration of the cathode. As shown by Kingdon and Langmuir, positive ions of the rare gases and of caesium and mercury, remove adsorbed thorium atoms from a thoriated tungsten filament when the energy of the ions exceeds 50 volts, and A. W. Hull has observed (1928) that in this case a threshold voltage exists for each type of ion below which sputtering does not occur. Similar observations also have been made on oxide coated cathodes. It is this fact that has made possible the development of hot cathode gaseous discharge lamps such as those containing neon and sodium vapor.

Effect of Intense Electric Fields

The effect of fields of low intensity has been discussed in a previous section of this article. The interpretation given by Schottky is that the emitted electrons are attracted to the surface by image forces. While his equation is found to be valid for pure metal surfaces, deviations are observed at low field strengths in the case of composite surfaces; Becker and D. W. Mueller have ascribed these results to the superposition of a Schottky image force field and a field caused by the layer of adsorbed atoms. The possible causes of these observations have also been discussed by K. T. Compton and Langmuir without reaching any definite conclusion.

Under the action of very intense fields of the order of 10^6 to 10^7 volts per centimeter, it has been shown that emission of electrons occurs even with the cathode at room temperature. This is known as the "cold cathode effect" or "autoelectronic" emission, and is observed with moderate anode potentials (1,000 to 10,000 volts) when a fine point is used as cathode. Empirically it is found that the emission varies exponentially with the field strength. An interpretation of the phenomenon has been given by R. H. Fowler and L. Nordheim (1928–9) on the basis of the theory of wave mechanics.

According to the classical point of view, the electrons in a metal at room temperature are prevented, because of their low kinetic energy, from leaving the surface by a potential barrier corresponding to the work function for emission. At higher temperatures, more and more electrons acquire sufficient kinetic energy to *pass over* this barrier, and hence follows the observed increase in emission with temperature. According to the new point of view, an intense electric field decreases the width of the potential barrier so that it becomes possible for an electron of low kinetic energy to *penetrate* it. The probability of the occurrence of this "tunnel effect"

increases rapidly with field strength and therefore it becomes possible to obtain emission at temperatures as low as room temperature if the field be increased sufficiently. This is a crude explanation of a phenomenon of which a more accurate discussion would require a great deal more space.

The relation derived by Fowler and Nordheim is of the form

$$I = \frac{CF^{r}}{\sqrt{\phi_0}} e^{-r\phi_0^{3/2}/F} \qquad (6)$$

where C and r are material constants, F is the field strength and ϕ_0 is the work function as determined from the variation in emission with temperature. Experimental data have been shown to be in satisfactory agreement with this theoretically deduced relation.

Concluding Remarks

Obviously, in an article of this length it has been possible to present only some of the more important observations and conclusions that have been obtained from investigations in this field. No mention has been made of the relation between thermionic and photoelectric effects, and only a brief reference has been made to the phenomena of positive ion emission. For a more complete discussion of these topics as well as of those touched upon in the present summary, the reader may consult the following references:

1. O. W. Richardson, Thermionic Emission, Longmans, Green and Company, London (1916).

2. S. Dushman, Reviews of Modern Physics, Vol. 2, 381 (1930). A review of the subject up to that date.

3. W. S. Stiles, Department of Scientific and Industrial Research, Special Report No. 11, London, England, 1932. "A survey of existing knowledge (on thermionic emission) with particular reference to the filaments of radio valves.

4. K. T. Compton and I. Langmuir, Review of Modern Physics, 3, 191 (1931). A review of gas discharge phenomena in general, including some of the topics discussed by the writer.

No mention has been made of the numerous treatises in German, especially that by Schottky, but references to these are given in the publications mentioned.

Insulator Arcover in Air

Although much is yet unknown about the many factors concerned in insulator arcover, humidity tests presented here lead to a theory of arcover. The geometrical design of the insulator is shown to be a minor factor at power frequencies, but of importance for withstanding impulse voltages.

By
F. W. MAXSTADT
MEMBER A.I.E.E.

California Institute of Technology, Pasadena

In many respects, the old problem of insulator arcover is in the same state of solution after nearly 40 years as it was in the early days of high voltage apparatus construction, for satisfactory explanations of some of the observed phenomena still are lacking. In this paper it is shown from test results that atmospheric humidity affects the arcover strengths of insulating materials in a somewhat erratic manner and quite independently of whether the material is hygroscopic or "greasy." Other factors that have large influences are enumerated and explained, and insulators whose arcover strengths are independent of humidity are described. A theory of arcover is offered, and test data obtained with continuous and impulse voltages, as well as with alternating voltages, are presented. Laboratory tests of commercial insulators are analyzed and correlated with the fundamental properties of the insulations. Briefly, it is shown that:

1. Atmospheric humidity may reduce the arcover strength of a clean, smooth surface to $^1/_3$ of the breakdown strength of the parallel path in air. The remedy is to break up the smooth surface into several shorter lengths by means of ribs or flanges of the same insulating material. If the flanges are spaced uniformly and sufficiently close together, they may offset entirely the effect of the atmosphere.

2. Correction of test data to "standard conditions" by means of the air density δ, whether necessitated by pressure or temperature differences from standard, is likely to lead to error if a linear relation is assumed.

3. Dirt, salt, water, and other semiconducting coatings give a real significance to surface resistance, but the latter need be calculated only as a length divided by circumference, integrated over the entire surface, instead of in actual ohms which may vary over a wide range and not affect the arcover strength.

4. Commercial insulators of approximately 1-ft arcing length have a 60-cycle arcover voltage when clean and dry of somewhat more than $^1/_4$ the ideal puncture voltage of a 1-ft air gap between plate electrodes. Suspension insulators of 12-ft length tested horizontally by Angus[26] have an arcover strength of only $^1/_4$ of that for the ideal air gap. One may obtain the ideal value for air by extrapolating the upper curve of Fig. 3. If transmission line voltages are to be pushed to considerably higher magnitudes than at present, some advantage no doubt will have to be taken of the greater arcover strength obtained by providing a uniform field in the neighborhood of each insulator. Another improvement can be obtained by more

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. Pacific Coast convention, Salt Lake City, Utah, Sept. 5-7, 1934. Manuscript submitted April 30, 1934; released for publication, May 24, 1934. *Not published in pamphlet form.*

closely spaced flanges, and the direct wetting by rain may need to be prevented.

5. Although impulse voltage searches out to a considerable extent certain weaknesses in insulator design, it is well to recognize that the numerical value usually exceeds the 60-cycle arcover voltage; hence, in the end, the latter may be the critical one.

6. Laboratory test reports should be more complete, including such essential information as the rating of the testing source and its impedance, and the protective resistance in series with the insulator under test. It is believed that many discrepancies will be explainable if this procedure is followed.

An Unexplained Phenomenon

As an example of one of the unexplained phenomena, 2 metal plates, Fig. 1a, approximately flat but with smoothly rounded edges, and supported parallel to each other 1 cm (0.394 in.) apart, can withstand an alternating or a continuous voltage having a maximum value of 30 kv before a spark will pass between the plates. (Crest values of alternating voltage will be used exclusively herein in order to facilitate comparison with continuous and impulse voltage tests.) A piece of insulation carefully shaped into the form of a right cylinder 1 cm long and placed between the plates, Fig. 1b, although theoretically having no disturbing influence on the electric field, will be found by test to have reduced the breakdown strength of the gap to perhaps 15 kv or less. A satisfactory reason for this behavior is not obvious, and in fact is not known.

Surface Effects

By means of the simple testing apparatus of Fig. 1 such uncertainties as nonuniform voltage distribution over the insulator surface, electric field distortion in the medium outside, corresponding field distortion inside the insulation material, and the influence of parasitic capacitance are eliminated.

Atmospheric humidity has become recognized as an important factor in the arcover strength of most insulation, but the exact degree of its influence is uncertain. Figure 2, curves A to G, gives results obtained by 2 different investigators[8,9] who used alternating voltages of power frequency. Space does not permit a full discussion of the advantages of plotting relative humidity as a coördinate in place of one or other of the absolute humidity scales. The chief reason for its use here is to avoid the discontinuity above 100 per cent humidity that is always bothersome with an absolute scale. A check of the values of Fig. 2 in the laboratory yields points well scattered over the area included between the 2 sets of curves, most points, however, lying in the lower part of the area. It was not possible to duplicate Ritz's curves A to C which are higher than those obtained by any other experimenter, and there is reason to believe that they are peculiar to his apparatus, which was mechanically the most perfect of all. A very elaborate test was made on heat-resistant glass in which the sample after first being baked in a vacuum at 300 deg C for 2 hours was next supplied with air at atmospheric pressure in the same apparatus. The air before being admitted was dried carefully by freezing at liquid air temperature. An arcover strength of this sample equal to the strength of the air gap alone was observed. This and a somewhat similar test made by Inge and Walther[11] seem to be the only results thus far obtained agreeing with Ritz's extraordinary observations, and even then his unusually high figures were not checked at humidities other than zero.

Such surface characteristics as roughness, oiliness and absorptiveness have no important influence on arcover strength. Tests show conflicting results, but these easily may be attributed to other effects. Rice[12] found that surface coatings of oil, grease, or varnish on insulation give rise to improved arcover strength, but there are too many other factors in-

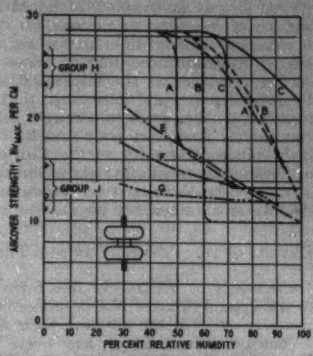


Fig. 2. Effect of relative humidity on arcover strength

Curve A. Paraffine right cylinder, Rogowski[3] electrodes, sparking distance 3.0 cm 50 cycles, series resistance 400,000 ohms, 45 to 20 deg C, 76 cm, absolute humidity constant at 1.8 cm mercury; from Ritz.[8] The uppermost horizontal line of curves A, B, and C corresponds to the strength of the air gap alone

Curve B. Glass right cylinder, conditions as for A; from Ritz

Curve C. Bakelite right cylinder, conditions as for A; from Ritz

Curve E. Paraffine right cylinder, flat electrodes with rounded edges; sparking distance 3.0 cm, 50 cycles, 20 deg C, 76 cm; from Schwaiger[9]

Curve F. Glass and unglazed porcelain right cylinders, conditions as for E; from Schwaiger

Curve G. Shellac right cylinder, conditions as for E; from Schwaiger

Points, Group H. Paraffine right cylinder, flat electrodes with curved edges of 20 cm radius; sparking distance 3.0 cm, 20 deg C, 76 cm. Upper point, surge voltage (wave form not given); middle point continuous; lower point 50 cycles; from Inge and Walther[11]

Points, Group J. Glass right cylinder, conditions as for H; from Inge and Walther

3. For all numbered references see bibliography at end of paper.

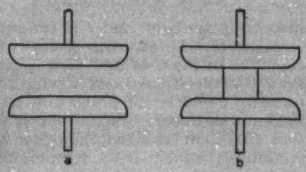


Fig. 1. Spark gap with plane parallel electrodes (a); and (b) same gap with insulation sample in place

volved in such experiments to lay much stress upon the results.

The terms "surface resistance" and "creepage distance" have been shown definitely to have no meaning in the "dry" arcover behavior of insulation, i. e., in the range of 0 to 100 per cent relative humidity, so long as no droplets of liquid appear on the surface of insulator or electrodes. The situation, however, is entirely different for wet, dirty, or salt-coated insulation according to Wood[1], who defines surface resistance as the integrated length-divided-by-circumference and proves it to be a practical measure of the arcover strength of complicated commercial insulators salt-coated. Tests in the high voltage laboratory of the California Institute of Technology on simple right cylinders coated with salt gave the same arcover potential per unit resistance as obtained by Wood.

Details of the Testing Gap and Testing Circuit

Electrodes of accurately flat form are unsuited to this type of arcover test because they produce an excessive stress in the air near their rounded edges. A much better contour has been suggested by Rogowski.[2] It is the same as an equipotential surface in the field between 2 thin flat sheet electrodes and was so chosen that the maximum stress in the air is nowhere appreciably greater than in the useful part of the gap. One such surface can be generated by rotating about the y axis the plane curve

$$x = 0.2385d\left[2.3026 \log \left\{4.83{,}5\left(\frac{y}{d} - \frac{1}{2}\right)\right\} - 2.4175\left(\frac{y}{d} - \frac{1}{2}\right) + 8.71\right]$$

where x and y are the ordinary variables and d is the desired length of spark gap in the same units. For other suitable equipotential curves the reader is referred to theoretical works on electrostatics. In order to complete the electrode its thickness should be made about $1.5d$, and a plane back may be used or the inside bored out to reduce the weight if of large size. It must be polished carefully and so maintained for all tests. The finished electrode resembles a door knob and may be used without great error for spark gaps from $^1/_2d$ to $2d$.

The mechanical fit between electrodes and insulation is of the utmost importance. Practically the whole range of observed arcover strengths, for a given relative humidity, Fig. 2, can be obtained by changes in the perfection of the fit between sample and electrodes, especially at the cathode. Ritz[3] secured test pieces made with optical precision and reports the best arcover strengths that have been observed below 70 per cent humidity, as shown by Fig. 2. Wax and oil as filters for the spaces left by poorly made ends of specimens are of little or no value because of their low dielectric constants.

Analogous to the Wagner[4] effect of protecting solid insulation from puncture by using high resistance electrodes is the insertion of resistance or reactance into the testing circuit to prevent arcover. Different experimenters use large, small, or medium capacity sources of voltage according to the available facilities in their respective laboratories. The results should not be expected to be comparable and can be compared legitimately only when all testing conditions are known, including impedance of the test circuit.

Geometrical Factors and Atmospheric Density

The free length has a strong influence on the arcover gradient. The upper curve of Fig. 3 shows how the breakdown strength of the spark gap alone varies

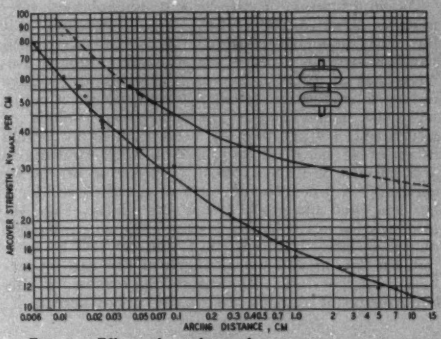


Fig. 3. Effect of sparking distance upon arcover strength

Lower Curve. Glass, "pyrex" and porcelain rightcylinders between polished flat electrodes, relative humidity 60 per cent, temperature 20 deg C (approx.), barometer 76 cm, 50 cycles. Upper Curve. Air only, between polished flat electrodes. Left end from experiments of Liebig[5] with plane to sphere as electrodes (corrected for curvature of sphere). Middle from Ritz[3] 1932, Rogowski electrodes. Right end from Schumann,[7] flat electrodes with long radius edges

with the sparking distance. The lower curve shows the nice manner in which the arcover strength of a solid under constant atmospheric conditions parallels the curve for air alone.

The relative diameter of the specimen has no influence except that very slender fibers show somewhat higher arcover voltages than a larger cross section of the same material. Strips of paper tested in the long direction had arcover strengths practically equal to that of the gap alone.

Atmospheric pressure and temperature different from standard conditions usually are corrected for by the use of a relative air density factor δ which is $\frac{3.92b}{273 + t}$ where b is barometric pressure in centimeters of mercury and t is temperature in degrees Centigrade. It assumes linear variations of both effects. In Figs. 4a and 4b it is shown clearly that even for the breakdown strength of air alone the pressure effect is not linear and for arcovers it may be far from linear. Fig. 4c shows that the temperature effect curves bend the other way, hence a correction in which both temperature and pressure

change δ in the same direction and by similar amounts is fairly accurate, but considerable error will be made under other circumstances.

A complete set of curves for correction to standard temperature and pressure would be quite laborious to make or use, and other influences of uncertain nature cause individual readings to vary from each other by margins large enough to discourage attempts at great precision in calculations. It is recommended, however, that arcover data not be corrected to standard conditions, but, instead, presented as obtained.

A Theory of Insulator Arcover

The surface of a solid object is not what the eye sees, but rather a molecular pattern against which gas molecules from the surrounding atmosphere are held in corresponding pattern. The succeeding layers in the direction away from the solid differ little by little until they merge with the atmosphere itself, but the lowermost layers of gas molecules are as dense as though at a pressure of several hundred atmospheres

Table I—Arcover Strength of 7.6-cm Bakelite Rod, 260 Threads Per Inch, With Varying Relative Humidity

Temperature 20–22 deg C, barometer 74 cm, protective resistance 2 megohms, flat electrodes with curved edges, 50 cycles, transformer impedance 10,000 ohms

Crest Voltage, Kv	Crest Gradient, Kv Per Cm	Per Cent Relative Humidity
*137	18.0	20
156	20.6	29
147	19.3	33
153	20.2	37
150	19.7	39
156	20.6	50
144	18.9	50
155	20.3	77
*123	16.1	89
150	19.7	95
160	21.1	95
161	21.2	95
157	20.7	95
** 80	10.5	100
†155	20.3	74
‡139	18.3	100
160	21.2	Air alone

* Are struck along the sample.
** Distilled water sprayed on sample previous to applying voltage. Droplets on both sample and electrodes.
† After drying for 1 hour in humidity as shown.
‡ Sprayed again more lightly with distilled water.

Langmuir[8] and Davisson and Germer[9] have given a great deal of information regarding such adsorbed layers of gas molecules. Most significant for present purposes is that a "clean" surface of glass in contact with the ordinary atmosphere holds to itself 100 times as many water as nitrogen molecules.

Glass is soluble in water, especially in the presence of carbon dioxide. Here, then, is the source of an electrolyte covering the surface of the glass insulator. This is confirmed by an experiment in which a glass specimen was washed thoroughly by rubbing with water and a mildly abrasive soap (such as mechanics use to clean the hands), after which it was dried in paper towels and not touched by the fingers. For 3 days it withstood an atmosphere of 85 to 90 per cent humidity without appreciable reduction in arcover strength; but finally the attack of the atmosphere aided by the heat of the arcs which occurred during the tests brought about the usual surface conditions and the arcover strength was reduced to that normally observed. A freshly drawn fiber of glass did not come to equilibrium with the atmosphere for about 24 hours.

The physical picture, then, of insulator arcover is that of a surface thinly covered by electrolyte. The applied voltage drives a current through the conducting medium, causes local heating, violent evaporation in patches and consequent alternate areas of high and low resistance. Arcs begin in the high resistance areas long before an arc would form simultaneously over the entire surface. When once an arc has formed, complete breakdown soon follows. Impulse arcover voltages are always higher than continuous or 60-cycle alternating voltages, and it may be assumed that the time-consuming nature of evaporation is an explanation of this.

That insulations other than glass behave similarly makes one search for another source of surface electrolyte. Minute dust particles, carbon dioxide from the air, and foreign substances not previously removed from the surface of the specimen are no doubt sufficient.

A bad mechanical fit between specimen and electrodes, especially at the cathode where spark formation always begins (according to Dunnington's[11] visual tests), affords air space where corona or a spark is sure to form at a voltage lower than the full strength of the test gap. Even an incipient spark, caused by short-circuiting part of the useful length of a specimen, can precipitate a complete arcover at subnormal voltage.

Table II—Arcover Strength of 9.1-cm "Pyrex" Rod, 260 Threads Per Inch, With Varying Relative Humidity

Temperature 16–19 deg C, barometer 75 cm, protective resistance 90,000 ohms, flat electrodes with curved edges, 50 cycles, transformer impedance 10,000 ohms

Crest Voltage, Kv	Crest Gradient, Kv Per Cm	Per Cent Relative Humidity
189	20.7	61
190	20.8	64
197	21.6	68
175	19.3	68
185	20.3	84
191	21.0	95
*123	13.5	95
191	21.0	Air alone

* Are struck along the sample.

An Application of Fundamentals

That the shorter is the striking distance, the greater is the unit strength of an insulator surface is shown by

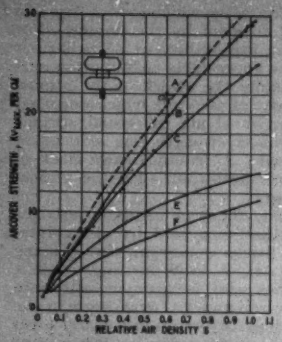


Fig. 4a. Effect of relative air density upon arcover strength

Constant temperature 20 deg C; 50 cycles
Curve A. Air only, sparking distance 1.0 cm, flat electrodes with curved edges of 20 cm radius from Inge and Walther[11]
Curve B. Pyrex right cylinder, sparking distance 0.73 cm, flat electrodes with rounded edges, relative humidity zero (approx.), series resistance 90,000 ohms, including transformer
Curve C. Glass right cylinder, sparking distance 1.04 cm, flat electrodes with rounded edges, relative humidity zero (approx.), series resistance as for B
Curve E. Glass right cylinder, sparking distance 1.0 cm, flat electrodes with curved edges of 20 cm radius, relative humidity zero (approx.), from Inge and Walther
Curve F. Glass right cylinder, sparking distance 3.0 cm, flat electrodes with curved edges of 20 cm radius, relative humidity zero (approx.), from Inge and Walther

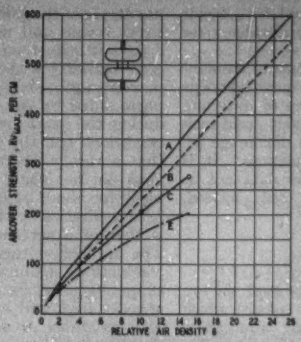


Fig. 4b. Effect of relative air density upon arcover strength

Constant temperature 20 deg C; 50 cycles
Curve A. Air only, sparking distance 0.3 cm, Rogowski electrodes; from Reher[10]
Curve B. Air only, sparking distance 1.0 cm, Rogowski electrodes; from Reher
Curve C. Hard rubber right cylinder, sparking distance 0.3 cm, relative humidity zero (approx.), Rogowski electrodes; from Reher
Curve E. Glass right cylinder, sparking distance 1.0 cm, relative humidity zero (approx.), values extrapolated from the works of several investigators

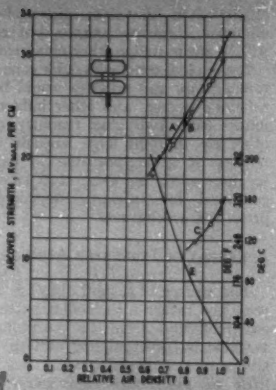


Fig. 4c. Temperature effect of relative air density upon arcover strength

Constant barometer 76.0 cm, 50 cycles
Curve A. Air only, sparking distance 1.0 cm, Rogowski electrodes, series resistance 120,000 ohms
Curve B. Pyrex right cylinder, sparking distance 0.73 cm, flat electrodes with rounded edges, relative humidity zero (approx.), series resistance 90,000 ohms
Curve C. Pyrex right cylinder, sparking distance 2.62 cm, flat electrodes with rounded edges, relative humidity 40 per cent
Curve E. Temperature deg C against relative air density, for convenience

Fig. 3. Rice[12] made use of this fact by stacking alternate glass and metal disks, the latter larger in diameter, forming several high strength samples in series, with electrodes between. He soon discovered, however, that alternate glass disks are better. There were 2 defects in his model. The glass disks were not flat enough to fit together well and they were too thick ($^1/_{16}$ in.). Tables I and II give test results for a bakelite and a "pyrex" rod, respectively, each having cut on its surface a screw of 260 threads per inch (102 per centimeter) for the entire length. Both ends carefully were fitted to the electrodes. The arcover potential per unit length of each is practically independent of humidity, showing the effect of flanges breaking up the surface into short lengths. Flanges provided on commercial insulators have a similar function: When the insulator is clean and dry they break up its length into many shorter insulator surfaces in series, the flanges themselves acting as new electrodes. The effect of flanges is quite different when the insulators are wet or dirty: They then serve to increase the surface resistance as previously described under "surface effects"; thus they have a double duty.

It is now easy to set up a rule for the best spacing of flanges. First determine the total length of the surface between the nearest electrodes. Find the arcover kilovolts per centimeter from Fig. 3 for the air gap alone of that length; multiply the value thus found by 3 and find on the same curve the corresponding length. It is the best spacing of flanges. As an example, suppose the distance between electrodes is 6 in. (15 cm). The corresponding unit strength of the air gap is 26 kv per centimeter, and $3 \times 26 = 78$. The length of air gap having 78 kv per centimeter breakdown strength is 0.015 cm or 0.006 in. It would be difficult to provide ribs or flanges at such minute spacing; hence it must not be expected that commercial insulators will have the same arcover strength as an equal length of air gap. The ratio 3 as just used is obtained from Fig. 2 in which the arcover strength for 100 per cent humidity is about $^1/_3$ that for the air gap alone.

Brasch and Lange[14] used the principle of uniformly spaced flanges in the construction of a 2.4-megavolt vacuum tube. Ritz[8] found that laminated paper rods in which the sheets were perpendicular to the axes had arcover strengths equal to the air gaps even in an atmosphere of 100 per cent humidity. Cotton tapes and string show similar properties.

A much more easily constructed test arrangement than those previously described and one which has many of the properties of a commercial pin or even suspension insulator was reported by Littleton and Shaver.[16] It consists of a rod of the test insulation

Table III—Influence of the Intervening Insulation Upon the Dry Arcover Voltage of 2 Similar Shield Rings

Diameter of rim material 2 1/2 in., outside diameter of entire ring 22 in., depth of ring fastening below rim 6 1/2 in., protective resistance zero, transformer 1,000 kva 1,000 kv, 50 cycles, 16 per cent impedance

Minimum Sparking Distance, Cm	Crest Voltage, Kv	Crest Gradient, Kv Per Cm	Per Cent Relative Humidity	Temperature, Deg C	Barometer, Cm Hg	Nature of Insulation
71	515	7.25	77	23	74.5	3 1/2-in. glazed porcelain tube 105 cm long
102	710	7.0	77	23	74.5	Same tube
100	720	7.2	77	23	74.5	5 1/2-in. cotton rope, each 130 cm long
100	720	7.2	77	23	74.5	8 10-in. standard suspension units spaced 4 3/4 in.
100	720	7.2	73	22	74.0	*7 high strength fog type units spaced 6 1/2 in.

* Data from tests by R. J. C. Wood, not published.

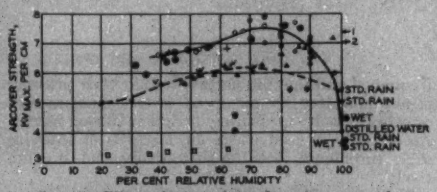


Fig. 5. Effect of atmospheric humidity upon the arcover strength of 3 types of commercial insulator; also rods with wire electrodes

o Glass rod 1 1/16 in. diameter; No. 8 AWG copper wire electrodes spaced 11.6 cm, 19 to 20 deg C, 74.5 cm mercury, 50 cycles

△ Pyrex rod 0.90 in. diameter; No. 6 AWG copper wire electrodes, spaced 35.5 cm, 21.7 to 30.2 deg C, 76.0 cm, 60 cycles; from Littleton and Shaver[16]

× Suspension string of 3 10-in. units, dry striking distance 49 cm, 25 deg C, 76.0 cm, 60 cycles; from Peek[14]

□ Apparatus bushing (not oil filled), bare conductor in place; striking distance 80 cm, wet or dry, 25 deg C, 76.0 cm, 60 cycles; from Frey and Hawley[17]

+ Apparatus bushing, as above; striking distance 12.7 cm; from Frey and Hawley

v Suspension string of 3 10-in. units; dry striking distance 49 cm; 30 to 31.5 deg C, 76.0 cm, 60 cycles; from Lloyd[18]

←1 Suspension string of 3 10-in. units spaced 5 3/4 in.; dry striking distance 49 cm, surge voltage of 2-μ sec front; from Torok and Archibald.[19] Same value wet or dry

←2 Suspension string of 18 10-in. units spaced 5 3/4 in.; dry striking distance 265 cm, surge voltage of 2-μ sec front; from Torok and Archibald. Same value wet or dry

● Pyrex pin type insulator; striking distance 13.2 cm, 10.6 to 26.8 deg C, 76.0 cm, 60 cycles; from Littleton and Shaver

⊗ Upper points string of 10-in. units (vertical) dry; arcing distance 100 in., 60 cycles

⊗ Lower points outdoor pedestal type insulator (vertical) dry; arcing distance 100 in., 60 cycles; from discussion by J. E. Clem of paper by Frey and Hawley[17]

near each end of which is wrapped snugly a piece of heavy copper wire.

The curve of arcover strength against relative humidity for this simple rod is identical in shape with that of the pin insulator or suspension string, and, perhaps even more important, the actual arcover potentials per unit length of arcing distance resemble each other very closely as shown in Fig. 5.

Commercial Insulators

Technical literature seems to abound in reports of insulator tests that attempt to prove the differences between this and that shape, size or arrangement. The striking fact, however, is their similarity. Figure 5 is a collection of tests from many sources, assembled to show this similarity. The solid curve was drawn for a Littleton and Shaver type glass rod specimen 11.6 cm long, the dashed curve for a suspension string of 3 10-in. units. Other points have been inserted to show the remarkable agreement in arcover strength among commercial insulators of totally different designs. *The spread of the points in any individual test is practically equal to the spread of points from radically different classes of structures.* The only offenders are the apparatus bushing, which, because of its internal electrode, behaves unlike any other insulator used in electrical engineering, and the rather long (100 in.) pedestal and insulator string which are actually out of the range of length represented by the other tests. Curves such as those in Fig. 5 can be drawn for insulators having approximately 100-in. arcing distance. They will show lower arcover strengths than the 12-in. insulators. Thus 2 prominent fundamental characteristics have been brought out. First, in dry arcover, different shaped insulators, exclusive of apparatus bushing, having the same arcing distance have roughly the same arcover strength, which is here expressed in kilovolts per centimeter. Second, the arcover potential per centimeter diminishes when the length is increased just as it does for the right cylinders in uniform fields, Fig. 3. Table III is given in order to show that even more drastic changes in the nature and form of the insulation do not influence the arcover strength in the dry test at 60 cycles when the electrodes have the form of shield rings. Impulse tests, on the contrary, are influenced strongly by the geometrical details of the insulator.

Bibliography

1. Spray and Fog Tests on 220-kv Insulators, R. J. C. Wood. A.I.E.E. Trans., v. 49, 1930, p. 9 and discussion.

2. Puncture Strength of Air With Plane Electrodes, H. Rengier. *Archiv. für Elektrotech.*, v. 16, 1926, p. 76.

3. Arcover Strength of Insulators, Hans Ritz. *Archiv. für Elektrotech.*, v. 26, 1932, p. 58.

4. Breakdown of Solid Dielectrics, K. W. Wagner. A.I.E.E. Trans., v. 41, 1922, p. 288.

5. G. A. Liebig, P. M. (5) v. 24, 1887, p. 106; also *Handbuch der Experimental Physik*, W. O. Schumann, 1930 edition, p. 407. See also references 6 and 7.

6. Theory of Dielectrics, A. Schwaiger, translation by R. W. Sorensen, John Wiley, 1930; or in the original German, *Elektrische Festigkeitslehre*, second edition, 1925, Julius Springer (Berlin).

7. Elektrische Durchschlagfestigkeit von Gasen, W. O. Schumann, Julius Springer (Berlin), 1925. Curve of dielectric strength of air, p. 25.

8. Irving Langmuir, A.I.E.E. Trans., v. 32, 1913, p. 1921, and *Am. Chem. Soc. Jl.*, v. 38, 1916, p. 2283; also *Am. Chem. Soc. Jl.*, v. 40, 1918, p. 1387.

9. C. J. Davisson and L. H. Germer, *Phys. Rev.*, v. 30, no. 6, 1927, p. 705; also *Zeit. für Phys.*, v. 54, 1929, p. 408.

10. Puncture and Arcover in Air at Pressures of 1 to 30 Atmospheres, Carl Reher. *Archiv. für Elektrotech.*, v. 25, 1931, p. 277.

11. Arcover of Solid Insulators in Air, L. Inge and A. Walther. *Archiv. für Elektrotech.*, v. 26, 1932, p. 409.

12. An Optical Study of Spark Breakdown, F. G. Dunnington. *Phys. Rev.*, v. 38, 1931, p. 1535.

13. An Experimental Solution of Electrical Problems, E. W. Rice. A.I.E.E. Trans., v. 36, 1917, p. 905.

14. A Vacuum Discharge Tube for 2.4 Megavolts, A. Brasch and F. Lange. *Naturwiss.*, v. 18, 1930, p. 765.

15. Dielectric Phenomena in High Voltage Engineering, F. W. Peek, Jr, McGraw-Hill, 1929, third edition.

16. The Effect of Humidity on Dry Flashover, J. T. Littleton and W. W. Shaver, A.I.E.E. Trans., v. 47, 1928, p. 438.

17. Normal Frequency Arcover Values of Insulators, H. A. Frey and K. A. Hawley. A.I.E.E. Trans., v. 51, 1932, p. 890.

18. Insulator Sparkover, W. L. Lloyd, Jr. A.I.E.E. Trans., v. 51, 1932, p. 669.

19. Suspension Insulators, Economic Selection, J. J. Torck and C. G. Archibald. A.I.E.E. Trans., v. 51, 1932, p. 660.

20. The Sixty-Cycle Flashover of Long Suspension Insulator Strings, R. H. Angus. A.I.E.E. Trans., v. 49, 1930, p. 15.

A Glow Discharge Anemometer

A glow discharge at atmospheric pressure is responsive to air velocity, and may be used as an anemometer. The properties of such a glow are discussed in this paper, and data relating to glow current, voltage, glow length, and air velocity are presented. It is also shown that the glow discharge responds to rapid fluctuations in air velocity and is therefore a practical device for investigating turbulence. A comparison of such an anemometer with the previously used hot wire method is given.

By
FREDERICK C. LINDVALL
ASSOCIATE A.I.E.E.
California Institute of Technology, Pasadena

RECENT aerodynamical research of both theoretical and experimental nature has indicated the important influence which air turbulence has on wind tunnel measurements. Experimental quantities, the lift and drag coefficients, are materially affected by the existence of small fluctuations superposed on the measured stream velocity. Moreover, these fluctuations in velocity, constituting turbulence, are characteristically of relatively high frequency and random nature, so that their presence is not indicated by air speed meters, manometers, or other velocity measuring devices involving inertia. Accordingly a need exists for methods of studying such turbulence both quantitatively and qualitatively.

Numerous schemes for meeting this need have been proposed and investigated heretofore, only one of which, the hot wire anemometer, satisfies at all well the aerodynamical requirements. This device, ostensibly simple and relatively satisfactory, consists of a fine wire heated electrically by current flow and subjected to the variable cooling induced by the velocity fluctuations in the moving air stream. The corresponding variations in voltage drop of the wire are amplified to measurable proportions for oscillographic study or direct meter indication.

Difficulties Inherent in Hot Wire Anemometer Scheme

Inherent in this scheme are 2 fundamental difficulties, compensation and calibration, both of which are surmountable but not without the introduction of some ambiguity into the results. Since ordinary turbulence has a frequency spectrum much like that of acoustic noise, compensation is essential because the hot wire response is much greater for low frequency velocity fluctuations than for those of high frequency. In order to obtain something approximating a faithful reproduction of turbulence a distorting circuit must be employed in the amplifying equipment, the characteristics of which are dictated by the various factors contributing to the "lag" of the wire. The lag characteristics of the wire are, in turn, determined from a theoretical analysis necessarily involving assumptions and approximations. Such procedure is a rational one and necessary; but, it is unfortunate that no standard turbulence exists nor has any velocity fluctuation thus far been devised whose characteristics, in magnitude and quality, are known without serious ambiguity to serve as an over-all check on the fidelity of the hot wire apparatus except for very low frequencies. Moreover, the fairly obvious test which may be made of compensation by passing through the wire a heat-

Full text of a paper recommended for publication by the A.I.E.E. committee on research, and scheduled for discussion at the A.I.E.E. Pacific Coast convention, Salt Lake City, Utah, Sept. 3–7, 1934. Manuscript submitted April 23, 1934; released for publication June 4, 1934. *Not published in pamphlet form.*
1. For all numbered references see list at end of paper.

ing current containing an alternating component of known frequency gives only a partial verification since conditions under which the wire operates for this measurement are not equivalent to those encountered in actual use as an anemometer. Then too, this compensation necessarily influences calibration, that is, affects the interpretation of amplifier output measurements in terms of actual or relative velocity fluctuation. The method of computing magnitudes of turbulence from hot wire observations is, of course, not relevant to the present paper. Significant, however, is the fact that compensation and calibration are both functions of average air speed, a circumstance which increases both the experimental work and the subsequent reduction of data.

These Difficulties Not Encountered in the Glow Discharge Anemometer

Thus, despite the many desirable attributes of the hot wire anemometer and the excellent work which it has made possible, the thermal lag of the wire introduces difficulties which have stimulated a search for other means of studying turbulence. This quest has led to a new electrical method employing as its sensitive element a minute glow discharge. Such an electrical discharge at atmospheric pressure is characterized principally by a cathode glow a few thousandths of a centimeter in length and potential of the order of 300 volts, and a positive column having a voltage gradient of approximately 1,500 volts per centimeter. The corresponding discharge current is in the range of from 10 to 30 ma. The total voltage of such a glow, about 400 volts, acted on by a transverse stream of air, was found to increase substantially with increasing air velocity, throughout a range in speed as great as that ordinarily employed in wind tunnel studies. Moreover, this glow is responsive to turbulence and gives results which are in excellent agreement with those obtained with the hot wire. A description of these results and the essential apparatus yielding them, together with a criticism of the glow discharge method of analyzing turbulence, form the substance of this presentation.

Apparatus of the Glow Discharge Anemometer

A few exploratory experiments served definitely to establish the essential fact that a glow discharge is sensitive to air velocity. Moreover, these qualitative tests indicated practical limits for the length of the glow and magnitude of the discharge current, which, together with aerodynamical requirements as to size and disposition of the discharge electrodes specified the essential apparatus and the electrical quantities involved.

A mounting of electrodes for practical work is shown in Fig. 1. The electrodes proper are silver-soldered to the supporting rods which are kept at proper spacing by the screw clamping device and terminate in an insulating block.

A more elaborate gap mounting employed to study the variation of glow voltage with length for several values of air velocity is indicated in Fig. 2. The illustration is self-explanatory, giving clearly the means of adjusting gap length as well as showing the section of glass rod which insulates one electrode from the rest of the assembly. The removable tapering tips which hold the electrode points make relatively simple a change of tip material.

The electrical circuit found to be most desirable appears in Fig. 3. A transformer and rectifier tube

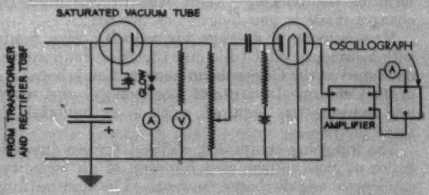
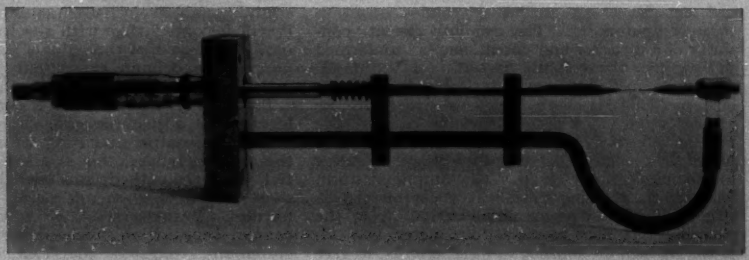


Fig. 1 (left). Glow anemometer mounting

Fig. 3 (right). Electrical circuit of glow and measuring apparatus

Fig. 2 (below). Glow anemometer with adjustable gap



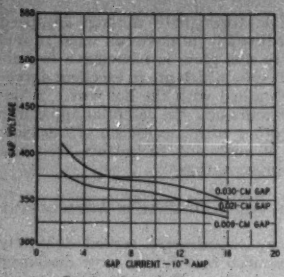


Fig. 4. Air velocity = 0

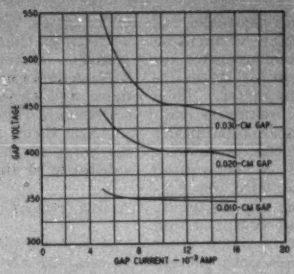


Fig. 5. Air velocity = 8 meters per second

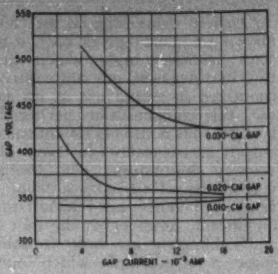


Fig. 6. Air velocity = 20 meters per second

Figs. 4–6. Glow voltage-current relationships

maintained the capacitor at a potential of approximately 5,000 volts. The glow discharge current was held constant by the saturated vacuum tube shown and was adjustable through filament current in a range of from zero to 50 ma. (This circuit is essentially that employed by Phillips Thomas in his studies on the microphonic properties of a glow discharge.[1]) The change in average voltage of the glow was measured with a microammeter having a series resistor of approximately 14 megohms and with a bucking circuit (not shown) set to give zero meter indication for the discharge operating in still air. Accordingly with the latter arrangement the increase in glow voltage produced by the air appears as a direct meter indication. An over-all calibration of this potential measuring circuit was effected by inserting in series with the glow voltage, by an obvious switching arrangement, a 45-volt battery which produced a meter deflection corresponding to this known increase in voltage. Such an arrangement was desirable inasmuch as frequent adjustment of the bucking circuit was necessitated by changes made in gap length or current.

Measurement of average air velocity was made with a standard pitot tube and precision manometer developed at the Guggenheim aeronautics laboratory of the California Institute of Technology, and when less accuracy was required, with a commercial air speed meter.

The foregoing equipment sufficed for an investigation of glow voltage as a function of air velocity, gap length, and discharge current. The fluctuations in voltage induced by turbulence in the moving air stream were transmitted through a coupling circuit and amplifier to an oscillograph and root-mean-square output meter. The coupling circuit, consisting of a capacitor and potentiometer, conformed to these important conditions: sufficient impedance to permit rapid fluctuation of glow voltage; adequate insulation in the capacitor to withstand the striking voltage of the gap and to prevent the running voltage of the glow from affecting the grid bias of the coupling tube; and appropriate shielding to minimize stray pick-up. The amplifier itself, following the coupling tube, was a commercial 2-stage unit. The over-all amplification, from the glow discharge input to the output meter, was adjusted, through the addition of filter circuits, to give very closely a uniform frequency response from 50 to 2,500 cycles.

Limits of Glow Current

The limits for glow current are empirical: too low a value leads to a stringy type of spark discharge at high voltage; too high a value leads to excessive heating and burning of the cathode, rendering impossible any reproducibility in curves of gap voltage as a function of air velocity. Moreover, for a certain limited range of current values, the gap voltage is nearly independent of current—a happy circumstance which makes small fluctuations in emission current of the control tube insignificant.

Details of Gap and Electrodes

The length of the discharge, or more precisely the length of the gap, since the former is indefinite due to spread of the cathode glow, is an important factor in this work as will be seen in the data to follow. Lengths ranging from 0.002 cm to 0.200 cm were tested and a useful range of from 0.010 cm to 0.025 cm was employed for most of the work with turbulent air flow. An extremely short gap is insensitive to air velocity while a long discharge is blown downstream into a bow shape having a greatly lengthened positive column with corresponding abnormally high voltage. Moreover, this "blowing back" gives an unstable type of discharge, apparently in a transition state between the spark and the glow types of conduction, which "sings" at a high audible frequency and therefore is worthless as a device for studying air velocity fluctuations. Accordingly, it will be noted that with the lengths of gap ordinarily employed, of the order of 0.015 cm, practically no positive column exists, only the characteristic cathode glows being visible.

For the investigation of the effect of discharge length, the adjustable gap, shown in Fig. 2, was used. The entire mounting with the exception of the cathode holder, was at anode or ground potential, while the cathode was insulated therefrom by a short length of glass rod rigidly gripped in metal ferrules. Various metals were used for electrodes: copper, brass, iron, steel, nichrome, nickel, silver, chromium, tungsten, platinum, and platinum-iri-

dium. All electrodes were approximately 0.15 cm in diameter with ends ground conically at about 20 deg taper. Of these various materials platinum, platinum-iridium, and tungsten were the most satisfactory, giving the minimum of difficulty from destruction of the points. Platinum gave a more consistently stable discharge as well as better reproducibility in data than did tungsten and therefore was used for the bulk of the tests.

In such a test device, the diameter of the electrodes should be comparable to the dimension of the glow itself in order that velocity, as measured, be definitely that of the stream flow and not the true velocity modified by the presence of bulky electrodes. Hence, only small diameter material may be used for cathode and anode with consequent small surface and cross section area for heat dissipation and conduction. Therefore, to minimize irregularities in behavior of the discharge due to heating of the electrodes a current value must be used which is as small as will give a satisfactory response of the gap over a particular velocity range.

Tests Without Turbulence Introduced

The first group of tests had as an object a study of the interdependence of glow voltage, glow current, gap length, and air velocity, the air flow being turbulent to a negligible extent. The procedure was to measure glow voltage as a function of current for specific values of air velocity and particular settings of gap length. Typical results of these measurements are given in Figs. 4, 5, and 6. Glow voltage is plotted against current, each figure being for a designated air velocity and each curve corresponding to the gap length indicated. In order to avoid confusion only 3 gap settings are given.

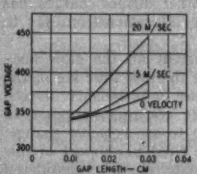


Fig. 7. Glow voltage as a function of gap length

Current = 10 ma
Air velocity = 0, 5, and 20 meters per second

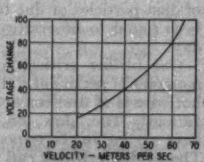


Fig. 8. Change of glow voltage with air velocity

Current = 14 ma

The nature of these curves is in accord with that of a normal glow discharge. The extremely short gap gives a glow voltage virtually independent of gap current, except for high air velocity. Indeed, one may say that the short glow is almost wholly a cathode phenomenon, and only when the discharge is effectively lengthened by the transverse air motion, does it exhibit the negative resistance quality so characteristic of the typical glow discharge. The longer gap, however, gives rise to a discharge having the familiar hyperbolic characteristic for all air velocities including zero. Yet, considering all of the curves with a view to finding an optimum current value for air flow study, one sees that for the velocity range of these data 10 or 15 ma in the discharge gives an over-all minimum of voltage change due solely to current fluctuation.

Choosing, then, a particular value of current to be maintained in the discharge, curves may be derived from the preceding data which indicate the dependence of gap voltage on gap length, air velocity being an arbitrary parameter. Such curves, presented in Fig. 7, exhibit the essentially linear nature to be expected as the relationship between voltage and length of discharge, and suggest that the increase in glow voltage with velocity is due largely to a lengthening of the discharge.

Then, finally, from such data were obtained curves relating the essential quantities, voltage and air velocity. These curves, such as the one of Fig. 8 could be made to have either increasing or decreasing slope with higher air speed, giving sensitivity in either the low or the high velocity range by suitable choice of gap length and current.

These calibration curves indicate a voltage change of the order of volts per meter per second velocity increment, a response which is ample for investigating turbulence of quite small magnitude. Indeed, the sensitivity of the glow to turbulence, as predicted by such data, is approximately 100 times as great as that of the hot wire anemometer, substantially simplifying the amplifier problem. Accordingly it remained to demonstrate that the glow discharge responds faithfully to turbulence and to that only.

Tests on Response to Turbulence

That the glow really responds to turbulence was shown qualitatively in the wakes behind cylinders and flat plates where conditions are fairly well known from accepted theoretical and experimental aerodynamical research.[2,5] Moreover, the oscillographic representation and the amplifier output meter readings observed during any traverse of the air flow downstream from an obstruction, conformed beautifully with results of similar tests made in air and other fluids by various means. The glow anemometer gave no indication of turbulence in those portions of the flow known to be steady, thus eliminating the possibility of microphonic response, but it responded unquestionably to the velocity fluctuations in regions of disturbed flow, bringing out, in addition

Fig. 9. Turbulence behind cylinder for 2 air velocities

Left, upper trace—9.9 meters per second velocity, frequency 133 cycles. Right, upper trace—16.3 meters per second velocity, frequency 220 cycles
Lower traces—50-cycle timing waves

to the usual random variations, the more or less regular sequence of vortices so characteristic of the wake behind a regular body. The oscillograms of Fig. 9 represent such a vortex sequence behind a cylinder for different air velocities, with a 50-cycle timing wave included to establish the frequency of the turbulence. These frequencies were found to agree with values computed from the vortex theory of von Kármán[3] which states that frequency is directly proportional to velocity and inversely proportional to the diameter of the cylinder. The factor of proportionality is 0.18 for any consistent set of units.[4]

Further confirmation of the response of the glow to turbulence came with simultaneous oscillograph records for hot wire and glow located at similar points in the 2-dimensional flow behind a cylinder.

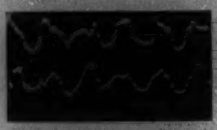


Fig. 10. Comparison between glow and compensated hot wire systems for measuring turbulence behind a cylinder

Upper trace. Hot wire scheme
Lower trace. Glow discharge scheme

The oscillograms of Fig. 10 show clearly that the glow response is as nearly like that of the compensated hot wire as the instantaneous velocities at 2 points in a turbulent fluid would compare. Moreover, simultaneous quantitative measurements of turbulence, root-mean-square velocity fluctuation divided by average air speed, gave good agreement between glow and hot wire methods.

The calibration of the glow anemometer for quantitative measurements of turbulence was achieved in a relatively simple way. Either mean-square or root-mean-square velocity fluctuation is a convenient quantity for theoretical consideration of turbulence, and either is conveniently metered in the amplifier output. Accordingly, if at a certain average speed, turbulence produced a particular root-mean-square output current, that same value of current was later caused to flow by impressing an adjustable alternating voltage at approximately 500 cycles across the terminals of the glow discharge. For example, suppose that 3 volts effective, 500 cycles, at the gap produced the same value of output current as the turbulence. A voltage fluctuation of 3 volts root-mean-square therefore must have been caused by air speed variation. A portion of the curve of gap voltage against average air speed establishes the value of the slope $\frac{\Delta e}{\Delta v}$ at the test velocity—only 1 or 2 points on either side being necessary—and leads at once to a value of root-mean-square velocity fluctuation. In short, the calibration as used was of the over-all type in which all essential data were taken at the time of the turbulence measurements.

Discussion of Results

The data which have been obtained with the glow anemometer demonstrate that such an electrical discharge is sensitive to air velocity in both the steady and turbulent states. Moreover, for the study of air turbulence this electrical method has certain definite advantages over the hot wire scheme, notably in calibration and simplicity of amplifying equipment. Yet, the glow itself has one notably outstanding defect which, fortunately, is more of a nuisance than an evil. Any such electrical discharge will inevitably result in some slow loss of electrode material, through sputtering and chemical modifications in the presence of air. And, as a consequence, a particular length of gap as used in this work will lengthen appreciably during the course of a run of 15 or 20 min duration, so that final data will not coincide with the original average calibration curve. Still, this difficulty is more apparent than real for 2 reasons. First, in turbulence studies made in the course of usual wind tunnel or other air flow work, ample opportunity exists for obtaining average voltage-speed data near the operating point at a time near enough to that of the turbulence measurement to give the characteristic slope. And, second, the slopes of 2 calibration curves corresponding to slightly different gap lengths are, for the same average air speed, practically identical. Consequently this defect in the glow anemometer is not serious, it merely prescribes a technique of measurement. And, indeed, the hot wire, because of accidental adherence of dust particles or due to other surface charges, has been found to be erratic in calibration from day to day.

One further critical comment on the glow anemometer is pertinent. The thermal time lag of the hot wire is of first importance in turbulence investigations. The glow, on the contrary, appears to have no lag in its response to air velocity change. The evidence which can be cited in support of this statement, however inadequate, must be considered in the absence of a satisfactory method of experimental verification, as previously discussed. Nothing in the mechanism of an atmospheric glow of the dimensions used could introduce a time lag significant in the frequency range of turbulence, for ion mobilities are adequately high.

Then, too, in the work which employed a glow as a microphone[1] it was found that a flat frequency response was approached as shorter gaps were employed, a fact which is significant when it is realized that for an anemometer a much shorter gap length was used than for a microphone. And, finally, the direct comparison of glow and compensated hot wire showed no indication of time lag in the glow discharge.

In conclusion, it may thus be stated that a new and interesting property of the atmospheric glow discharge—the variation of voltage with air velocity—has been shown to exist and that this property may be utilized in an anemometer for the study of turbulent air flow. Such an anemometer, the author believes, is a useful adjunct to the hot wire equipment, and, because of the essential ruggedness of the glow mounting, may be incorporated in a wind tunnel for routine measurements, an opinion which was encouraged largely by the consistent interest shown in this work by Dr. Theodor von

Kármán, director of the Guggenheim laboratory of aeronautics at the California Institute of Technology.

REFERENCES

1. A DIAPHRAGMLESS MICROPHONE FOR RADIO BROADCASTING, Phillips Thomas. A.I.E.E. TRANS., v. 43, 1923, p. 1111–14.

2. EFFECT OF TURBULENCE IN WIND TUNNEL MEASUREMENTS, H. L. Dryden and A. M. Kuethe. Nat'l. Advisory Committee on Aeronautics, 1930, Report No. 342, p. 147–73.

3. ÜBER DEN MECHANISMUS DES FLÜSSIGKEITS- UND LUFTWIDERSTANDES, T. v. Kármán and H. Rubach. *Physikalische Zeitschrift*, v. 13, 1912, p. 49–59.

4. ON THE FREQUENCY OF THE EDDIES GENERATED BY THE MOTION OF CIRCULAR CYLINDERS THROUGH A FLUID, E. F. Relf and L. F. G. Simmons. *Philosophical Mag.*, v. 49, Feb. 1925, p. 509–11.

5. HYDRODYNAMICS (a book), Horace Lamb. Cambridge University press, ed. 6, 1932, p. 208 et seq.

Distance Relay Action During Oscillations

The behavior of distance relays during system oscillations is analyzed in this paper, and curves are presented for determining whether the oscillations are likely to cause relay operation. Different types of distance relays are considered and general methods of analyzing system conditions are discussed.

By
E. H. BANCKER
MEMBER A.I.E.E.

E. M. HUNTER
ASSOCIATE A.I.E.E.

General Elec. Co., Schenectady, N. Y.

OPERATING experience with directional distance relays has demonstrated their ability to clear short circuits rapidly and reliably. However, a few instances have been reported in which apparently a circuit breaker was opened when portions of the system were subjected to a power oscillation or lost synchronism because of a fault. Within recent years much study has been devoted to the effect of relay characteristics upon system stability and it now appears desirable to consider the converse, namely, the effect of an unstable system upon the relays protecting the unfaulted portions.

The term "unstable" is here used to denote any condition of operation during which the rotors of the connected synchronous apparatus do not maintain a substantially constant angular relationship with each other. Under this classification there can be 2 kinds of instability; (1) one is a continuous, unidirectional angular departure of one or more rotors with respect to the others which results in loss of synchronism, slip, or out-of-step operation; (2) the other is a fluctuating change of relative rotor positions, termed oscillating, swinging, or surging, which eventually will damp down to a condition of stable equilibrium.

There is some diversity of opinion as to whether or not distance relays should open any circuit breakers during out-of-step operation, some engineers believing that the essential separation should be performed manually or automatically at a predetermined point in conformity with the load conditions, and others caring little where it occurs, provided no load is left without a source of power.

On the other hand, opinion is nearly unanimous in preferring that under oscillating conditions no circuit breaker shall be opened by any protective relay. Since such an eventuality is within the bounds of possibility, this paper is presented to point out the procedure to be followed in determining whether distance relays in a particular location are in any danger of tripping unnecessarily during swings. Methods of avoiding such false operation are presented which may be used should a study show a need for remedial measures.

TYPES OF RELAYS AND THEIR CHARACTERISTICS

Two general types of directional distance relays are available, one using line reactance and the other line impedance as the measure of the distance to the point of fault. Both types have 3 distinct elements: (1) a directional unit; (2) an ohm unit or units consisting, in the reactance relay, of one or more reactance measuring devices, and in the impedance relay of several impedance measuring devices corresponding to the number of steps in the relay; and (3) a timing unit. In the impedance relay the indicated line impedance is obtained by comparing the magnitude of the voltage with that of the current. In the reactance relay the comparison is made between the current and the inductive component of the voltage.

Both types of these relays have a "step characteristic" giving definite operating times for different fault locations, as shown in Fig. 1. A fault in zone 1 (often called instantaneous zone), which covers approximately 80 per cent of the line distance to relay station 2, is cleared in minimum time. A fault in zone 2, which covers the last 20 per cent of the line to relay station 2 and something less than 80 per cent of the line distance to station 3, is cleared in intermediate time, and a fault in zone 3 is cleared in back-up time (so called because no relay should ever operate in this time unless some other device has failed to operate correctly). In considering

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and discussed at the A.I.E.E. North Eastern District meeting, Worcester, Mass., May 16–18, 1934, and also scheduled for discussion at the A.I.E.E. Pacific Coast convention, Salt Lake City, Utah, Sept. 3–7, 1934. Manuscript submitted Feb. 27, 1934; released for publication March 19, 1934. *Not published in pamphlet form.*

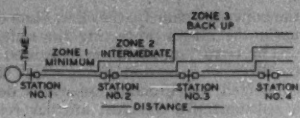


Fig. 1. Time-distance characteristics of directional distance relay

distance relay performance during power swings, these operating zones are important and subsequently will be designated as instantaneous, intermediate, and back-up zones.

Directional distance relays are generally installed to take care of 3-phase, line-to-line, and double-line-to-ground faults. A few installations have been made for line-to-ground faults, but since ground distance relays are not affected by balanced 3-phase power swings, only line relaying is here considered.

Origin and Nature of Instability

The nature of short circuits and their effect upon distance relays has been amply treated in published literature. Methods of calculating system oscillations have also been described in previous papers but it is believed that a brief review of the origin and nature of instability will facilitate the study of its effect upon distance relays. In a loaded stable system all synchronous apparatus rotates at a constant electrical speed with certain constant angular displacements between the generated voltages, since in a synchronous system energy is transferred by an angular separation of voltages. (See Fig. 2.) Two opposing torques act upon the rotor of each machine, a mechanical shaft torque and an electrical stator torque. In equilibrium these must be exactly equal and opposite at all times (as at 0, curve A, Fig. 2). When either changes, the affected rotor will start to move at a different angular velocity from the rest of the system in an endeavor to find some new angle which again equates the torques, but while so moving its mass has been acted upon by the torque difference, and stored energy of motion away from system angular velocity has been imparted to it. For example, consider a motor connected to a large system having a shaft torque T_1 in Fig. 2. Assume the load to change suddenly so that the mechanical torque is T_2. The generated or excitation voltage of the motor has the angle α with respect to the system voltage which only results in an electrical torque of T_1. The rotor accordingly begins to slow down and increase the angle, thereby raising the electrical torque, which varies as the sine of the angle. When the voltages are separated by angle β (point 2) the 2 torques are equal but the rotor has put out more energy than it received and is traveling at a speed corresponding to a different frequency from that of the system. It does not stop at angle β but continues to drop behind the system, now having more input than output. It will continue to some angle γ (point 4) until the previous excess output is canceled by the excess input, at which instant it rotates at system frequency, but with more input than output. The process is now reversed and the rotor advances, changing the electrical torque along the curve from 4 to 2 toward 0, after which the entire cycle is repeated and would continue indefinitely if it were not for damping factors which reduce the amplitude of each oscillation, until finally equilibrium is reached at point 2.

A sudden change in electrical torque produces an analogous but opposite action. Assume the same motor to have a mechanical torque of T_1 and to be operating with angle α at point 0 on curve A. Let the electrical torque angle characteristic of the system and motor suddenly change to curve B. The rotor is still at angle α but the input is less than the output as at point 5. Again, the rotor drops back in angle to δ (point 7) and oscillates between 5 and 7. Thus, a sudden reduction in electrical torque initiates the same kind of phenomenon as a sudden increase in mechanical torque.

Example of Unstable Operation

In both of the examples given, the motor eventually would become stable and continue to operate in synchronism with the system. Had the mechanical

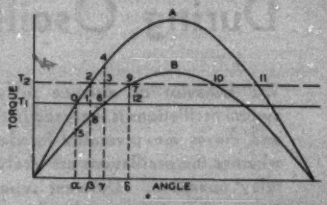


Fig. 2. Torque-angle characteristic of a synchronous system

A and *B*—electrical torque-angle characteristic T_1 and T_2—mechanical torque

load in the last example been T_2 originally, a different result would be obtained when the torque angle characteristic is suddenly changed from curve A to curve B. In this case the rotor would start at angle β (point 2) and the torque would drop to point 8. The rotor would slow down, increase the angle and input along curve B but when it reaches point 10 there would still be an excess of energy output over input so that it would continue to drop back. After passing point 10 the input drops below the output and the motor rapidly falls off in speed. Eventually, it will stop entirely or perhaps run as an induction motor at some slip below system frequency. In either event it is definitely out of step with the rest of the system. It has been proved that the final result of a sudden torque change will be determined by the available area lying above the mechanical torque line and within the electrical torque angle curve upon which the system happens to be operating. (See reference 2 in list at end of paper.) In the first example, the area 0, 1, 2 is equaled by area 2, 3, 4, and there is still an area 4, 3, 11 remaining in which the input exceeds the output and the rotor velocity may be stopped. Similarly area 6, 12, 7 equals 0, 5, 6 and there is more available if needed. In the last example, however, area 9–10 does not equal 2, 8, 9, and the machine loses synchronism.

Causes of Sudden Changes

Sudden changes in electrical torque will be caused by short circuits and switching operations. Mechanical changes arise from poor synchronizing or suddenly applied loads. The result is invariably either a new stable condition or loss of synchronism by one or more machines or groups of machines. During the unstable period the current and voltage rise and fall alternately and oppositely and the voltage at any given instant is different in magnitude and phase position at different points on the system.

Vector Relations

Consider a simple loaded system comprised of a generator and motor with interconnecting lines between them. When operating stably, or at some particular instant during instability, the vector relations are as shown in Fig. 3. E_1 represents the internal voltage of the generator and may be either the excitation voltage or the voltage back of transient reactance, depending upon whether steady or transient conditions are under consideration. E_2 is the corresponding motor voltage, which normally would be nearly equal to E_1, but which is enlarged in Fig. 3 to show more clearly the distinction between the electrical and impedance centers. The total angle between generator and motor voltages is called displacement angle. At some point in the system, the voltage will be a minimum, and this point is referred to as the electrical center of the system. At the same or some other point the current and voltage are in phase with each other and this is denoted as the unity power factor point. When the excitation voltage of the generator and motor are equal and the system consists of reactance only, both of these points coincide with the impedance center, which is one-half of the total system reactance away from either end. If the system contains some resistance the electrical center still coincides with the impedance center but the unity power factor point is a fixed angle φ on the generator side of the electrical center, the angle φ being 90 deg $- \tan^{-1} \frac{X}{R}$ where X and R are total reactance and resistance including generator, system, and motor. If the excitation voltages are unequal neither point falls at the impedance center and both vary their position with the angle between generator and motor voltages, but the unity power factor point remains the same angle ahead of the electrical center at all times.

Study of a Representative System

The electrical characteristics of a synchronous system can probably best be shown by giving the results of a study of a representative system. The system for this study consisted of 2 equivalent machines, a generator, and a motor with a single reactance tie between them. The machines had equal excitations and normal power occurred at a system angle of 45 deg. Synchronizing power and the magnitude and phase relations of the current and voltage at 3 relay stations on the line between the equivalent machines were determined. Relay station 1 was located midway between the equivalent generator and the electrical center, relay station 2 at the electrical center, and relay station 3 at one-quarter of the distance between the electrical center and the equivalent motor.

The variation of the system electrical characteristics as a function of the displacement angle is shown in Fig. 4. Synchronizing power varies proportionally as the sine of the displacement angle; line current as the sine of half this angle. The voltage and angle between current and voltage at the various relay stations are functions not only of the displacement angle but also of the location of the relay station with respect to the electrical center of the system, the lowest voltage occurring at the relay station nearest the electrical center of the system.

The time variation of these electrical quantities depends upon the rate of change of the displacement angle. In an actual system, the rate of change of the displacement angle is not uniform, the angle increasing slowly at first as the rotating machines start to accelerate and later changing more rapidly if the machines go out of step.

In Fig. 5 are shown the curves of Fig. 4 replotted to a time scale which is representative of an unstable system. As the rotating machines go out of synchronism, the line current increases with the displacement angle and becomes a maximum at a displacement angle of 180 deg. The voltage at the several relay stations decreases as the displacement angle increases and the angle between the current and voltage at these stations increases. At 180-deg total displacement angle the voltage at the electrical center of the system is zero and the current is a maximum, a condition that appears to the other relay stations as a 3-phase fault at the electrical center of the system.

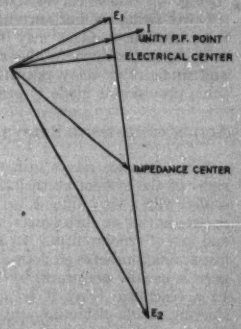
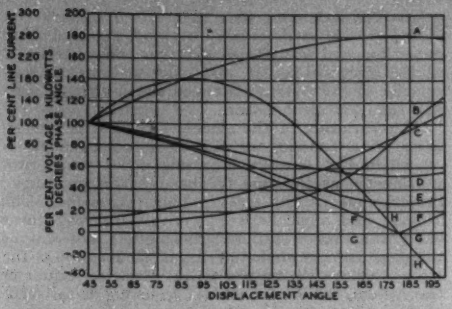
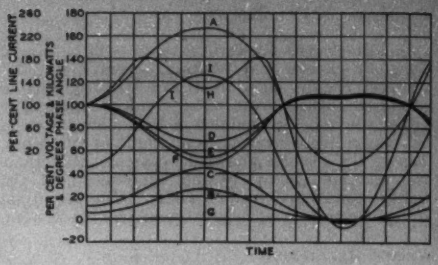


Fig. 3. Vector relations of a 2-machine synchronous system

When a system swings but does not go out of synchronism, the line current reaches a maximum and the voltages at the relay stations become a minimum at the maximum angle of swing. While it is theoretically possible for a system to swing to an angle of 179 deg, the practical limit in most cases





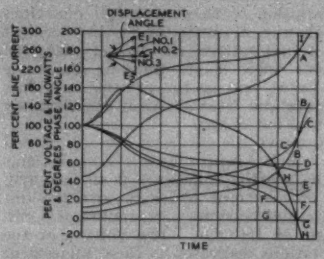


Fig. 4 (left, above). Variation of system electrical characteristics as a function of displacement angle

Fig. 5 (left). Variation of electrical characteristics of an unstable system as a function of time

Fig. 6 (right, above). Variation of electrical characteristics of an oscillating system as a function of time

A. Line current
B. Angle current leads voltage No. 3
C. Angle current lags voltage No. 1
D. Voltage at relay station No. 1
E. Voltage at relay station No. 3
F. Voltage at relay station No. 2
G. Angle of current with voltage No. 2
H. Kilowatts
I. Displacement angle

probably does not greatly exceed 120 deg, with maintained synchronism. The current and voltage conditions at the 3 relay stations during a power swing which ultimately resumes stability are shown in Fig. 6. These curves indicate that during such a power swing the line current may increase and the relay station voltages may dip sufficiently to give tripping indications to the relays at the stations, and undesirable relay operations may occur unless some provision is made to prevent them.

Action of Distance Relays

Since distance relays utilize the electrical dimensions of the system at their location, they are presented with a very difficult problem of discrimination in attempting to distinguish between faults, swings, and loss of synchronism. In an impedance relay the discrimination between normal and abnormal conditions is usually performed by the impedance devices. In a reactance relay it is performed chiefly by a starting, fault detecting unit rather than by the reactance elements, because, except during faults, reactance elements as usually connected will indicate the distance to the unity power factor point of the system and would operate in a time depending upon the location of the relay with respect to this point, unless there is a change in the number of parallel circuits between the relay location and the unity power factor point. The reactance elements are of some benefit in preventing undesirable tripping by relays located at some distance from the unity power factor point. Hence a study of the susceptibility of directional distance relays must include the starting units as well as the distance measuring elements.

An impedance relay, except during fault conditions, indicates any value from infinity down to the impedance between its location and the electrical center of the system, depending upon the total displacement angle between machines and the location of the relay with respect to the electrical center.

In a pure reactance system at 180-deg displacement angle, impedance and reactance relays indicate alike, but at stable system angles, impedance relays measure something greater than the distance to the electrical center.

At first glance it would appear that a swing of sufficient amplitude to operate either reactance or impedance relays would result in clearing only the section containing the electrical center, because both the reactance and impedance measurements are a minimum at its ends; but unfortunately this does not invariably hold true. As will be brought out later, the starting units of reactance relays remote from the center may operate earlier in the swing than those nearer the center. The ohm units will indicate intermediate or back-up time, but as this expires and the relay is about to trip, the starting unit of the relay on the line containing the unity power factor point may operate and its ohm unit indicate instantaneous tripping so that 2 circuit breakers open simultaneously. With the impedance type, the relay nearest the electrical center will have the lowest indicated impedance in any portion of the cycle but those adjacent to it may have but little more and may have a higher ohmic setting because

of different line lengths. As with the reactance relays, the gradually decreasing ohmic indication may start to trip some breaker in back-up or intermediate time, but as the timer completes its travel the instantaneous element of some other relay operates also. Unless the starting unit, or instantaneous impedance element, of the relay nearest the center operates there will be a time delay before the relay trips, and if the swing is rapid the indicated ohms may rise and cause the relay to reset without completing its contact circuit. Hence, the prediction of the behavior of distance relays during system oscillations or out-of-step conditions requires a study of both relay and system characteristics.

Characteristics of Relay Starting Units

The type *GAX* relay is a single-phase 3-step directional distance relay operating on the reactance principle. The type *GCX* relay is similar in principle, but incorporating certain mechanical refinements.

The operating torque of the starting unit of the type *GAX* reactance relay is approximately *EI* sine (θ + 15 deg) with E^3 restraint. The characteristics of the starting unit of the type *GCX* reactance relay deviate only slightly from those of the type *GAX* relay, the principal difference being a means for changing the sensitivity to several values of minimum operating current. These values are approximately 8, 12, and 16 amp at the angle of maximum torque and 100 per cent voltage. At the reduced voltages existing during faults the minimum operating current also goes down, the actual value depending upon the type of short circuit and angle of lag of the fault current. Thus the tap values are by no means the fault current required to operate the relays. These starting units will have a maximum tendency to operate at various distances from the electrical center depending upon the total angle between the machines. Relays having double current coils, delta connected current transformers, or quadrature connection and located near the electrical center would not operate since the sine (θ + 15 deg) is small, causing a high pick-up.

The impedance relay has the greatest tendency to operate when located at the electrical center for this is the place of lowest voltage on the system and the current is probably as high as anywhere else.

Curves of Relay Susceptibility

The likelihood of false operation of either the impedance or reactance relay during stable power swings depends upon: (1) the location of the relay station with respect to the electrical center of the system; (2) the maximum angle of the swing; and (3) the sensitivity of the fault detecting elements. In order to enable users to determine the possibility of an incorrect relay operation arising from system oscillations, a set of curves has been prepared to show the relative susceptibility of these relays to power swings. In the preparation of these, certain simplifying assumptions have been made which, nevertheless, do not detract from their usefulness. It is assumed that the relays under study are located on the tie between portions of a system and that there is an interchange of power over this tie. The system is then considered as 2 machines, an equivalent generator and a motor connected through the tie, each having the combined impedance of the group up to the relay bus at its end of the tie. This method of grouping and the calculation of the swing resulting from a shock such as a short circuit has been described in previous papers. The machines are assumed to have equal excitation and the tie is assumed to be pure reactance. The starting units of the reactance relays are assumed to have maximum torque when the current lags the voltage by 90 deg. However, these curves also apply to relays which have maximum torque at some other angle when it coincides with the natural angle of the system. (The term natural angle of the system refers to the angle whose tangent is the total reactance from end to end including the equivalent machines, divided by the total resistance.) Various maximum displacement angles have been assumed and the operating characteristics of the relays when located at and away from the electrical center have been plotted.

In order to employ the curves it becomes necessary to reduce the system to an equivalent 2 machine group and either calculate or assume a maximum stable angle of swing. If the maximum load over the tie is known the maximum angle with ultimate stability may be assumed as the same number of degrees above 90 deg that the stable operating angle is below 90 deg, *e. g.*, if the system operates with 60 deg between voltages at the maximum load, the maximum displacement angle is 120 deg. This does not mean that the system will necessarily swing to the maximum angle after every disturbance but it cannot go beyond this angle and retain synchronism. A large amount of labor is saved if the angle is assumed and the relay performance found to be satisfactory should this angle be reached. Naturally

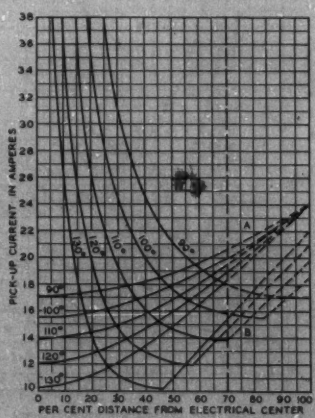


Fig. 7. Characteristics of 12-amp tap of type GCX relay starting unit with 4.8-ohm "ohm unit" and 4.8-ohm impedance relay for several displacement angles

A. Impedance relay
B. Reactance relay, type GCX

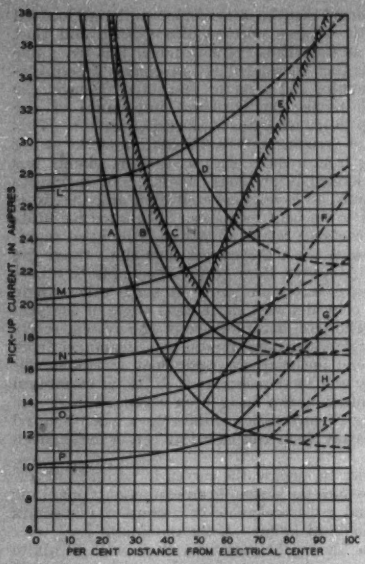


Fig. 8. Displacement angle 90 deg

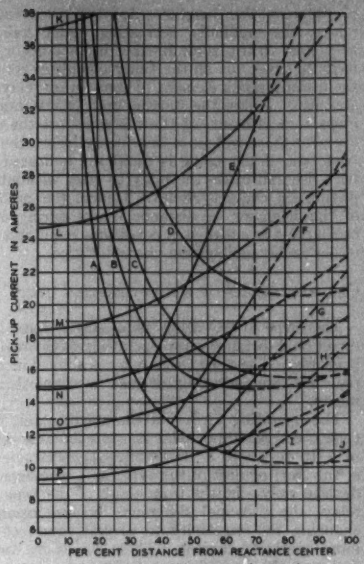


Fig. 9. Displacement angle 100 deg

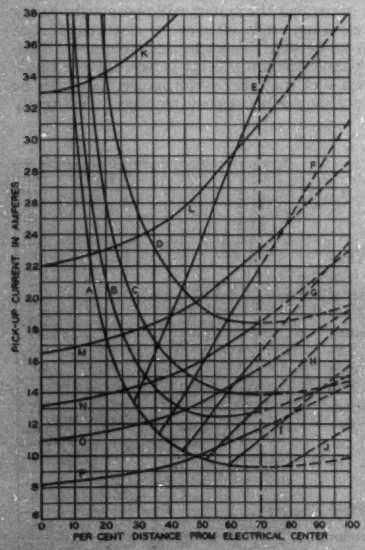


Fig. 10. Displacement angle 110 deg

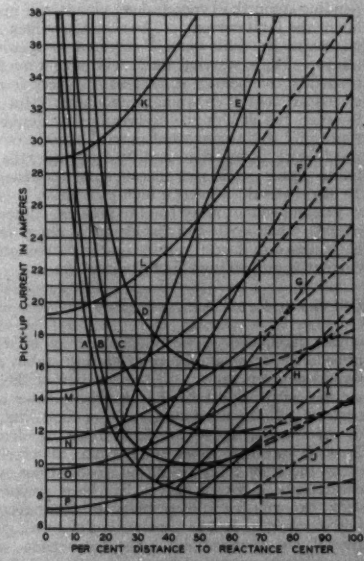


Fig. 11. Displacement angle 120 deg

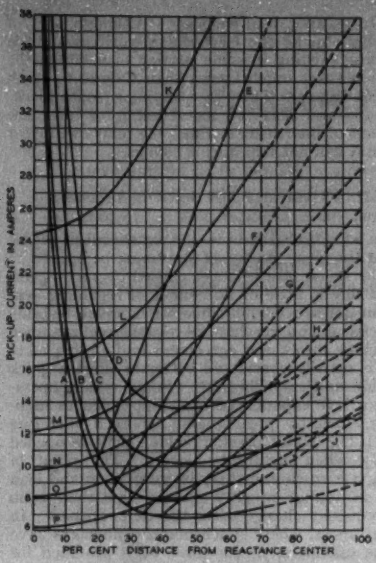


Fig. 12. Displacement angle 130 deg

Figs. 8–12. Characteristics of directional distance relays

A. Starting unit of type GCX relay, 8-amp tap
B. Starting unit of type GAX, relay standard
C. Starting unit of type GCX relay, 12-amp tap
D. Starting unit of type GCX relay, 16-amp tap
E. Reactance ohm unit, 2-ohm setting
F. Reactance ohm unit, 3-ohm setting
G. Reactance ohm unit, 4-ohm setting
H. Reactance ohm unit, 5-ohm setting
I. Reactance ohm unit, 6-ohm setting
J. Reactance ohm unit, 8-ohm setting
K. Impedance relay, 2-ohm setting
L. Impedance relay, 3-ohm setting
M. Impedance relay, 4-ohm setting
N. Impedance relay, 5-ohm setting
O. Impedance relay, 6-ohm setting
P. Impedance relay, 8-ohm setting

if it appears that the relays will operate to trip at the assumed angle, it becomes necessary to calculate the maximum angle for the assumed load, type of fault, and fault duration in order to determine whether the relays will be stable or not under actual operating conditions. Methods for doing so have already been published.

In addition to determining the maximum displacement angle, the secondary current in the relays must be found. This is a function of the system impedance, the maximum angle, the current transformer ratio, and the relay connection, and may be readily calculated. It is also necessary to express the location of the relay station in the system as a percentage of the total impedance from the electrical center to the end. With these factors established, the accompanying curves may be used to ascertain the stability of distance relays at any particular location for the specified disturbance and subsequent system oscillations.

Comparison of Relays

A comparison between the characteristics of the 12-amp tap of the type *GCX* relay starting unit and an impedance relay of equal sensitivity when located at the electrical center is shown in Fig. 7. The ohmic setting of the impedance relay was selected by dividing the voltage at the electrical center of the system for any given displacement angle by the minimum current required to operate the type *GCX* relay under the same conditions at its most sensitive location. Each curve is drawn for a different displacement angle and shows the minimum operating current as a function of the location of the relay station with respect to the electrical center. The curves demonstrate that for the 2 types of relays the point of maximum sensitivity varies both with location and displacement angle and the variations are entirely different. For example, with a total angle of 110-deg displacement, the impedance relays having the same minimum operating current as the type *GCX* starting unit will be more sensitive for any location within 40 per cent of the electrical center while the type *GCX* starting unit will be more sensitive in the end zone. This comparison is given because any system may have both types of relays in service and each type may be in the region where it is most likely to give an unwanted operation.

In Fig. 7 and all of the succeeding curves, a line has been drawn at 70 per cent of the distance between the electrical center and end to indicate the probable boundary of any relay station locations, the remaining 30 per cent representing transformer and machine impedance.

Two types of reactance relays with impedance relays set for 2, 3, 4, 5, 6, and 8 ohms are compared in Figs. 8 to 12. These are more useful for general use, since it is possible to interpolate to obtain the characteristic of any ohmic setting of impedance relay. Each is drawn for a different displacement angle and represents as static, conditions that in reality are changing with time. It does not necessarily follow that a relay will close its contacts even though an angle is reached which, if maintained, would cause it to do so, because the system may return to a smaller angle before the relay had time to operate. For example, the 12-amp type *GCX* relay starting unit with the instantaneous ohm unit set for 2 ohms can trip in instantaneous time only if the pick-up current at a given relay station lies within the "V" formed by the crossing of the starting and 2-ohm unit characteristic as shown by the shaded portion of the curves in Fig. 8. Should the current be sufficient to pick up the starting unit but lie outside of this shaded area, the relay would trip after a time delay depending upon the ohmic settings of the intermediate and back-up zones, and providing that the swing current remained above the pick-up value for a time long enough to allow the relay to complete its timing.

All of these curves indicate that under certain conditions it is possible for distance relays to operate during power swings unless provision is made to prevent such operation. The impedance relay is more sensitive to swings when located in a relay station at or near the electrical center of the system while the reactance relays have their maximum sensitivity at a point away from the electrical center, the location varying with the maximum angle of swing.

Location of Electrical Center

The location of the electrical center of a system depends upon the number of lines in service and the connected apparatus. As system connections change from time to time, so will the electrical center change, and a relay station located a considerable distance away from the center for one system set-up may be near the electrical center with another set of connections. A study of any given relay installation should utilize the particular one of the usual operating conditions which is most unfavorable to the relay.

Distinguishing Faults From Swings

Having determined that there is a possibility of incorrect operation, and bearing in mind that directional distance relays should operate correctly for faults and should not operate for swings, it is fitting to examine what preventive measures may be taken. In order to prevent undesirable relay operations during power swings, in installations where they would otherwise occur, some means should be provided for distinguishing between faults and swings. When the faults and oscillations do not result in identical current, voltage, and power factor relationships, a change in current transformer ratio or tap setting may enable the relays to discriminate between them. A fault suddenly applies an active and reactive load to a system and in effect increases the impedance of the tie between the machines, with a resultant reduction of synchronizing power. On the other hand, it requires an appreciable time for a power swing to take place, and unlike a fault, the synchronizing power increases with the system angle up to an angle of 90 deg. Thus, there are 2 characteristics by which swings can be distinguished from faults: (1) synchronizing power; and (2) time.

It has been suggested that a true power relay could be used to block distance relays against tripping during power swings. To use such a power relay it should be set low enough to block for all power swings, and high enough so that there would be no danger of blocking on high resistance faults.

An arcing fault introduces resistance which varies with the arc length and changes the current, voltage, power, and power factor, and may bring these to the same value they have during a swing. An arc usually starts over an insulator string and in the course of time is stretched by wind or convection air currents. Since all faults should persist no longer than the intermediate time setting of the distance relays, the maximum arc length is determined by this setting and wind velocity. Although arcs of such length make the electrical quantities coincide with those existing in some portion of a swing, the oscillation takes much longer than the arc to reach these conditions. Thus by providing some blocking means and delaying its action until after the expiration of intermediate time, the relays will clear faults and will not trip during swings.

Separating Unstable Portions of a System

When a fault results in loss of synchronism the tie between the elements out of step must be opened to avoid the severe disturbances caused by such operation. There is little or no chance of regaining synchronism unless action of some sort is taken to bring the electrical and mechanical torques acting upon the machine into closer agreement and as this takes time it is usually considered better to effect a quick separation and resynchronize. Some system operators who have experienced instability plan to minimize its effect by prearranging for each operating condition the circuit breakers which shall be opened manually when instability occurs. The point of separation is so chosen that the generation and load in each section are roughly equal so that there is no great frequency change when the tie is opened. In other instances, where synchronous condensers have been the offenders, means have been provided for taking them off the line automatically, the loss of their capacity causing less distress than operation out of step.

The most satisfactory automatic method of separating unstable portions of a system would seem to be the use of an out-of-step relay especially designed for the purpose. Relays operating upon this principle may be installed at the point where separation is desired, or if this changes with system operation, several may be installed and the proper one placed in service manually for each particular operating set-up.

References

1. Steady State Stability in Transmission Systems, Edith Clarke. A.I.E.E. Trans., v. 45, 1926, p. 23–41.

2. System Stability as a Design Problem, R. H. Park and E. H. Bancker. A.I.E.E. Trans., v. 48, 1929, p. 170–93.

3. Progress in the Study of System Stability, I. H. Summers and J. B. McClure. A.I.E.E. Trans., v. 49, 1930, p. 132–58.

4. Calculation of Alternator Swing Curves, F. R. Longley. A.I.E.E. Trans., v. 49, 1930, p. 1129–50.

5. Torque-Angle Characteristics of Synchronous Machines Following System Disturbances, S. B. Crary and M. L. Waring. A.I.E.E. Trans., v. 51, 1932, p. 764–73.

6. Two Machine Stability Problems, H. L. Byrd and S. R. Pritchard. *Gen. Elec. Rev.*, v. 36, 1933, p. 81–93.

7. N.E.L.A. Relay Handbook and Supplement.

8. New High Speed Distance Relay, S. L. Goldsborough and W. A. Lewis. Elec. Engg., March 1932, p. 157–60.

9. A New High Speed Reactance Relay, A. R. Van C. Warrington. Elec. Engg., April 1933, p. 248–52.

10. Modern Requirements of Protective Relays, O. C. Traver and L. F. Kennedy. A.I.E.E. Trans., v. 49, 1930, p. 1226–31.

11. Operating Experience With the Reactance Type Distance Relays, E. E. George. A.I.E.E. Trans., v. 50, 1931, p. 288–93.

12. Relaying of High Voltage Interconnections, H. P. Sleeper. Elec. Engg., June 1933, p. 402–9.

Reignition of an Arc at Low Pressures

An investigation of factors influencing the reignition potential of an alternating current arc at low pressure is reported in this paper. The investigation was undertaken to determine if such data could throw more light on the transition from a glow discharge to an arc. The results are consistent with a theory proposed previously by one of the authors.

By
S. S. MACKEOWN
MEMBER A.I.E.E.

F. W. BOWDEN
ENROLLED STUDENT A.I.E.E.

J. D. COBINE
ENROLLED STUDENT A.I.E.E.

All of the Calif. Inst. of Tech., Pasadena

RESULTS of a study of the factors influencing the reignition potential of an alternating current arc at low pressures are presented in this paper. The data were obtained from oscillograms of arcs at different currents, between electrodes of different materials in air at pressures ranging from 2 cm of mercury to atmospheric pressure, and for a gap setting of one millimeter.

At low current densities and at low pressures the reignition potentials using electrodes of carbon, copper, and graphite were approximately the same, proportional to the pressure, and lower than the sparking potential. At low pressures a high reignition potential is necessary to establish the arc even when the electrodes are carbon. At higher pressures and at higher current densities the reignition potential of carbon and graphite decreased with increase in pressure; no such decrease was found for copper electrodes. Impurities having a low work function decreased the reignition potential markedly. Conditions favoring high temperature of the electrodes also tended to decrease the reignition potential.

The experimental results are consistent with the theory that the transition from a glow discharge to an arc is due to the establishment of a high positive space charge at the surface of the cathode producing an electric field of high intensity.

General

Todd and Browne[1] have shown that the potential required to restrike an alternating current arc when the current reverses is low and of the order of the burning potential at atmospheric pressure, providing the electrodes are of carbon or tungsten. However, if the electrodes are of copper, brass, or other materials that cannot exist in the solid state at very high temperatures, the potential necessary to restrike the arc is very high compared to the burning potential. It is well known that in order to supply sufficient thermions to yield the large current densities found in the region of the cathode spot that a temperature exceeding 3,000 deg K is necessary. Both carbon and tungsten are solid at this temperature, and it is extremely probable that with these materials both electrodes of an alternating current arc are at a sufficiently high temperature to furnish all the electrons necessary for carrying the arc current by thermionic emission.

With electrodes of material that is not solid at these high temperatures, the thermionic current is so low that it is necessary to postulate some other mechanism of producing the large electron current that exists in the region of the cathode spot. In the cases where the electrodes cannot exist at very high temperatures, the most generally accepted theory of the cathode drop is that the electrons are drawn out from the cathode by the extremely high intensity electric fields that exist there. The intensity of these electric fields is of the order of 10^6 volts per centimeter.[6] When the current in an alternating current arc reverses, it is necessary to produce an electric field of very high intensity at the surface of the electrode that was formerly the anode. In order to do this it is assumed that a glow discharge first forms with its relatively high cathode drop, extending over a relatively large distance. As the current in this discharge increases, the magnitude of the cathode drop increases and at the same time the region over which the cathode drop exists decreases, both of these effects producing an increase in the strength of the electric field existing at the cathode. At some critical value the large cathode drop of the glow discharge collapses into the low cathode drop of the arc which, however, extends over a very small region. Transition from a glow to an arc occurs very rapidly if the current is high, but it occurs at every reversal of the current, and a relatively high restriking potential is necessary if the electrode material is not a solid at a very high temperature.

The present study was undertaken to determine if data obtained at low pressures could throw more light on the transition from a glow discharge to an arc.

Description of Apparatus

The circuit used is shown in Fig. 1. Resistance R_1 is a high resistance which, when the circuit is energized, will prevent the arc from striking. The relay, which short circuits R_1, operates after the oscillograph has recorded approximately one cycle of the impressed voltage. Resistance R_2 is used to adjust the arc current, which is measured by the ammeter A. Resistance R_3 determines the amplitude of the swing of the oscillograph element. All these resistances are water resistors.

Full text of a paper recommended for publication by the A.I.E.E. committee on research, and scheduled for discussion at the A.I.E.E. Pacific Coast convention, Salt Lake City, Utah, Sept. 5–7, 1934. Manuscript submitted June 5, 1933; released for publication Feb. 20, 1934. *Not published in pamphlet form.*

1. See bibliography at end of paper for all numbered references.

In all cases the arc occurred between the plane end surfaces of cylindrical electrodes 0.64 cm in diameter. The distance between the electrodes always was adjusted to 1 mm. The arc was allowed to burn only long enough to complete the oscillogram, and frequent adjustments of the gap were made to insure the desired separation of the electrodes. The electrodes and their holders were mounted in a bell jar which was connected to vacuum pumps and gauges by

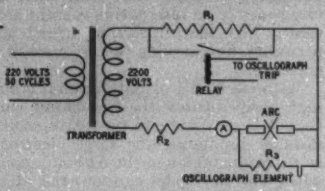


Fig. 1. Experimental circuit

means of which the pressure was adjusted to the desired value prior to striking the arc. In the pressure range covered, no increase in pressure was observed after striking the arc. No other gas than air was used. Power was supplied to the circuit by the regular 50-cycle mains.

Experimental Results

The reignition potential is taken to be the maximum voltage reached prior to the restriking of the arc. In general, this voltage is not constant, but varies from cycle to cycle; and in the case of carbon electrodes the variation of the reignition potential in a single oscillogram might be as high as 50 per cent. When both electrodes were copper or very pure graphite the variation was not so great and was less than when one electrode was copper and one carbon. The most consistent results were obtained when both electrodes were pure graphite, in which the variation was less than 5 per cent (see Fig. 2). There was no consistent variation with time or *average* temperature of the electrodes. All data given were obtained from about 400 oscillograms and each point is the average of at least 7 measurements.

Figures 2 and 3 are typical oscillograms representing the drop in potential across an arc between graphite electrodes for 8 values of air pressure. The rms value of the current for each of these was kept constant at 1.5 amp. Figure 2 is an oscillogram showing the voltage drop across the gap as a function of time for low pressures. It may be noted that the voltage rises before the current reverses, to a value approximately equal to that of the cathode drop of the normal glow discharge in each case recorded here. At the time corresponding to point A the relay short circuiting the resistance R_1 was closed, starting the arc. At a pressure of 1 cm of mercury an arc did not strike each half cycle, but the voltage did drop in some cases to a value intermediate between that of the arc and the normal cathode drop. The explanation for this behavior is not known. The graphite electrodes for this oscillogram were obtained from 2 different sources which may account for the differences between the individual characteristics; this will be discussed later in this paper. By comparing Figs. 2 and 3, it may be seen that the duration of the glow discharge which precedes the arc is shortened greatly at the higher pressures.

The variation in reignition potential between pure graphite electrodes as the pressure is changed is shown in Fig. 4 for a range of arc currents. It may be noted that, in general, the reignition potential increases as the current in the arc is decreased, and for low currents the reignition potential is nearly proportional to the pressure; but for currents higher than about 13 amp, the curves show a decrease in reignition potential as the pressure is increased. At about 13 amp the reignition potential seems to be independent of pressure for pressures above 10 cm of mercury, maintaining a value of the order of 550 volts. In every case there is a definite reignition potential which is higher than the arc voltage. For comparison purposes the curve marked "spark," computed from Peek's data,[2] gives the initial breakdown voltage for a gap of 1 mm.

Reignition potential for different arc currents, at constant pressure, is shown by Fig. 5. There are 3 definite regions of behavior. The region between 10 and 15 amp is a transition region, the curves all crossing at about 13 amp and reversing their order. All data for the reignition potentials of these electrodes taken at pressures between 2 and 50 cm of mercury give the same value for a current of about 13 amp. The reason for this is not known.

When 2 different materials are used as electrodes

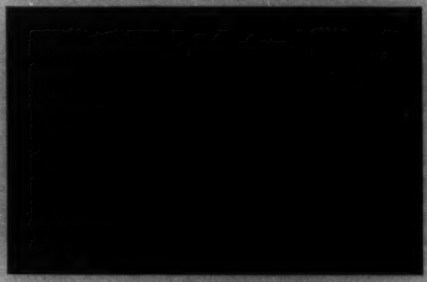


Fig. 2. Oscillogram of arc between pure graphite electrodes

Voltage scale shown in the upper right-hand corner is the same for each pressure; pressures are indicated at the left. The arc starts at "A"

in an alternating current arc, the reignition potential is different in the 2 half cycles and depends on the material of the new cathode for a given current. This is shown in Fig. 6. A curve for 2 pure graphite electrodes is included for comparison. The copper used in these tests was conductor copper; the carbon was the National Carbon Company's projector carbon, made from very pure lamp black having about 0.02 per cent ash. Very small quantities of impuri-

ties such as boron, iron, aluminum, manganese, calcium, and magnesium were present. It may be noted that for the carbon cathode there is for each current a pressure at which the reignition potential is a maximum. When copper is the cathode this effect is not observed.

The results of using carbons that were impregnated with a fair quantity of sodium hydroxide against untreated carbons of the same stock are shown in Fig. 7. The reignition potentials of both the treated and the untreated electrodes were reduced very markedly from the reignition potentials necessary when the untreated electrode was run against copper. In Fig. 7 are shown also the results obtained from using a pure graphite electrode operating against a carbon electrode containing about 35 per cent ash, consisting of 15 per cent of the rare earths, cerium, neodymium, and lanthanum, and 20 per cent calcium fluoride. The curves in Fig. 7 show the remarkable lowering of the reignition potential of the arc because of impurities in one of the electrodes. It is interesting to note that the reignition potential of the pure electrode is affected almost as much as that of the one containing the impurities.

Table I shows that in general the reignition potential is higher for materials of high thermal conductivity, other conditions such as current, pressure, gas, and freedom of impurities, being the same. As the current is increased the decrease in reignition potential is greater for the materials having the lowest thermal conductivity. Preliminary experiments indicate that the reignition potential is a function of

Fig. 3. Oscillogram of arc between pure graphite electrodes

Voltage scale shown in upper right-hand corner is the same for each pressure; pressures are indicated at the left. The arc starts at "A"

the frequency of the arc current, the reignition potential decreasing as the frequency is increased.

Discussion of Results

For the values of pressure, current, and frequency at which this work was done the reignition potential would be approximately the same as the sparking potential if the characteristics of the electrodes did not change during the discharge. This is true because the time required for all the ions and electrons to recombine is extremely short.[2] There may be some slight effect due to an increase in the average temperature of the gas; but large deviations between the reignition potential and the sparking potential must be explained by changes in the properties of the electrodes, and particularly in that electrode which

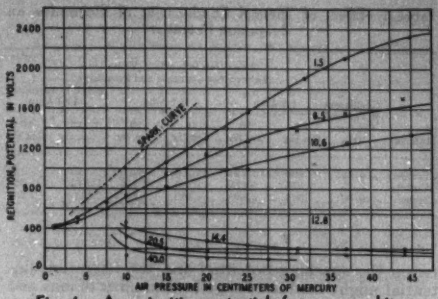


Fig. 4. Arc reignition potentials for pure graphite electrodes

Numerical designations on curves indicate arc currents in amperes

is to become the cathode. Only those changes need be considered that would affect the number of electrons emitted by the cathode or the ease with which they might be emitted by high intensity electric fields. The only factors would seem to be the temperature of *that portion of the electrode which emits electrons* and the presence of electropositive materials having low work functions.

At high temperatures the electric field intensity necessary to produce sufficient electrons to maintain the arc is reduced. If the temperature of the electrode is high enough a sufficient number of electrons may be emitted by thermionic action to reignite the arc with a voltage no higher than that required to maintain it. This latter condition did not obtain in any of the cases cited in this paper, since in all cases a reignition potential was necessary. At the higher pressures and at the higher currents with carbon electrodes, this reignition potential was not high. It is believed that in these cases the carbons were hot enough to emit some thermions though not sufficient in number for the large current density known to exist at the cathode spot, namely, a density of the order of 1,000 amp per square centimeter. When the reignition potential is relatively low, sufficient electrons to maintain the arc probably are produced by a combination of high temperature and high intensity electric field. It is interesting to note that at the low values of current and pressure the reignition potential for carbon is almost as high as for copper. Here the temperature is too low to play any essential part and the restriking of the arc is due to the electric field of high intensity that exists there.

It is well known that field currents due to high intensity electric fields are independent of the temperature of the electrodes until their temperature exceeds about 1,000 deg K.[4] Consequently, it is only at temperatures higher than this that any marked difference between the reignition potential and the sparking potential would be expected. If the temperature is lower than this the difference between the sparking potential and the reignition potential might be due to a greater number of ions and electrons remaining in the space between the electrodes, because of previous arc current, when the arc is restruck. The fact that the reignition potential does not decrease with an increase of the average temperature of the electrode, i. e., it is not noticeably lower after 10 half cycles than after the first half cycle, is in accord with the theory that the field current is independent of temperature provided the temperature is low.

Table I—Effect of Thermal Conductivity of Electrodes on Reignition Potential

		Reignition Potentials (Volts) for Various Arc Currents and Pressures					
	Coefficient of Thermal Conductivity	1.5 Amp		8.1 Amp		12.3 Amp	
Material		25 Cm Hg	50 Cm Hg	25 Cm Hg	50 Cm Hg	25 Cm Hg	50 Cm Hg
Carbon	0.09	1,400	2,330	450	400	200	150
Graphite	0.25	1,575	2,425	1,210	1,550	730	900
Copper	0.80	1,656	2,850	1,400	1,800	1,000	1,600

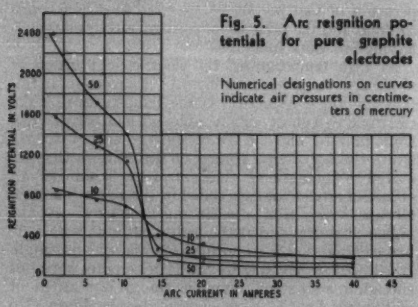


Fig. 5. Arc reignition potentials for pure graphite electrodes

Numerical designations on curves indicate air pressures in centimeters of mercury

On the other hand anything that either increases the temperature of the cathode spot or decreases the cooling while that electrode is anode, is found to decrease the reignition potential. Thus both an increase in current and an increase in pressure cause a greater difference between the reignition potential and the sparking potential because both increase the temperature of the cathode spot. Increases in pressure increase the temperature of the cathode spot because the size of the cathode spot decreases as the pressure increases, and consequently the current density to the cathode spot is increased. Higher frequency has been found to decrease the reignition potential because it allows less time for the cathode spot to cool. In the same way it is found that a higher heat conductivity of the electrode, in general, is accompanied by a higher reignition potential. The reason that the reignition potential for copper is higher than that of graphite and that of carbon is the lowest of the three is believed to be due, at least at the relatively low pressures, to the fact that their heat conductivities are in the same order—copper, graphite, and carbon.

Effect of Impurities

Materials that have a low work function will emit electrons much more readily than those with a high work function. Consequently if there is in the electrodes impurities such as the alkali earths, which have a much lower value of work function than the electrode material itself, their reignition potentials would be expected to be much lower than that of a pure electrode. The experimental results show that this is true. The experiments show that the amount of such impurity need be very small to affect the reignition potential greatly, for if a pure material is used as one electrode, its reignition potential is decreased nearly as much as that of the electrode having the impurity in it. Since material is being vaporized continuously from the surfaces of both electrodes, there can be no accumulation of impurities on the pure electrode. A trace of impurities such as the alkali metals in relatively pure electrodes can account for the random variation of the reignition potential. The reignition potential would be low if a trace of alkali metal happened to be on the surface of the electrode becoming the cathode.

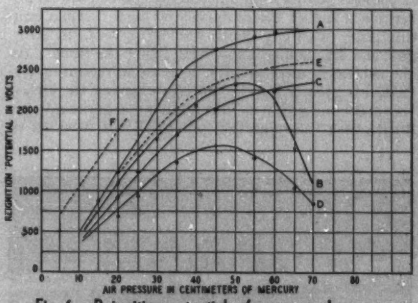


Fig. 6. Reignition potentials of copper-carbon arcs

A—Copper cathode, carbon anode, current 1.5 amp
B—Carbon cathode, copper anode, current 1.5 amp
C—Copper cathode, carbon anode, current 4.8 amp
D—Carbon cathode, copper anode, current 4.8 amp
E—Both electrodes pure graphite, current 1.5 amp
F—Spark curve

All the experimental facts are in accord with the following theory of the transition from the glow discharge to an arc which has been proposed previously by one of the authors:[8] When the current reverses, a glow discharge first is formed with a relatively high

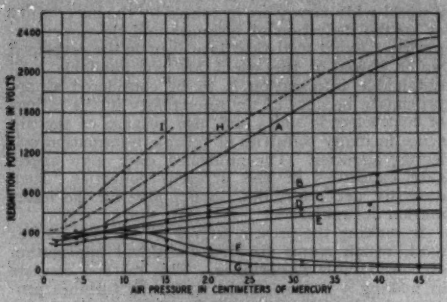


Fig. 7. Effects of impurities on the reignition potentials of carbon arcs

A—Carbon cathode, copper anode, 1.5 amp
B—Carbon cathode, carbon anode with 15% rare earths, 1.5 amp
C—Carbon cathode with 15% rare earths, carbon anode, 1.5 amp
D—Carbon cathode, carbon anode treated with sodium hydroxide, 1.5 amp
E—Carbon cathode treated with sodium hydroxide, carbon anode, 1.5 amp
F—Same as D, but for 6.5 amp
G—Same as E, but for 6.5 amp
H—Both electrodes pure graphite, 1.5 amp
I—Spark curve

cathode drop. As the current density at the cathode increases in the region of the abnormal cathode drop, the magnitude of the cathode drop increases and also this cathode drop occurs in a region closer to the cathode. Both of these effects cause an increase in the intensity of the electric field existing in the cathode drop and consequently increase the energy that the positive ions have when they hit the cathode. As the energy of the positive ions increases, they produce a larger number of electrons from the cathode by bombardment. If now some impurity is assumed on the surface of the cathode or some irregularity that produces a high intensity local electric field, then that portion of the cathode will produce a larger number of electrons than any other portion of the cathode. The electrons freed from the cathode will produce ionization that will be more intense near the active spot on the cathode surface. Due to the high mobility of the electrons compared to the positive ions, the former will disperse into the body of the gas leaving behind the positively charged gas ions. This will increase further the field near the active surface of the cathode with a corresponding increase in the number of electrons emitted from that spot. This process is cumulative and proceeds rapidly until the intensity of the electric field existing at this active spot is high enough to pull large numbers of electrons from the cathode surface. When this occurs an arc exists with its characteristic "hot spot" with a very high current density and with a low cathode drop. A high temperature at the cathode will decrease the magnitude of the electric field necessary to produce these electrons.

Bibliography

1. Restriking of Short A-C Arcs, F. C. Todd and T. E. Browne, Jr. *Phys. Rev.*, v. 36, 1930, p. 732.

2. Dielectric Phenomena in High Voltage Engineering, F. W. Peek, Jr. McGraw-Hill Book Co., New York, N. Y.

3. Extinction of an A-C Arc, J. Slepian. A.I.E.E. Trans., v. 47, 1928, p. 1398.

4. Laws Governing the Pulling of Electrons Out of Metals by Intense Electric Fields, Millikan and Eyring. *Phys. Rev.*, v. 27, 1926, p. 51.

5. The Cathode Drop in Arc Discharges, S. S. Mackeown. Elec. Engg., v. 51, June 1932, p. 386.

6. The Cathode Drop in an Electric Arc, S. S. Mackeown. *Phys. Rev.*, v. 34, 1929, p. 611.

7. Extinction of Short A-C Arcs, T. E. Browne, Jr. A.I.E.E. Trans., v. 50, 1931, p. 1461.

8. Reignition of Metallic A-C Arcs in Air, S. S. Attwood, W. C. Dow, and W. Krausnick. A.I.E.E. Trans., v. 50, 1931, p. 854.

9. Electrical Discharges in Gases, K. T. Compton and I. Langmuir. Part I, *Rev. of Modern Phys.*, v. 2, Apr. 1930; Part II, *Rev. of Modern Phys.*, v. 3, Apr. 1931.

10. Positive Ion Currents in the Positive Column of the Mercury Arc, I. Langmuir. *G. E. Rev.*, 1923, No. 11, p. 731.

11. Über die Wechselstromcharakteristik von Metallichtbogen, J. J. Sommer. *Phys. Zeit.*, April 15, 1933, p. 324.

12. Über den Mechanismus des Elektrischen Lichtbogens, W. Ramberg. *Ann. d. Phys.*, v. 12, 1932, p. 319.

13. Die Stromstärke Glimmentladung bei Atmosphärendruck sin Neue Entladungsform, H. Thoma and L. Hoer. *Zeit. f. Tech. Phys.*, v. 13, 1932, p. 464.

14. Electric Discharges in Gases at Low Pressures, I. Langmuir. *Jl.* of the Franklin Inst., v. 214, 1932, p. 275.

15. Über die Glimmentladung bei Hohen Drucken, Engel and Steenbeck. *Zeit. f. Phys.*, 85, 144, Sept. 4, 1933.

16. Zur Theorie der Bogenentladung, R. Seeliger and K. Bock. *Phys. Zeit.*, 20, v. 34, 1933, p. 767.

17. Backfires in Mercury Arc Rectifiers, J. Slepian and L. R. Ludwig. A.I.E.E. Trans., v. 51, 1932, p. 157.

18. Electric Arc Circuit Breakers, J. Slepian. *Jl.* of the Franklin Inst., v. 214, Oct. 1932, p. 413.

19. Arcs in Low Voltage A-C Networks, J. Slepian and A. P. Strom. A.I.E.E. Trans., v. 50, 1931, p. 1111.

20. Extinction of a Long A-C Arc, J. Slepian. A.I.E.E. Trans., v. 49, 1930, p. 310.

21. Flames From Electric Arcs, J. Slepian. A.I.E.E. Trans., v. 49, 1930, p. 56.

22. Theory of Current Transference at the Cathode of an Arc, J. Slepian. *Phys. Rev.*, v. 27, April 1926, p. 407.

23. The Transition From Glow to Arc Discharge at Atmospheric Pressure, J. Slepian. *Jl.* of the Franklin Inst., v. 201, 1926, p. 79.

24. Extinction of A-C Arcs in Turbulent Gases, T. E. Browne, Jr. A.I.E.E. Trans., v. 51, 1932, p. 185.

25. The Electric Arc, K. T. Compton. A.I.E.E. Trans., v. 46, 1927, p. 888.

26. Theory of the Electric Arc, K. T. Compton. *Phys. Rev.*, v. 21, 1923, p. 286.

27. Studies of Electric Discharges in Gases at Low Pressures, Langmuir and Mott-Smith. *G. E. Rev.*, v. 37, 1924, p. 449, 538, 616, 762, 810.

28. Probe and Radiation Measurements in the Copper Arc, W. B. Nottingham. *Jl.* of the Franklin Inst., v. 207, 1929, p. 299.

29. Probe Measurements and Potential Distribution in Copper A-C Arcs, W. G. Dow, S. S. Attwood, and G. S. Timoshenko. A.I.E.E. Trans., v. 52, 1933, p. 926.

30. Langmuir Probe Measurements in the Normal Copper Arc, E. H. Bramhall. *London Phil. Mag.*, v. 13, 1932, p. 682.

31. Probe Measurements of the Normal Electric Arc, W. B. Nottingham. *Jl.* of the Franklin Inst., v. 206, 1928, p. 43.

32. The Nature of the Processes Occurring in Certain Electric Arcs. *Jl.* of the Franklin Inst., v. 205, 1928, p. 810.

33. Some Experiments With Arcs Between Metal Electrodes, G. M. Shrum and H. G. Wiest, Jr. A.I.E.E. Trans., v. 50, 1931, p. 650.

A Survey of Hydroelectric Developments—II

A general outline of the status of modern hydroelectric developments is presented in this report by an A.I.E.E. subcommittee,* continued from the June issue.

IN THE PART of this paper published in the June 1934 issue of ELECTRICAL ENGINEERING beginning on p. 988 the present trend in utilization of water power, and the subject of hydroelectric and hydrodynamic research were discussed. Statistics concerning the developed water power of the world are given on this and the following pages.

WATER POWER AS PART OF THE GENERAL ENERGY SUPPLY

The present civilization depends on constantly increasing amounts of energy that are spent to satisfy the varied requirements of the human race. The principal sources of energy are the carbon deposits contained in the earth's crust (coal, oil, and gas) and water power.

Table I, compiled from World Power Conference data, compares the relative importance of different energy sources of the world on the basis of energy production. While the table is for the year 1927, the present relationship is substantially the same.

Tables II and III show the relative importance of different energy sources, using the installed prime mover capacity as a basis of comparison. These data, applying only to the United States, were supplied by Prof. C. R. Daugherty of the University of Pittsburgh (Pa.). The importance of automobiles is quite evident. Also of considerable interest is the rapid increase in the capacity of steam driven prime movers, internal combustion engines, and water wheels. Although the installed capacity of water wheels is small compared with that of other prime movers, the amount of energy generated per installed horsepower is comparatively large.

Developed Water Power of the World

Recently several different agencies, such as the World Power Conference, the United States Geological Survey, and others, were collecting and publishing data pertaining to the ultimate and developed water power of the world.

The usual difficulties in the collection of data for a world-wide survey are increased by the uncertainty as to the definition of ultimate and developed capacity. Exact statistical data even on the developed water power of the world are not available. All obtainable information is to be considered as approximate because of the uncertainty in the ratings of hydroelectric units and also because of the absence in many countries of reliable information collecting agencies. The published data give aggregate capacities of the different countries. Such data are necessary, but do not give all the information desirable.

In making the present survey a new method was used, which seems to give additional information of considerable importance. This method consists in making a survey of the hydraulic turbines produced in the different countries of the world.

WORLD PRODUCTION OF HYDRAULIC TURBINES

The present status of the turbine art is such that it seems justifiable to classify the different developments as high, medium, and low head developments depending upon the kind of turbines. High head developments would be those using impulse turbines, better known the world over as Pelton turbines; medium head developments, those using Francis turbines; and low head developments, those using any kind of propeller turbines with fixed or adjustable blades, including the well-known Kaplan turbines.

Although such classification may place some of the developments in 2 classes (when 2 different kinds of turbines are used) or show an overlapping of heads, nevertheless it seems better justified than a limiting head arbitrarily chosen. By such classification of the data pertaining to turbines manufactured in different parts of the world, a complete picture can be formed of the developed water power represented by numerous very different developments distributed throughout many countries. Notwithstanding the many countries in which water power developments are located, the number of manufacturers of hydraulic turbines is rather limited.

Tables IV, V, VI, and VII give data on the hydraulic turbine industry in the United States, Canada, Europe, and Japan, during the 5-yr period 1928 to 1932, inclusive. Table VIII gives a world summary for the same period; the data of this table cover well over 90 per cent of the world production of modern water wheels.

In studying these tables, the large aggregate capacity of hydraulic turbines produced in Europe may be noted, also the considerable difference between water power practice in the United States and Canada and that in Europe.

The large proportion of Pelton turbines built in Europe reflects the importance of the high head

Concluding part of a report prepared by the A.I.E.E. subcommittee on hydroelectric survey recommended for publication by the A.I.E.E. committee on power generation, and discussed at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. *Not published in pamphlet form.*

*For subcommittee personnel, see ELECTRICAL ENGINEERING, June 1934, p. 988.

developments in the Alps and Pyrenees, as well as the use of such European turbines for high head developments in other parts of the world.

So far as low head developments are concerned, it is of interest to note that propeller turbines with fixed or manually operated blades are much more popular than Kaplan turbines (propeller type with automatically adjustable blades) in the United States and Canada, and that there is almost an absence of propeller and Kaplan turbines in Japan. In Europe, 76 per cent of the low head turbines and nearly 13 per cent of all turbines produced are of the Kaplan type. The probability is that the future trend in the United States and Canada will be to increase considerably the percentage of the aggregate horsepower capacity of Kaplan turbines, with a corresponding reduction in the percentage of propeller and Francis turbines.

Developed Water Power in Different Countries

According to the best possible estimates, the developed water power of the world in the year 1933 approaches 60 million shaft horsepower for turbines installed and in actual operation. Table IX shows the distribution of the developed water power among the different countries of the world. From these data it can be seen that at present the water power actually developed is confined mostly to industrialized and highly developed countries. About 24 million horsepower or 40 per cent of the world total is located on the North American continent, about 28 million or 47 per cent in Europe, and about 6 million or 10 per cent in Japan. The appreciable water power possibilities are not utilized at all in the less developed countries, most of which are situated in the mainland of Asia, Africa, and South America.

The present tendency is to concentrate in a single development as large capacities as possible. In

Table I—Millions of Kilowatt Hours Produced in the World During the Year 1927, Assuming All Fuel Is Transformed into Electrical Energy

Source	America	Europe	Asia	Oceania	Africa	World
Coal	558,300	649,100	74,900	17,300	12,100	1,310,800
Oil	222,000	34,800	14,800			261,400
Water Power	42,000	35,000	6,500	900	400	84,800
Totals	822,200	708,900	95,300	18,100	12,500	1,657,000

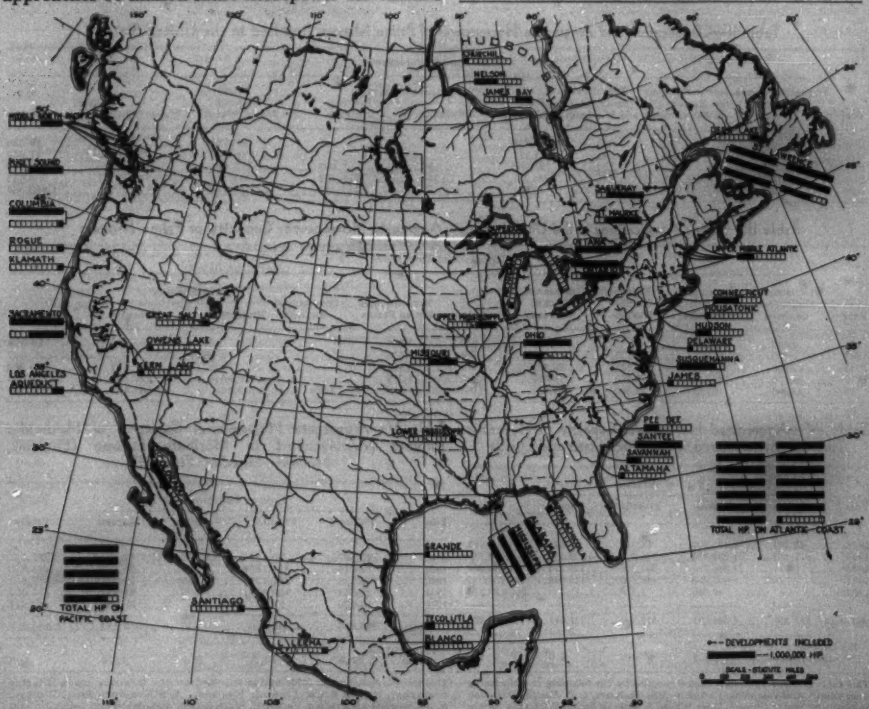


Fig. 2. Aggregate horsepower at turbine shafts installed or being installed (1934) in the different drainage basins in North America, based upon hydroelectric developments exceeding 20,000 hp ultimate capacity

Table X are listed the major developments of the world in operation or under construction, classified according to the proposed ultimate aggregate horsepower capacity at the turbine shafts. A study of this table discloses that a few of the power plants in the United States and Canada after ultimate development will be in the 2,000,000-hp class. Only a few years ago such large plants were considered impractical. The expectations are that the future developments on the Columbia River in the United States and in some parts of Africa and South America will result in power plants of considerably larger capacities.

Major Water Power Developments of the North American Continent

Major developments on the North American continent are shown on Fig. 1, classified according to the drainage areas as established by the United States Geological Survey. Each development shown on the map is listed in Table XI under the corresponding drainage area and number, together with pertinent data. The map and table cover developments the ultimate capacity of which is 20,000 hp or over at the turbine shafts and includes all developments that were in operation or construction in the year 1934. These data probably include more than 75 per cent of the total capacity of the developments of the North American continent.

Table XII gives the aggregate capacity of turbines installed or being installed classified according to the different drainage basins. Tables XIII and XIV give the aggregate capacity of turbines installed or in installation in different drainage areas and in the main drainage basins of the North American continent. These 3 tables are based upon data contained in Table XI.

These tables indicate the large aggregate turbine capacities installed in a few of the drainage basins in the United States and Canada. Table XIII shows also the particular importance of the Great Lakes and St. Lawrence River drainage basin for Canada.

Based on the same data the aggregate horsepower capacity at turbine shafts in the different drainage basins in North America are shown in Fig. 2. The completely blackened rectangles representing each one million horsepower and the partly blackened rectangles a corresponding part of one million horsepower. The large capacities installed on the St.

Table II—Classification and Aggregate Horsepower of Prime Movers Installed in the United States

	Thousands of Horsepower								
					Automobiles		Total		
Year	Steam Engines and Turbines	Internal Combustion Engines (Not in Automobiles)	Wind Power (Sailing Ships and Windmills)	Work Animals	Productive	Pleasure	Without Water Wheels	Water Wheels	Totals
1869	6,215		343	11,275			17,833	1,205	19,038
1889	24,294	9	511	31,311			46,125	1,512	47,637
1909	77,236	5,541	701	25,262	256	7,458	116,454	3,860	120,314
1919	116,348	16,704	665	24,221	10,964	219,468	388,270	7,241	395,611
1929	173,610	31,951	678	19,561	162,483	1,262,497	1,650,780	12,777	1,663,557

Table III—Power Applications in the United States—Aggregate Horsepower Capacity of Prime Movers

	Thousands of Horsepower										
								Automobiles			
Year	Manufacturers, Mines, and Quarries	Agriculture, Irrigation, and Drainage	Electric Central Stations	Steam and Electric Railroads	Ships	Work Animals Not on Farms	Commercial Aircraft	Productive	Pleasure	Totals
1869	2,696	9,588		4,100	967	1,687				19,038
1889	7,150	19,865	120	16,440	1,384	2,675				47,637
1909	21,206	31,118	5,225	48,491	3,155	3,405		256	7,458	120,314
1919	25,175	39,713	15,350	76,660	6,402	1,979		10,964	219,468	395,611
1929	25,606	44,582	43,000	111,881	9,017	1,400	3,091	162,483	1,262,497	1,663,557

Table IV—Aggregated Horsepower Capacity of Hydraulic Turbines Manufactured in the United States and Canada

	Type of Turbines				
Year	Pelton	Francis	Propeller	Kaplan	Totals
1928	42,200	1,495,303	84,317	13,631	1,635,451
1929	73,200	1,233,990	128,729	28,590	1,464,579
1930	75,185	1,325,724	347,228	138,125	1,886,262
1931	2,708	603,950	10,700	140,698	758,056
1932		27,960	1,313		29,273
Totals	193,293	4,686,927	572,357	321,044	5,773,631
Per Cent of Total	3.4	81.1	9.9	5.6	100

This table is based upon information supplied by the following manufacturing companies: Allis-Chalmers, Canadian Allis-Chalmers, I. P. Morris, Dominion Engineering Works, Pelton Water Wheel, S. Morgan Smith, S. Morgan Smith-Iagiia, and Newport-News Shipbuilding and Dry Dock. It probably covers at least 95 per cent of the total production in the United States and Canada.

Table V—Aggregate Horsepower Capacity of Hydraulic Turbines Manufactured in Northern Europe (England, Norway, Sweden, Finland)

	Type of Turbines				
Year	Pelton	Francis	Propeller	Kaplan	Totals
1928	157,627	85,144	2,060	32,401	277,232
1929	75,114	324,147	1,360	15,202	415,823
1930	105,332	168,794	2,030	92,661	367,817
1931	39,633	360,874	100	88,487	479,094
1933	13,620	96,331		30,360	140,311
Totals	380,326	1,035,290	5,550	259,111	1,680,277
Per Cent of Total	22.8	61.5	0.3	15.4	100

This table is based upon information supplied by the following manufacturing companies: Boving & Co. Limited, England; A/S Kvaerner Brug, Norway; A/B Karlstads Mekaniska Verkstad, Verkstaden, Kristinehamn, Sweden; and Tammerfors Linne & Jern Manufactur A/B, Finland. It probably covers at least 90 per cent of the total production in northern Europe.

Table VI—Aggregate Horsepower Capacity of Hydraulic Turbines Manufactured in Central and Southern Europe (Switzerland, France, Germany, Italy)

Year	Type of Turbines: Pelton	Francis	Propeller	Kaplan	Totals
1928	788,639	1,238,621	355,336	288,863	2,571,459
1929	475,744	1,233,316	50,898	154,180	1,914,038
1930	378,913	834,657	27,823	182,637	1,424,030
1931	210,328	376,946	11,495	188,102	786,871
1932	311,533	80,380	17,395	64,977	474,285
Totals	2,165,157	3,763,820	462,947	878,759	7,170,683
Per Cent of Total	30.2	52.5	5.1	12.2	100

This table is based upon information supplied by the following manufacturing companies: Ateliers des Charmilles, Switzerland; Escher Wyss, Switzerland; Th. Bell, Switzerland; Ateliers Neyret-Beylier & Piccard-Pictet, France; Schneider, Jaquet & Cie, France; Constructions Electriques et Mecaniques ALSTHOM, France; Société Anonyme Tosi-Dujardin, France; J. M. Voith, Germany; Société Franco Tosi & San Giorgio, Italy; S. A. dePretto-Escher Wyss, Italy; and Costruzioni Meccaniche Riva, Italy. It probably covers at least 90 per cent of the total production of central and southern Europe.

Table VII—Aggregate Horsepower Capacity of Hydraulic Turbines Manufactured in Japan

Year	Type of Turbines: Pelton	Francis	Propeller	Kaplan	Totals
1928	22,736	277,588			300,324
1929	33,923	282,331			316,254
1930	37,813	252,180	1,925	2,000	293,918
1931	73,805	111,951	61		185,817
1932	11,707	87,699	2,513	2	101,921
Total	179,984	1,011,749	4,499	2,002	1,198,234
Per Cent of Total	15.00	84.5	0.4	0.1	100

This table is based upon information supplied by the following manufacturing companies: Dengyosha Prime Mover Works, Ltd.; Hitachi, Ltd.; and Mitsubishi Shipbuilding Works, Ltd. It probably covers at least 95 per cent of the total production in Japan.

Table IX—Developed Water Powers of the World—at the Turbine Shafts

	Millions of Horsepower 1933		Millions of Horsepower 1933
United States	15.8	India	0.7
Canada	7.0	Mexico	0.6
Italy	7.0	Finland	0.5
Japan	5.6	England	0.4
France	4.0	New Zealand	0.3
Germany	3.5	Jugoslavia	0.2
Switzerland	3.5	Czechoslovakia	0.2
Norway	2.5	Chile	0.2
Sweden	2.0	Ireland	0.2
Spain	1.2	New Foundland	0.2
U. S. S. R.	1.0	Chosen	0.1
Austria	1.0	Tasmania	0.1
Brazil	0.8		
		Total	58.6

Lawrence River, as well as the amount of power developed in the Hudson Bay, may be noticed. The Santee River seems to be the most highly developed river in proportion to its length and drainage area.

Table X—Major Developments of the World, in Operation or Under Construction, Classified According to the Ultimate Aggregate Horsepower Capacity at the Turbine Shafts

Development	Country	River	Capacity in Horsepower: Ultimate	Installed or in Installation*
Developments of more than 500,000 Horsepower				
Grand Coulee	U. S.	Columbia	3,660,000	*147,000
Beauharnois	Canada	St. Lawrence	2,000,000	266,000
Boulder (Hoover)	U. S.	Colorado	1,835,000	*515,000
Shipshaw (Chute a Caron)	Canada	Saguenay	1,260,000	260,000
Dnieperstroy	U. S. S. R.	Dnieper	810,000	810,000
Serra do Cubato	Brazil	Tietê	750,000	166,000
Bonneville	U. S.	Columbia	688,000	*114,600
Wilson Dam (Muscle Shoals)	U. S.	Tennessee	610,000	260,000
Conowingo	U. S.	Susquehanna	594,000	378,000
Queenston	Canada	Niagara	560,000	560,000
Duna	Norway	Sunndalfjord	550,000	*550,000
Ile Maligne	Canada	Saguenay	540,000	495,000
Fort Peck	U. S.	Missouri	532,000	*
Safe Harbor	U. S.	Susquehanna	510,000	212,500
Developments of from 200,000 to 500,000 Horsepower				
Schoellkopf	U. S.	Niagara	452,500	452,500
Paugan	Canada	Gatineau	476,000	238,000
Galleto	Italy	Nera	400,000	200,000
Wheeler	U. S.	Tennessee	375,000	* 48,000
Saluda	U. S.	Saluda	330,000	220,000
Abitibi Canyon	Canada	Abitibi	330,000	132,000
Diablo	U. S.	Skagit	320,000	*166,000
Gorge	U. S.	Skagit	320,000	78,000
Esla	Spain	Esla	300,000	*225,000
Bridge River	Canada	Bridge	300,000	* 56,000
Carlo Cicogna (Cardano)	Italy	Isacro	285,000	269,000
Chats Falls	Canada	Ottawa	280,000	224,000
Shawinigan	Canada	St. Maurice	278,500	278,500
Brommat	France	Bromme	270,000	270,000
Bagnel (Osage)	U. S.	Osage	268,000	201,000
Rapid Blanc	Canada	St. Maurice	240,000	160,000
Flathead	U. S.	Flathead	234,000	*
Ardnacrusha	Irish Free State	Ardnacrusha	230,000	155,000
Dixence	Switzerland	Dixence	225,000	*225,000
Seven Sisters	Canada	Winnipeg	225,000	112,500
Cedars	Canada	St. Lawrence	220,000	220,000
Kembs	France	Rhine	220,000	*183,000
Timpa Grande	Italy	Arvo	220,000	107,000
Sarrans	France	Truyere	200,000	156,000
Jordan	U. S.	Coosa	216,000	144,000
Imatra	Finland	Vuoksen	216,000	108,000
Comerford (15 Mile Falls)	U. S.	Connecticut	215,000	215,000
Mareges	France	Dordogne	210,000	*210,000
Rock Island	U. S.	Columbia	210,000	84,000
Ilha dos Pambos	Brazil	Parahyba	204,000	116,000
Trollhattan	Sweden	Gotaelf	200,000	164,000
Arapuni	New Zealand	Waikato	200,000	100,000

* Asterisk indicates plants under construction.

Table VIII—World Production of Hydraulic Turbines During the 5-Year Period 1928 to 1932, Inclusive

	Type of Turbines: Pelton Aggregate Horsepower	Pelton Per Cent	Francis Aggregate Horsepower	Francis Per Cent	Propeller Aggregate Horsepower	Propeller Per Cent	Kaplan Aggregate Horsepower	Kaplan Per Cent	Totals Aggregate Horsepower	Totals Per Cent
United States and Canada	193,293	3.4	4,686,927	81.1	572,357	9.9	321,044	5.6	5,773,621	100
Europe	2,545,483	28.5	4,799,110	54.1	368,497	4.3	1,187,870	12.9	8,850,960	100
Japan	179,984	15.0	1,011,749	84.5	4,499	0.4	2,002	0.1	1,198,234	100
Totals	2,918,760	18.4	10,497,786	66.3	945,353	6.1	1,460,916	9.2	15,822,815	100

This table probably covers at least 90 per cent of the World production.

Table XI—Major North American Hydroelectric Power Developments* in Operation or Under Construction (1934) the Ultimate Capacity of Which Is More Than 20,000 Hp on the Turbine Shafts

Development	River	Drainage Basin	State or Province	Operating Company	Ultimate Horsepower	Installed or in Actual Installation: Hp	Year of Initial Operation	Year of Completion
I—North and Middle Atlantic Drainage Area								
Deer Lake	Humber	Deer Lake	Newfoundland	International Power & Paper Co. of Newfoundland Ltd.	156,000	156,000	1925	1930
Grand Falls	St. John	St. John	New Brunswick	Gatineau Pwr. Co.	80,000	80,000	1928	1931
Millinocket	Penobscot	Penobscot	Maine	Great Northern Paper Co.	42,500	42,500	1900	1922
Wyman	Kennebec	Kennebec	Maine	Cen. Maine Pwr. Co.	102,000	63,000	1931	1931
Rumford Falls	Androscoggin	Androscoggin	Maine	Rumford Falls Pwr. Co.	42,000	38,000	1903	1926
Gulf Island	Androscoggin	Androscoggin	Maine	Cen. Maine Pwr. Co.	27,000	27,000		1925
Lewiston	Androscoggin	Androscoggin	Maine	Union Water Pwr. Co.	25,000	23,666	1856	1921
Bonny Eagle & West Buxton	Saco	Saco	Maine	Cumberland County Pwr. & Lt. Co.	23,000	23,000		1927
Amoskeag	Merrimac	Merrimac	New Hampshire	Amoskeag Mfg. Co.		33,910		
Comerford (15 Mile Falls)	Connecticut	Connecticut	New Hampshire & Vermont	Connecticut River Power Co.	215,000	215,000	1930	1930
Bellows Falls	Connecticut	Connecticut	New Hampshire	Bellows Falls Hydro Elec. Corp.	66,000	66,000	1928	1928
Vernon	Connecticut	Connecticut	New Hampshire & Vermont	Connecticut River Power Co.	41,700	41,700	1909	1921
Turners Falls (Cabot)	Connecticut	Connecticut	Massachusetts	Turners Falls Pwr. & Elec. Co.	77,000	66,000	1916	1918
Harriman	Deerfield	Connecticut	Vermont	New England Pwr. Co.	60,000	60,000	1924	1925
Deerfield No. 5	Deerfield	Connecticut	Massachusetts	New England Pwr. Co.	20,400	20,400	1915	1915
Cobble Mt.	Westfield Little	Connecticut	Massachusetts	Turners Falls Pwr. & Elec. Co.	46,950	46,650	1932	1932
Rocky River	Housatonic	Housatonic	Connecticut	Connecticut Lt. & Pwr. Co.	66,000	33,000	1929	1929
Stevenson	Housatonic	Housatonic	Connecticut	Connecticut Lt. & Pwr. Co.	35,000	25,000	1919	1919
E. J. West	Sacandaga	Hudson	New York	New York Pwr. & Lt. Corp.	51,500	34,300	1930	1930
Spier Falls	Hudson	Hudson	New York	New York Pwr. & Lt. Corp.	154,000	92,200	1904	1930
Sherman Island	Hudson	Hudson	New York	Inter. Hydro. Elec. Corp.	60,000	40,000	1923	1923
School Street	Mohawk	Hudson	New York	New York Pwr. & Lt. Corp.	54,000	54,000	1915	1924
Schaghticoke	Hoosic	Hudson	New York	New York Pwr. & Lt. Corp.	20,000	20,000	1908	1908
Beardslee Falls	E. Canada Cr.	Hudson	New York	New York Pwr. & Lt. Corp.	30,000	21,200	1924	1924
Trenton Falls	W. Canada Cr.	Hudson	New York	Utica Gas & Elec. Co.	36,800	36,800	1901	1922
Wallenpaupack	Wallenpaupack	Delaware	Pennsylvania	Penna. Pwr. & Lt. Co.	57,000	57,000	1926	1926
York Haven	Susquehanna	Susquehanna	Pennsylvania	Metropolitan Edison Co.	29,213	29,213	1904	1914
Safe Harbor	Susquehanna	Susquehanna	Pennsylvania	Safe Harbor Water Pwr. Corp.	510,000	225,000	1931	1934
Holtwood	Susquehanna	Susquehanna	Pennsylvania	Penna. Water & Pwr. Co.	158,000	158,000	1910	1924
Conowingo	Susquehanna	Susquehanna	Maryland	Susquehanna Elec. Co.	594,000	378,000	1928	1928
II—South Atlantic and East Gulf of Mexico Drainage Area								
Reusens	James	James	Virginia	Appalachian Electric Pwr. Co.	30,200	20,200	1904	1931
High Rock	Yadkin	Pee Dee	North Carolina	Carolina Alum. Co.	44,100	44,100	1928	1928
Badin Narrows	Yadkin	Pee Dee	North Carolina	Carolina Alum. Co.	108,000	108,000	1917	1924
Yadkin Falls	Yadkin	Pee Dee	North Carolina	Carolina Alum. Co.	28,980	28,980	1919	1919
Norwood	Yadkin	Pee Dee	North Carolina	Carolina Pwr. & Lt. Co.	118,900	87,800	1928	1928
Blewett	Pee Dee	Pee Dee	North Carolina	Carolina Pwr. & Lt. Co.	34,000	34,000	1912	1912
Bridgewater	Catawba	Santee	North Carolina	Duke Pwr. Co.	35,600	35,600	1919	1919
Rhodhiss	Catawba	Santee	North Carolina	Duke Pwr. Co.	42,000	42,000	1925	1925
Oxford	Catawba	Santee	North Carolina	Duke Pwr. Co.	56,000	56,000	1928	1928
Lookout Shoals	Catawba	Santee	North Carolina	Duke Pwr. Co.	33,840	33,840	1915	1915
Mountain Island	Catawba	Santee	North Carolina	Duke Pwr. Co.	83,400	83,400	1923	1923
Catawba	Catawba	Santee	South Carolina	Duke Pwr. Co.	86,000	86,000	1925	1925
Fishing Creek	Catawba	Santee	South Carolina	Duke Pwr. Co.	64,125	64,125	1916	1916
Great Falls	Catawba	Santee	South Carolina	Duke Pwr. Co.	41,600	41,600	1907	1907
Dearborn	Catawba	Santee	South Carolina	Duke Pwr. Co.	52,500	52,500	1923	1923
Cedar Creek	Catawba	Santee	South Carolina	Duke Pwr. Co.	51,300	51,300	1926	1926
Rocky Creek	Wateree	Santee	South Carolina	Duke Pwr. Co.	41,600	41,600	1909	1909
Wateree	Wateree	Santee	South Carolina	Duke Pwr. Co.	105,500	105,500	1910	1919
99 Islands	Broad	Santee	South Carolina	Duke Pwr. Co.	31,200	31,200	1910	1910
Parr Shoals	Broad	Santee	South Carolina	Broad River Pwr. Co.	21,600	21,600	1914	1921
Saluda	Saluda	Santee	South Carolina	Lexington Water Pwr. Co.	330,000	220,000	1930	1930
Terrora	Tallulah	Savannah	Georgia	Georgia Pwr. Co.	30,400	30,400	1925	1925
Tallulah Falls	Tallulah	Savannah	Georgia	Georgia Pwr. Co.	108,000	108,000	1913	1913
Tugalo	Tugalo	Savannah	Georgia	Georgia Pwr. Co.	88,000	88,000	1924	1924
Yonah	Tugalo	Savannah	Georgia	Georgia Pwr. Co.	42,600	42,600	1925	1925
Stevens Creek	Savannah	Savannah	Georgia	So. Carolina Pwr. Co.	31,250	25,000	1914	1914
Furman Shoals	Oconee	Altamaha	Georgia	Georiga Pwr. Co.	80,000	80,000	Postponed	
Lloyd Shoals	Ocmulgee	Altamaha	Georgia	Georgia Pwr. Co.	33,000	33,000	1911	1911
Morgan Falls	Chattahoochee	Appalachicola	Georiga	Georiga Pwr. Co.	23,100	23,100	1904	1904
Bartletts Ferry	Chattahoochee	Appalachicola	Georgia	Georgia Pwr. Co.	88,000	66,000	1926	1926
Goat Rock	Chattahoochee	Appalachicola	Georgia	Georgia Pwr. Co.	65,000	25,500	1912	1912
Martin Dam (Cherokee Bluffs)	Tallapoosa	Alabama	Alabama	Alabama Pwr. Co.	180,000	135,000	1927	1927
Upper Tallassee	Tallapoosa	Alabama	Alabama	Alabama Pwr. Co.	75,000	50,000	1928	1928
Thurlow (Lower Tallassee)	Tallapoosa	Alabama	Alabama	Alabama Pwr. Co.	72,000	72,000	1931	1931
Lay Dam (Lock No. 12)	Coosa	Alabama	Alabama	Alabama Pwr. Co.	110,000	110,000	1914	1914
Mitchell	Coosa	Alabama	Alabama	Alabama Pwr. Co.	120,000	72,000	1923	1923
Jordan (Lock No. 18)	Coosa	Alabama	Alabama	Alabama Pwr. Co.	216,000	144,000	1929	1929

* The developments are classified in accordance with the following drainage areas, which may be identified on the accompanying map of the United States:

I North and Middle Atlantic
II South Atlantic and East Gulf of Mexico
III Great Lakes and St. Lawrence River
IV Upper Mississippi River
V Missouri River
VI Ohio River
VII Lower Mississippi River
VIII Western Gulf of Mexico
IX Gulf of California and Lower South Pacific
X Great Basin
XI Upper South Pacific
XII Lower North Pacific
XIII Middle North Pacific
XIV Hudson Bay

Table XI—(Continued)—Major North American Hydroelectric Power Developments* In Operation or Under Construction (1934) the Ultimate Capacity of Which Is More Than 20,000 Hp on the Turbine Shafts

Development	River	Drainage Basin	State or Province	Operating Company	Ultimate Horsepower	Installed or in Actual Installation: Hp	Installed or in Actual Installation: Year of Initial Operation	Installed or in Actual Installation: Year of Completion
III(A)—Great Lakes Drainage Area								
Thompson	St. Louis	Lake Superior	Minnesota	Miss. Pwr. & Lt. Co.	89,700	89,700	1909	1912
Kakabeka	Kaministiquia	Lake Superior	Ontario	Kaministiquia Pwr. Co.	35,000	35,000	1914	1914
Cameron Falls (Nipigon)	Nipigon	Lake Superior	Ontario	Hydro-Elec. Pwr. Comm.	75,000	75,000	1920	1926
Alexander	Nipigon	Lake Superior	Ontario	Hydro-Elec. Pwr. Comm.	72,000	54,000	1931	1931
High Falls	Michipicoten	Lake Superior	Ontario	Great Lakes Pwr. Co.	35,000	22,000	1929	1931
Sault Ste. Marie	St. Mary	Lake Huron	Ontario	Great Lakes Pwr. Co.		41,600	1900	1931
Sault Ste. Marie	St. Mary	Lake Huron	Michigan	Mich. Northern Pwr. Co.		40,000		
High Falls	Spanish	Lake Huron	Ontario	Huronian Co.	20,500	20,500	1906	1916
Big Eddy	Spanish	Lake Huron	Ontario	Huronian Co.	28,200	28,200	1929	1929
Espanola	Spanish	Lake Huron	Ontario	Abitibi Pwr. & Paper Co.	20,800	20,800	1911	1911
Hardy	Muskegon	Lake Michigan	Michigan	Consumers Pwr. Co.	40,000	40,000	1931	1931
Junction	Manistee	Lake Michigan	Michigan	Consumers Pwr. Co.	26,675	26,675	1918	1918
Hodenpyl	Manistee	Lake Michigan	Michigan	Consumers Pwr. Co.	24,000	24,000	1925	1925
De Cew Falls	Welland Canal	Lake Ontario	Ontario	Hydro-Elec. Pwr. Comm.	51,500	51,500	1898	1912
Queenston	Niagara	Lake Ontario	Ontario	Hydro-Elec. Pwr. Comm.	560,000	560,000	1921	1930
Ontario Power	Niagara	Lake Ontario	Ontario	Hydro-Elec. Pwr. Comm.	195,700	195,700	1905	1930
Canadian Niagara (Wm. B. Rankin)	Niagara	Lake Ontario	Ontario	Canadian Niagara Pwr. Co.	130,500	130,500	1905	1924
Toronto Power	Niagara	Lake Ontario	Ontario	Hydro-Elec. Pwr. Comm.	180,500	180,500	1906	1914
Schoellkopf	Niagara	Lake Ontario	New York	Niagara Falls Pwr. Co.	453,500	453,500	1907	1924
Adams (American Niagara)	Niagara	Lake Ontario	New York	Niagara Falls Pwr. Co.	105,000	105,000	1895	1904
Rochester No. 5	Genesee	Lake Ontario	New York	Rochester Gas & Elec. Corp.	54,000	54,000	1917	1928
Bennetts Bridge	Salmon	Lake Ontario	New York	Niag. Lockport & Ont. Pwr. Co.	40,000	40,000	1914	1914
Soft Maple	Beaver	Lake Ontario	New York	Northern N. Y. Utilities Inc.	31,500	21,000	1925	1925
III(B)—St. Lawrence River Drainage Area								
Browns Falls	E. Branch Oswegatchie	Oswegatchie	New York	Northern N. Y. Utilities Inc.	23,000	23,000	1923	1923
Colton (Browns Bridge)	Raquette	Raquette	New York	St. Lawrence Valley Pwr. Corp.	37,700	37,700	1919	1923
Massena	St. Lawrence	St. Lawrence	New York	Alum. Co. of America	71,375	71,375	1903	1914
St. Timothee	St. Lawrence	St. Lawrence	Quebec	Canadian Lt. & Pwr. Co.	28,800	28,800	1911	1914
Beauharnois	St. Lawrence	St. Lawrence	Quebec	Beauharnois Lt. Heat & Pwr. Co.	2,000,000	266,000	1932	1934
Quinze (Ka-Ka-Ke Falls)	Quinze	Ottawa	Quebec	Can. Northern Pwr. Corp.	60,000	40,000	1928	1928
Kipawa	Gordon Creek	Ottawa	Quebec	Gatineau Pwr. Co.	24,000	24,000	1930	1930
Bryson	Ottawa	Ottawa	Quebec	Gatineau Pwr. Co.	77,100	51,400	1925	1929
Chats Falls	Ottawa	Ottawa	Quebec & Ontario	Hydro-Elec. Pwr. Comm. / Ottawa Valley Pwr. Corp.	280,000	224,000	1931	1923
Chaudiere	Ottawa	Ottawa	Quebec	Gatineau Pwr. Co.	44,100	36,800	1909	1923
Paugan	Gatineau	Ottawa	Quebec	Gatineau Pwr. Co.	476,000	238,000	1928	1931
Chelsea	Gatineau	Ottawa	Quebec	Gatineau Pwr. Co.	170,000	136,000	1927	1929
Farmers	Gatineau	Ottawa	Quebec	Gatineau Pwr. Co.	120,000	96,000	1927	1929
High Falls	Liévre	Ottawa	Quebec	Maclaren-Quebec Pwr. Co.	120,000	90,000	1930	1930
Masson	Liévre	Ottawa	Quebec	Maclaren-Quebec Pwr. Co.		136,000	1933	1933
Cedars	St. Lawrence	St. Lawrence	Quebec	Cedars Rapids Mfg. & Pwr. Co.	220,000	220,000	1914	1924
Montreal Island (Back River)	des Prairies	St. Lawrence	Quebec	Montreal Island Pwr. Co.	75,000	45,000	1929	1929
Chambly	Richelieu	Richelieu	Quebec	Montreal Lt. Heat & Pwr. Co.	21,600	21,600	1899	1909
Hemming Falls	St. Francis	St. Francis	Quebec	Southern Canada Pwr. Corp.	33,600	33,600	1925	1925
Rapide Blanc	St. Maurice	St. Maurice	Quebec	Shawinigan Water & Pwr. Co.	340,000	160,000	1934	1934
Laurentide (Grand Mere)	St. Maurice	St. Maurice	Quebec	Shawinigan Water & Pwr. Co.	189,000	189,000	1915	1930
Shawinigan	St. Maurice	St. Maurice	Quebec	Shawinigan Water & Pwr. Co.	278,500	278,500	1908	1929
LaGabelle	St. Maurice	St. Maurice	Quebec	Shawinigan Water & Pwr. Co.	152,000	152,000	1924	1930
St. Narcisse	St. Lawrence	St. Lawrence	Quebec	North Shore Pwr. Co.	44,400	22,200	1926	1926
St. Ferreol	St. Anne de Beaupré	St. Lawrence	Quebec	Quebec Pwr. Co. Ltd.	24,000	24,000	1916	1926
Ile Maligne	Saguenay	Saguenay	Quebec	Duke Price Pwr. Co. Ltd.	540,000	495,000	1925	1925
Shipshaw (Chute à Caron)	Saguenay	Saguenay	Quebec	Alcoa Pwr. Co. Ltd.	1,260,000	260,000	1931	1931
IV—Upper Mississippi River Drainage Area								
Blanchard	Mississippi	Mississippi	Minnesota	Minnesota Pwr. & Lt. Co.	27,000	18,000	1924	1924
St. Croix Falls	St. Croix	St. Croix	Wisconsin	Northern States Pwr. Co.	35,400	35,400	1905	1905
Wissota	Chippewa	Chippewa	Wisconsin	Northern States Pwr. Co.	45,000	45,000	1916	1916
Chippewa Falls	Chippewa	Chippewa	Wisconsin	Northern States Pwr. Co.	30,000	30,000	1928	1928
Prairie Du Sac	Wisconsin	Wisconsin	Wisconsin	Wisconsin Pwr. & Lt. Co.	41,150	41,150	1909	1926
Keokuk	Mississippi	Mississippi	Iowa	Mississippi River Pwr. Co.	184,420	154,420	1913	1913
Lockport	Illinois	Illinois	Illinois	Sanitary District of Chicago	46,000	42,000	1907	1911
V—Missouri River Drainage Area								
Hauser Lake	Missouri	Missouri	Montana	Montana Pwr. Co.	25,000	25,000	1911	1914
Holter	Missouri	Missouri	Montana	Montana Pwr. Co.	70,000	70,000	1918	1918
Black Eagle	Missouri	Missouri	Montana	Montana Pwr. Co.	25,000	25,000	1913	1927
Volta	Missouri	Missouri	Montana	Montana Pwr. Co.	84,000	84,000	1916	1916
Rainbow	Missouri	Missouri	Montana	Montana Pwr. Co.	49,000	49,000	1910	1917
Morony	Missouri	Missouri	Montana	Montana Pwr. Co.	62,000	62,000	1930	1930
Fort Peck	Missouri	Missouri	Montana	U. S. Govt.	532,000		1939	
Casper Alcova	North Platte	North Platte	Wyoming	U. S. Govt.	42,000	42,000	1936	1940
Osage (Bagnell)	Osage	Osage	Missouri	Union Elec. Lt. & Pwr. Co.	268,000	201,000	1931	1931

* The developments are classified in accordance with the following drainage areas, which may be identified on the accompanying map of the United States:

I	North and Middle Atlantic	V	Missouri River	IX	Gulf of California and Lower South Pacific	XIII	Middle North Pacific
II	South Atlantic and East Gulf of Mexico	VI	Ohio River	X	Great Basin	XIV	Hudson Bay
III	Great Lakes and St. Lawrence River	VII	Lower Mississippi River	XI	Upper South Pacific		
IV	Upper Mississippi River	VIII	Western Gulf of Mexico	XII	Lower North Pacific		

Table XI—(Continued)—Major North American Hydroelectric Power Developments* in Operation or Under Construction (1934) the Ultimate Capacity of Which Is More Than 20,000 Hp on the Turbine Shafts

Development	River	Drainage Basin	State or Province	Operating Company	Ultimate Horsepower	Installed or in Actual Installation: Hp	Installed or in Actual Installation: Year of Initial Operation	Installed or in Actual Installation: Year of Completion
VI—Ohio River Drainage Area								
Piney	Clarion	Allegheny	Pennsylvania	Clarion River Pwr. Co.	34,000	34,000	1924	1928
Deep Creek	Deep Creek	Monongahela	Maryland	Youghiogheny Hydro Elec. Corp.	24,000	24,000	1925	1925
Lake Lynn (Cheat Haven)	Cheat	Monongahela	W. Virginia	West Penn Pwr. Co.	72,000	72,000	1926	1927
Byllesby	New	New	Virginia	Appalachian Elec. Pwr. Co.	32,000	32,000	1912	1912
Hawks Nest	New	New	W. Virginia	New Kanawha Pwr. Co.	175,000	140,000	1935	1936
Dix Dam	Dix	Dix	Kentucky	Kentucky Utilities Co.	32,724	32,724	1925	1925
Ohio Falls	Ohio	Ohio	Kentucky	Louisville Gas & Elec. Co.	135,000	108,000	1928	1928
Great Falls	Caney Fork	Cumberland	Tennessee	Tenn. Elec. Pwr. Co.	35,510	35,510	1916	1916
Waterville	Pigeon	Tennessee	No. Carolina	Carolina Pwr. & Lt. Co.	147,000	147,000	1930	1930
Norris Dam (Cove Creek)	Clinch	Tennessee	Tennessee	Tenn. Valley Auth.	120,000	120,000	1936	1936
Santeetlah	Cheoah	Tennessee	No. Carolina	Carolina Alum. Co.	66,000	66,000	1927	1927
Cheoah	Little Tenn.	Tennessee	No. Carolina	Carolina Alum. Co.	96,000	96,000	1918	1925
Calderwood	Little Tenn.	Tennessee	Tennessee	Aluminum Co. of America	168,000	112,000	1930	1930
Blue Ridge	Toccoa	Tennessee	Georgia	Tenn. Elec. Pwr. Co.	26,700	26,700	1931	1931
Ocoee No. 1	Ocoee	Tennessee	Tennessee	Tenn. Elec. Pwr. Co.	30,150	30,150	1912	1912
Ocoee No. 2	Ocoee	Tennessee	Tennessee	Tenn. Elec. Pwr. Co.	24,120	24,120	1913	1913
Hales Bar	Tennessee	Tennessee	Tennessee	Tenn. Elec. Pwr. Co.	56,720	56,720	1913	1913
Wheeler (Dam No. 3)	Tennessee	Tennessee	Alabama	Tenn. Valley Auth.	375,000	48,000	1936	...
Wilson Dam (Muscle Shoals)	Tennessee	Tennessee	Alabama	Tenn. Valley Auth.	610,000	360,000	1925	1926
VII—Lower Mississippi River Drainage Area								
Ozark Beach	White	Arkansas	Missouri	Empire Dist. Elec. Co.	48,000	24,000	1913	1931
Carpenter	Ouachita	Red	Arkansas	Arkansas Pwr. & Lt. Co.	118,500	79,000	1931	1932
VIII—Western Gulf of Mexico Drainage Area								
Boquilla	Conchos	Grande	Chihuahua	Cia Agricola y de Fuerza Elec. del Rio Conchos	26,000	26,000	1910	1915
Necaxa	Necaxa	Tecolutla	Puebla	Cia Mex. Luz y Fuerza Motriz, S. A.	108,000	108,000	1912	1923
Tepexic	Necaxa	Tecolutla	Puebla	Cia Mex. Luz y Fuerza Motriz, S. A.	60,000	60,000	...	...
Tuxpango	Blanco	Blanco	Vera Cruz	Puebla Tramway Lt. & Pwr. Co.	50,000	50,000	1911	1931
IX—Gulf of California and Lower South Pacific Drainage Areas								
Boulder (Hoover)	Colorado	Colorado	Ariz. & Nev.	U. S. Govt.	1,835,000	515,000	1935	1941
Parker	Colorado	Colorado	Arizona	U. S. Govt.	160,000	...	...	...
Verde	Verde	Colorado	Arizona	U. S. Govt.	21,000	...	...	...
Roosevelt	Salt	Colorado	Arizona	Salt River Valley Water Users Assoc.	26,240	26,240	1907	1924
Horse Mesa	Salt	Colorado	Arizona	Salt River Valley Water Users Assoc.	47,180	47,180	1927	1927
Puente Grande	Santiago	Santiago	Jalisco	Cia Elec. Chapala	22,700	22,700	1912	1912
Tepuxtepec	Lerma	Lerma	Michoacan	Cia Lus y Fuerza del Suroeste de Mexico	130,000	65,000	1930	1930
X—Great Basin Drainage Area								
Soda	Bear	Grt. Salt L.	Idaho	Utah Pwr. & Lt. Co.	20,000	20,000	1924	1924
New Grace	Bear	Grt. Salt L.	Idaho	Utah Pwr. & Lt. Co.	46,000	46,000	1914	1923
Oneida	Bear	Grt. Salt L.	Idaho	Utah Pwr. & Lt. Co.	42,000	42,000	1915	1920
Cutler	Bear	Grt. Salt L.	Utah	Utah Pwr. & Lt. Co.	43,000	43,000	1927	1927
Bishop (11 plants)	Owens	Owens Lake	California	So. Sierras Pwr. Co.	109,420	93,420	1905	1924
XI—Upper South Pacific Drainage Area								
Copco No. 1	Klamath	Klamath	California	Calif.-Oregon Pwr. Co.	37,200	37,200	1925	1925
Copco No. 2	Klamath	Klamath	California	Calif.-Oregon Pwr. Co.	40,000	40,000	1918	1918
Pit No. 1	Pit	Sacramento	California	Pac. Gas & Elec. Co.	93,834	93,834	1922	1922
Pit No. 3	Pit	Sacramento	California	Pac. Gas & Elec. Co.	108,580	108,580	1925	1925
Coleman	Battle Creek	Sacramento	California	Pac. Gas & Elec. Co.	22,118	22,118	1911	1911
Caribou	Feather	Sacramento	California	Grt. West. Pwr. Co. of Calif.	179,738	89,369	1921	1921
Bucks Creek	Bucks Creek	Sacramento	California	Grt. West. Pwr. Co. of Calif.	67,024	67,024	1928	1928
Big Bend (Las Plumas)	Feather	Sacramento	California	Grt. West. Pwr. Co. of Calif.	134,000	87,131	1916	1916
Colgate	Yuba-Mid. Fk.	Sacramento	California	Pac. Gas & Elec. Co.	20,878	20,878	1909	1906
Drum	Bear	Sacramento	California	Pac. Gas & Elec. Co.	73,726	73,726	1913	1928
Eldorado	American-S. Fk.	Sacramento	California	Pac. Gas & Elec. Co.	33,512	33,512	1924	1924
Kern R. No. 3	Kern	Kern Lake	California	So. Calif. Edison Co. Ltd.	46,245	46,245	1921	1921
Kern R. No. 1	Kern	Kern Lake	California	So. Calif. Edison Co. Ltd.	29,490	29,490	1907	1907
Big Creek No. 1	Big Creek	San Joaquin	California	So. Calif. Edison Co. Ltd.	109,920	109,920	1913	1925
Big Creek No. 2	Big Creek	San Joaquin	California	So. Calif. Edison Co. Ltd.	88,470	88,470	1913	1925
Big Creek No. 2a	Big Creek	San Joaquin	California	So. Calif. Edison Co. Ltd.	124,665	124,665	1928	1928
Big Creek No. 3	Big Creek	San Joaquin	California	So. Calif. Edison Co. Ltd.	175,000	131,567	1923	1923

* The developments are classified in accordance with the following drainage areas, which may be identified on the accompanying map of the United States:

I Northern and Middle Atlantic
II South Atlantic and East Gulf of Mexico
III Great Lakes and St. Lawrence River
IV Upper Mississippi River
V Missouri River
VI Ohio River
VII Lower Mississippi River
VIII Western Gulf of Mexico
IX Gulf of California and Lower South Pacific
X Great Basin
XI Upper South Pacific
XII Lower North Pacific
XIII Middle North Pacific
XIV Hudson Bay

Table XI—(Continued)—Major North American Hydroelectric Power Developments* in Operation or Under Construction (1934) the Ultimate Capacity of Which Is More Than 20,000 Hp on the Turbine Shafts

Development	River	Drainage Basin	State or Province	Operating Company	Ultimate Horsepower	Installed or in Actual Installation: Hp	Year of Initial Operation	Year of Completion
Big Creek No. 8	Big Creek	San Joaquin	California	So. Calif. Edison Co. Ltd.	77,750	77,750	1931	1929
Kerchoff	San Joaquin	San Joaquin	California	San Joaquin Lt. & Pwr. Corp.	57,105	57,105	1920	1920
San Joaquin No. 1	San Joaquin	San Joaquin	California	San Joaquin Lt. & Pwr. Corp.	21,448	21,448	1910	1911
Balch	San Joaquin	San Joaquin	California	San Joaquin Lt. & Pwr. Corp.	176,944	44,236	1927	1927
Exchequer	Merced	San Joaquin	California	Merced Irrig. Dist.	64,000	42,000	1926	1926
Mocassin	Tuolumne	San Joaquin	California	Hetch Hetchy Water Supply	130,000	100,000	1925	1925
Don Pedro	Tuolumne	San Joaquin	California	Turlock & Modesto Irrig. Dist.	70,000	41,100	1923	1923
Stanislaus	Stanislaus	San Joaquin	California	Pac. Gas & Elec. Co.	45,576	45,576	1908	1908
Melones	Stanislaus	San Joaquin	California	Pac. Gas. & Elec. Co.	36,193	36,193	1927	1927
Tiger Creek	Mokelumne	San Joaquin	California	Pac. Gas & Elec. Co.	30,430	30,430	1931	1931
Electra	Mokelumne	San Joaquin	California	Pac. Gas & Elec. Co.	75,000	26,810	1902	
Pardee	Mokelumne	San Joaquin	California	East Bay Municipal Utility Dist (Oakland)	20,000	20,000	1930	1930
San Francisquito No. 1	Los Angeles Aqueduct	Los Angeles Aqueduct	California	City of Los Angeles	96,200	96,200	1917	1928
San Francisquito No. 2	Los Angeles Aqueduct	Los Angeles Aqueduct	California	City of Los Angeles	62,000	62,000	1920	1932
XII—Lower North Pacific Drainage Area								
Diablo	Skagit	Puget Sound	Washington	City of Seattle	320,000	166,000	1936	1936
Gorge	Skagit	Puget Sound	Washington	City of Seattle	320,000	78,000	1924	1928
Baker River	Baker	Puget Sound	Washington	Puget Sound Pwr. & Lt. Co.	80,429	53,619	1925	
Snoqualmie	Snoqualmie	Puget Sound	Washington	Puget Sound Pwr. & Lt. Co.	26,810	26,810	1899	1911
Cedar Falls	Cedar	Puget Sound	Washington	City of Seattle	56,800	56,800	1904	1929
Electron	Pyallup	Puget Sound	Washington	Puget Sound Pwr. & Lt. Co.	30,161	30,161	1904	1929
White River	White	Puget Sound	Washington	Puget Sound Pwr. & Lt. Co.	134,000	80,429	1912	1916
Nisqually	Nisqually	Puget Sound	Washington	City of Tacoma	...	32,000	1912	1912
Cushman No. 1	Skokomish-N. Fk.	Puget Sound	Washington	City of Tacoma	50,000	50,000	1926	1926
Cushman No. 2	Skokomish-N. Fk.	Puget Sound	Washington	City of Tacoma	112,500	75,000	1931	1931
Corra Linn	Kootenay	Kootenay	Br. Columbia	West Kootenay Pwr. & Lt. Co.	57,000	57,000	1932	1932
Upper Bonnington	Kootenay	Kootenay	Br. Columbia	West Kootenay Pwr. & Lt. Co.	62,000	32,000	1907	1916
Lower Bonnington	Kootenay	Kootenay	Br. Columbia	West Kootenay Pwr. & Lt. Co.	53,000	53,000	1925	1926
South Slocan	Kootenay	Kootenay	Br. Columbia	West Kootenay Pwr. & Lt. Co.	75,000	75,000	1928	1929
Flathead	Flathead	Columbia	Montana	Montana Pwr. Co.	234,000			Postponed
Thompson Falls	Thompson	Columbia	Montana	Montana Pwr. Co.	49,000	49,080	1916	1916
Little Falls	Spokane	Columbia	Washington	Wash. Water Pwr. Co.	42,000	42,000	1910	1911
Long Lake	Spokane	Columbia	Washington	Wash. Water Pwr. Co.	98,000	98,000	1916	1924
Grand Coulee	Columbia	Columbia	Washington	U. S. Govt.	2,660,000	147,000	1937	
Lake Chelan	Chelan	Columbia	Washington	Chelan Elec. Co.	136,000	68,000	1927	1928
Rock Island	Columbia	Columbia	Washington	Puget Sound Pwr. & Lt. Co.	210,000	84,000	1933	1933
American Falls	Snake	Columbia	Idaho	Idaho Pwr. Co.	41,500	41,500	1912	1927
Bull Run "O"	Sandy	Columbia	Oregon	Portland Gen. Elec. Co.	28,150	28,150	1912	1922
Bonneville	Columbia	Columbia	Oregon	U. S. Govt.	688,000	114,600	1938	
Oak Grove "P"	Clackamas	Columbia	Oregon	Portland Gen. Elec. Co.	102,546	50,940	1924	1931
Cazadero "G"	Clackamas	Columbia	Oregon	Portland Gen. Elec. Co.	20,442	20,442	1907	1910
West Linn (Clackamas Mill "A")	Willamette	Columbia	Oregon	Crown Williamette Paper Co.	29,982	29,982	1889	1920
Ariel	Lewis	Columbia	Washington	Inland Pwr. & Lt. Co.	126,000	63,000	1931	1931
Prospect No. 2	Rogue	Rogue	Oregon	Calif.-Oregon Pwr. Co.	70,200	46,800	1928	1928
XIII—Middle North Pacific Drainage Area								
Falls River	Falls	Skeena	Br. Columbia	Northern B. C. Pwr. Co. Ltd.	32,000	4,000	1930	1930
Ocean Falls	Link	Link	Br. Columbia	Pacific Mills Ltd.	...	30,000		
Powell River	Powell	Powell	Br. Columbia	Powell River Co. Ltd.	...	51,000	1910	1926
Lois River	Lois	Lois	Br. Columbia	Powell River Co. Ltd.	50,000	24,800	1931	1931
Coquitlam-Buntzen	Burrard Inlet	Burrard Inlet	Br. Columbia	British Columbia Pwr. Corp.	64,000	64,000	1904	1913
Bridge River	Bridge	Fraser	Br. Columbia	British Columbia Pwr. Corp.	300,000	56,000		Postponed
Stave Falls	Stave	Fraser	Br. Columbia	British Columbia Pwr. Corp.	79,000	79,000	1912	1925
Ruskin	Stave	Fraser	Br. Columbia	British Columbia Pwr. Corp.	188,000	47,000	1930	1930
Campbell	Campbell	Campbell	Br. Columbia	British Columbia Pwr. Corp.	110,000	Postponed		
Jordan River	Jordan	Jordan	Br. Columbia	British Columbia Pwr. Corp.	41,750	41,750	1911	1914
XIV—Hudson Bay Drainage Area								
Island Falls	Churchill	Churchill	Saskatchewan	Churchill River Pwr. Corp.	86,400	44,400	1930	1930
Ghost	Bow	Nelson	Alberta	Calgary Pwr. Co.	55,000	38,000	1929	1929
Horseshoe Falls	Bow	Nelson	Alberta	Calgary Pwr. Co.	30,000	30,000	1911	1911
Great Falls	Winnipeg	Nelson	Manitoba	Manitoba Pwr. Co.	168,000	168,000	1928	1928
Pinawa	Winnipeg	Nelson	Manitoba	Winnipeg Elec. Co.	37,800	37,800	1906	1906
Seven Sisters	Winnipeg	Nelson	Manitoba	North Western Pwr. Co.	235,000	112,500	1931	1931
Slave Falls	Winnipeg	Nelson	Manitoba	City of Winnipeg Hydro Elec. System	96,000	24,000	1931	1931
Pointe du Bois	Winnipeg	Nelson	Manitoba	City of Winnipeg Hydro Elec. System	105,000	105,000	1911	1926
Smoky Falls	Mattagami	James Bay	Ontario	Spruce Falls Pwr. & Paper Co.	75,000	75,000	1928	1931
Twin Falls	Abitibi	James Bay	Ontario	Abitibi Pwr. & Paper Co.	30,000	30,000	1922	1930
Iroquois Falls	Abitibi	James Bay	Ontario	Abitibi Pwr. & Paper Co.	28,000	28,000	1914	1917
Island Falls	Abitibi	James Bay	Ontario	Abitibi Pwr. & Paper Co.	60,000	60,000	1925	1926
Abitibi Canyon	Abitibi	James Bay	Ontario	Hydro-Elec. Pwr. Comm.	330,000	132,000	1933	1933

* The developments are classified in accordance with the following drainage areas, which may be identified on the accompanying map of the United States:

I North and Middle Atlantic
II South Atlantic and East Gulf of Mexico
III Great Lakes and St. Lawrence River
IV Upper Mississippi River
V Missouri River
VI Ohio River
VII Lower Mississippi River
VIII Western Gulf of Mexico
IX Gulf of California and Lower South Pacific
X Great Basin
XI Upper South Pacific
XII Lower North Pacific
XIII Middle North Pacific
XIV Hudson Bay

Table XII—Aggregate Horsepower Capacity of Turbines Installed or in Installation—Classified According to the Different Drainage Basins

	Canada and New Foundland	Mexico	United States	Total
I—North and Middle Atlantic Drainage Areas				
Deer Lake	156,000			156,000
St. John	80,000			80,000
Penobscot			42,500	42,500
Kennebec			68,000	68,000
Androscoggin			86,666	86,666
Saco			23,000	23,000
Merrimac			33,910	33,910
Connecticut			516,050	516,050
Housatonic			58,000	58,000
Hudson			298,500	298,500
Delaware			57,000	57,000
Susquehanna			820,213	820,213
Totals	236,000		2,003,839	2,239,839
II—South Atlantic and Eastern Gulf of Mexico Drainage Area				
James			20,200	20,200
Pee Dee			302,880	302,880
Santee			965,265	965,265
Savannah			294,000	294,000
Ateltamaha			93,000	93,000
Appalachicola			114,700	114,700
Alabama			583,000	583,000
Totals			2,373,045	2,373,045
III—Great Lakes and St. Lawrence River Drainage Area				
Lake Superior	186,000		69,700	255,700
Lake Huron	111,100		40,000	151,100
Lake Michigan			90,675	90,675
Lake Ontario	1,088,200		672,500	1,760,700
Oswegatchie			23,000	23,000
Raquette			37,700	37,700
Ottawa	1,072,000			1,072,000
Des Prairies	45,000			45,000
Richelieu	21,600			21,600
St. Francis	33,600			33,600
St. Maurice	779,500			779,500
St. Anne de Beaupré	24,000			24,000
Saguenay	755,000			755,000
St. Lawrence Proper	537,000		71,375	608,375
Totals	4,653,000		1,004,950	5,657,950
IV—Upper Mississippi River Drainage Area				
St. Croix			35,400	35,400
Chippewa			75,000	75,000
Wisconsin			41,150	41,150
Illinois			42,000	42,000
Mississippi			172,420	172,420
Totals			365,970	365,970
V—Missouri River Drainage Area				
North Platte			42,000	42,000
Osage			201,000	201,000
Missouri			315,000	315,000
Totals			558,000	558,000
VI—Ohio River Drainage Area				
Allegheny			34,000	34,000
Monongahela			96,000	96,000
New			172,000	172,000
Dix			32,724	32,724
Cumberland			35,510	35,510
Tennessee			986,690	986,690
Ohio			108,000	108,000
Totals			1,464,924	1,464,924
VII—Lower Mississippi River Drainage Area				
Arkansas			24,000	24,000
Red			79,000	79,000
Totals			103,000	103,000
VIII—Western Gulf of Mexico Drainage Area				
Grande		26,000		26,000
Tecolutla		168,000		168,000
Blanco		50,000		50,000
Totals		244,000		244,000
IX—Gulf of California Drainage and Lower South Pacific Area				
Colorado			588,420	588,420
Santiago		22,700		22,700
Lerma		65,000		65,000
Totals		87,700	588,420	676,120
X—Great Basin Drainage Area				
Great Salt Lake			151,000	151,000
Owens Lake			93,430	93,430
Totals			244,430	244,430
XI—Upper South Pacific Drainage Area				
Klamath			77,200	77,200
Sacramento			895,172	896,173
San Joaquin			1,047,070	1,047,070
Kern Lake			75,735	75,735
Los Angeles Aqueduct			158,300	158,300
Totals			1,954,377	1,954,377
XII—Lower North Pacific Drainage Area				
Puget Sound			648,819	648,819
Kootenay	217,000			217,000
Columbia			836,614	836,614
Rogue			46,800	46,800
Totals	217,000		1,532,233	1,749,233
XIII—Middle North Pacific Drainage Area				
Skeena	4,000			4,000
Link	30,000			30,000
Powell	51,000			51,000
Lois	24,800			24,800
Burrard Inlet	64,000			64,000
Fraser	182,000			182,000
Jordan	41,750			41,750
Totals	397,550			397,550
XIV—Hudson Bay Drainage Area				
Churchill	44,400			44,400
Nelson	505,300			505,300
James Bay	325,000			325,000
Totals	874,700			874,700

Table XIII—Aggregate Horsepower Capacity of Turbines Installed or in Installation in Different Drainage Areas of the North American Continent

Drainage Areas	Capacity in Horsepower: Canada and New Foundland	Mexico	United States	Totals
I....North and Middle Atlantic	236,000		2,003,839	2,239,839
II....South Atlantic and Eastern Gulf of Mexico			2,373,045	2,373,045
III....Great Lakes and St. Lawrence River	4,653,600		1,004,950	5,657,950
IV....Upper Mississippi River			365,970	365,970
V....Missouri River			558,000	558,000
VI....Ohio River			1,464,924	1,464,924
VII....Lower Mississippi River			103,000	103,000
VIII....Western Gulf of Mexico		244,000		244,000
IX....Gulf of California and Lower South Pacific		87,700	588,420	676,120
X....Great Basin			244,430	244,430
XI....Upper South Pacific			1,954,377	1,954,377
XII....Lower North Pacific	217,000		1,532,233	1,749,233
XIII....Middle North Pacific	397,550			397,550
XIV....Hudson Bay	874,700			874,700
Totals	6,378,250	331,700	12,193,178	18,903,128

Table XIV—Aggregate Horsepower Capacity of Turbines Installed or in Installation in the Main Drainage Basins of the North American Continent

Drainage Basin	Horsepower Capacity	Drainage Basin	Horsepower Capacity
St. Lawrence River	5,657,950	Puget Sound	648,819
Mississippi River	2,443,894	Connecticut River	516,050
Columbia River	1,053,614	Nelson River	505,300
San Joaquin River	1,047,070	James Bay	325,000
Santee River	965,265	Pee Dee River	302,880
Susquehanna River	820,213	Hudson River	298,500
Sacramento River	896,172	Savannah	294,000
Colorado River	588,420		
Alabama River	583,000	Total	16,846,147

Report of the Board of Directors

The board of directors of the American Institute of Electrical Engineers presents herewith to the membership its fiftieth annual report, for the fiscal year ending April 30, 1934. A general balance sheet showing the condition of the Institute's finances on April 30, 1934, together with other detailed financial statements, is included herein. This report contains a brief summary of the principal activities of the Institute during the year, more detailed information having been published from month to month in ELECTRICAL ENGINEERING.

Fiftieth Anniversary of A.I.E.E.

THE BOARD of directors approved recommendations of the publication committee and the committee on coördination of Institute activities, and provided for the observance of the fiftieth anniversary of the organization of the Institute, on May 13, 1884, by the publication of a special issue (May 1934) of ELECTRICAL ENGINEERING and by the presentation, through the corresponding Section, of a suitable type of membership badge and certificate to each surviving Charter Member still on the membership list. It authorized the appointment by the President of the fiftieth anniversary committee, which coöperated with the publication committee in the preparation of the special issue of ELECTRICAL ENGINEERING, and has arranged for addresses commemorating the anniversary to be given at the summer convention by Past-President William McClellan and by Dr. William E. Wickenden.

Directors' Meetings

The board of directors held 5 meetings, 4 in New York, and 1 in Chicago, Ill. The executive committee held meetings in December and March, substituted for the regular meetings of the board, and acted upon various matters between board meetings.

Information regarding the more important activities of the Institute which have been under consideration by the board of directors, the committees, and the various officers is published each month in the section of ELECTRICAL ENGINEERING devoted to "News of Institute and Related Activities."

President's Visits

President Whitehead attended the winter convention and visited a large number of the Sections. The following is a list of places visited: Philadelphia, and Pittsburgh, Pa.; Washington, D. C.; Kansas City, Mo.; Omaha, Neb.; Denver, Colo.; Salt Lake City, Utah; Los Angeles, and San Francisco, Calif.; Portland, Ore.; Seattle, and Spokane, Wash.; Vancouver, B. C., and Toronto, Ont., Canada; Bozeman, Mont.

An invariable feature of these visits was a conference with the executive committee and other prominent members of the respective Sections, in which President Whitehead reviewed recent matters considered by the board of directors and other important questions still before them. Emphasis was laid on the financial condition of the Institute as related to losses of membership and the importance of support to the active membership campaign now under way. Attention was also devoted to the numerous questions which have recently arisen concerning the profession of engineering as a whole, but which do not fall within the sphere of the normal functions of the Institute. President Whitehead described the several existing agencies which have already been set up in conjunction with the other founder societies for handling questions of this character, dwelling especially on the purposes of American Engineering Council, the Engineers' Council for Professional Development, United Engineering Trustees, Inc., and other similar joint organizations. These reviews brought out much profitable discussion, and it was extremely satisfactory to find that there is little or no difference of opinion that the strength of the Institute rests largely in its adherence to its traditional ideals and functions, and that our participation in discussion of questions of controversial and semi-political character should be made through joint agencies with other branches of the profession, such as those referred to.

These business meetings with the local Sections were usually held either before or during a dinner tendered the President by the Section. Thereafter adjourning to another hall and a much larger meeting, Doctor Whitehead delivered a lecture entitled "Liquid Dielectrics," reporting some of the results of recent research in this field. The lecture was usually followed by a profitable discussion. In several Sections, Doctor Whitehead also addressed student Branches of the Institute and in such places faculties and student bodies contributed substantially to the success of the meetings.

Doctor Whitehead is especially appreciative of the many pleasures and courtesies of social character extended him everywhere. The board of directors wishes to add here its own appreciation and thanks to those of President Whitehead for his cordial reception everywhere by the Sections.

In May and June, President Whitehead's visits will include the summer convention in Hot Springs, Va., and other Sections.

Meetings

Two national conventions and one District meeting were held during the year, and a brief report on each follows.

Annual Meeting

The annual business meeting of the Institute was held at the Edgewater Beach Hotel, Chicago, Ill., Monday morning, June 26, 1933, as part of the opening session of the annual summer convention. The annual report of the board of directors for the fiscal year ending April 30, 1933, was presented in abstract, and the committee of tellers reported upon the election of officers for the administrative year beginning August 1, 1933. President-elect Whitehead responded with a brief address.

Election of Honorary Members

Six distinguished members of the Institute were elected Honorary Members by the board of directors on May 22, 1933: W. L. R. Emmet, G. A. Hamilton, A. E. Kennelly, R. A. Millikan, E. W. Rice, Jr., and Edward Weston. Announcement of their election was made, certificates were presented, and each who was present responded briefly, during the opening session of the summer convention, Monday morning, June 26.

Summer Convention

The forty-ninth annual summer convention was held at Chicago, Ill., June 26–30, 1933. Thirty-three papers were presented at 6 technical sessions. The annual conference of officers, delegates, and members, under the auspices of the Sections committee and the committee on student Branches, was held on Monday, June 26, and Tuesday, June 27, and 60 Section delegates, 3 District secretaries, and 6 counselor delegates were present. The entertainment features included golf and tennis tournaments, a dinner-dance, and various trips. The Lamme Medal for 1932 which was awarded to Dr. Edward Weston was presented during the opening session, being received, in the absence of Dr. Weston, by his son Edward F. Weston. 968 members and guests attended the convention.

Engineers' Week

Many engineering societies held their annual conventions in Chicago during the week of June 26–30, 1933, which was designated as Engineers' Week at the Century of Progress Exposition. The week was notable for the large number of joint meetings held by the various engineering and scientific societies. Wednesday, June 28, was devoted to joint activities of interest to members of practically all societies.

Winter Convention

The twenty-second winter convention was held in New York, January 23–26, 1934. Fifty-three papers were presented at 11 sessions. At an evening session, the Edison Medal was presented to Dr. Arthur E. Kennelly. Numerous inspection trips, a demonstration of the transmission and reproduction of speech and music in auditory perspective, a smoker, and a dinner-dance were held. The registration was 1,227.

District Meeting

Information on the District meeting held is given in Table I.

Table I—District Meeting

District No.	Location	Dates	Papers	Registration
1	Schenectady, N. Y.	May 10–13, 1933	15	431

Thirteen Student papers were presented.

Sections

Practically all Sections carried on a normal amount of activity, and nearly all of them agreed to keep their expenses for the present budget year at least 20 per cent below the maximum amounts that would be available under the by-laws, as suggested by the board of directors. The total number of meetings held was only slightly below the total of last year.

President Whitehead visited many of the Sections (see heading "President's Visits"), and will visit others in May.

The 4 groups of the New York Section and the power group of the Chicago Section continued a normal amount of activity and their meetings have been very popular among the members.

In connection with the work of the national membership committee, many of the Sections have made special efforts to retain their members and to encourage those who had been forced to relinquish membership to be reinstated.

The New Orleans Section was organized in January with the entire state of Louisiana as its territory. This brought the total number of Sections to 61.

With the adoption of a publication plan under which members and enrolled students are receiving in Electrical Engineering practically twice the amount of technical material previously supplied, it was necessary to reduce the news content. The publication committee, therefore, decided to discontinue the publication of detailed reports on local meetings, but to provide for suitable news items on Section and Branch activities, the details to be developed between the publication committee and the Sections committee and the committee on student Branches, respectively.

The fiftieth anniversary committee suggested that each Section and each Branch hold a meeting during May for appropriately observing the fiftieth anniversary of the organization of the Institute. Many Sections and Branches are planning such meetings and making special arrangements for the presentation of interesting historical information concerning the development of the Institute.

Student Activities

Nearly all Branches continued their activities in a normal manner, and the total number of meetings was almost equal to that for last year. Many of them have continued to place strong emphasis upon talks by students.

Upon the recommendations of the counselor delegates at the summer convention, the conference of officers, delegates, and members recommended to the board of directors the adoption of provisions for the enrollment in the Institute of evening students in electrical engineering in institutions offering evening courses considered by the committee on student Branches to meet the requirements outlined in the by-laws and for the organization of such evening students for Branch activities. Amendments to the by-laws to provide for such enrollment and for the organization of evening divisions of the corresponding student Branches were adopted, and the committee on student Branches approved the enrollment of evening students of the following institutions: Polytechnic Institute of Brooklyn, University of Cincinnati, Cooper Union, George Washington University, College of the City of New York, and New York University.

In adopting the budget for the present year, the board of directors provided an allowance for traveling expenses for a District conference on student activities in each District having a committee on student activities.

Nearly 50 per cent of the enrolled students whose periods of enrollment expired on April 30, 1934, applied for admission as Associates.

New Branches were organized at South Dakota State College, Brookings, So. Dakota, and Villanova College, Villanova, Pa., bringing the total number to 113.

See the last 2 paragraphs under the heading "Sections" which contain material concerning Sections and Branches.

Section and Branch Statistics

Data on the Sections and Branches are given in Table II.

Table II—Section and Branch Statistics

	For Fiscal Year Ending			
	April 30, 1928	April 30, 1930	April 30, 1932	April 30, 1934
Sections				
Number of Sections	52	56	60	61
Number of Section meetings held	431	480	497	472
Total attendance	64,276	84,615	105,325	73,271
Branches				
Number of Branches	96	106	109	113
Number of Branch meetings held	915	1,009	1,135	1,015
Total attendance	44,334	50,401	54,197	41,772

Technical Program Committee

In addition to its routine functions the technical program committee has devoted a good portion of its time to analysis of its duties, division of work between technical committees, and like matters with a view toward achieving better balance among technical activities. It has obtained working agreements as to division of work between technical committees, better delineation of scopes of individual committees, and in general a more harmonious and efficient functioning of this portion of Institute work.

Analysis of the character of material presented has been continued with the result that some of the committees which previous analysis showed to lag in the amount of material presented have been encouraged to greater activity. In the field of electrochemistry and electrometallurgy a symposium on electric furnaces was held during the winter convention, which brought out 7 valuable papers and considerable discussion on this subject. In the field of education a session also was held which proved to be of broad general interest.

The committee has reviewed 175 papers during the year. Of this number, 101 were presented at the 2 national conventions and 1 District meeting held during the year and 90 of these have been recommended for publication in the Transactions. Of the remainder, 74 papers, 26 have been published in Electrical Engineering and some of these have been scheduled for future meetings, while others are awaiting publication; a few have been returned to the authors. The total attendance for the 3 meetings during the year was 2,626, 9.9 per cent less than the total attendance of the previous year, during which 2 more meetings were held. The attendance at the winter convention alone was 1,227, representing an increase of $11^1/_2$ per cent over the attendance for the same convention the previous year. Details regarding the attendance and number of papers presented at each convention are given in Table III.

The committee has fostered the attempt to achieve short and interesting presentation of papers, thus allowing more time for discussion. Presentation of papers by title only has been tried experimentally with quite good results. The papers thus presented were all published previously and presumably had been read by practically every one in attendance. Stricter adherence to time limit on discussions was also urged with the result that the conduct of meetings is approaching a smoother performance.

The new publication policy of the Institute has resulted in a material change in scheduling the receipt and publication of papers. The committee

Table III—Attendance and Numbers of Papers Presented April 30, 1933, to April 30, 1934

Meetings	No. Papers Presented	No. Pages Printed	No. Papers Recommended for TRANS.	No. of Sessions	Attendance
National Conventions					
Summer convention, Chicago, Ill., June 26–30, 1933	53	226	31	10*	968
Winter convention, New York, January 23–26, 1934	53	337	49	11	1,227
Total	86	563	80	21	2,195
District Meetings					
North Eastern District, Schenectady, N. Y., May 10–12, 1933	15	62	10	4	431
Grand total	101	625	90	25	2,626

* Includes 4 joint meetings with other societies.

has been able to offer the publication committee complete coöperation and the transition from the old basis to the new is being accomplished with no major difficulties.

The code of the meetings and papers committee has been revised to conform to the recent changes in routine and procedure and will be reissued as the code of the technical program committee.

Suggestions from individuals, Sections, Districts, and other committees have been received, examined, and, if possible, incorporated within the activities of the committee.

Acknowledgment by the committee for coöperation in handling its complex interrelationships is due to authors, technical committee members, reviewers, the headquarters staff, and to the committee's permanent secretary.

Publication Committee

The completion of further studies of the many problems involved in the production of the Institute's publications made information available upon the basis of which the publication committee early in the fiscal year recommended extensive and important changes in the publication policy and procedure. Recognizing the pressing necessities of the present economic situation, and recognizing also the desirability of improving the Institute's publication service to its individual members, the committee recommended the elimination of the costly duplication in publication represented by the traditional issuance of individual pamphlet copies of technical papers, and recommended the consolidation of the monthly and the quarterly publications.

The several related proposals were discussed at length at the conference of officers, delegates, and members held in connection with the forty-ninth annual summer convention in Chicago, and by that body were recommended favorably to the board of directors. Accordingly, at its regular meeting August 8, 1933, the board of directors ratified the proposals involved in the new publication policy and recommended their immediate application, with the understanding that further details would be developed by the publication committee. The details involved have been dealt with extensively in Electrical Engineering (first and second covers, September 1933; p. 665, October 1933; p. 793, November 1933) and consequently they will be only summarized here.

Electrical Engineering will continue to be published monthly as the Institute's official technical organ, becoming the primary publication by virtue of enlargement to include the full text of all recommended A.I.E.E. papers, and the acceptable discussions thereon. The quota of special articles and other features that have proved so popular since January 1931 is scheduled to be maintained as previously established. Some routine departmental material that proved to be of but little value and only limited interest has been omitted or reduced to a conciseness commensurate with its usefulness. Thus every member of the Institute will receive month-by-month in a timely fashion all the Institute's technical material in addition to other material of current interest. This is a further step in the development of an adequate publication policy undertaken seriously by the publication committee in 1929, and continuously under consideration and development since that time.

The Transactions, previously issued quarterly, now are to be issued at the close of each calendar year as an annual volume embracing the contents of the 12 issues of the monthly publication for that year. Because this annual volume will be a duplicate publication and will be desired only by a minority of the membership, a nominal subscription price ($4 yearly to members) is being charged for a cloth bound volume estimated to contain about 1,400 pages.

Technical papers and discussions, to a large degree if not entirely, will be released for publication in Electrical Engineering immediately upon the logical completion and technical review of the manuscripts, instead of having the release of contemporary manuscripts controlled artificially by some advance meeting date. Because of this improved general distribution of technical papers, the production and free distribution of separate pamphlet copies of technical papers has been discontinued.

For economic reasons the application of the unified plan was undertaken in the fall and winter of 1933–4. This rapid changeover caused several new, although temporary, problems to be involved, such as oversize monthly issues of Electrical Engineering. However, both the Institute membership and the Institute budget have profited by the advanced changeover. It is contemplated that the program will be in full and smooth operation by the close of the current calendar year, if not before.

In commemoration of the founding of the Institute May 13, 1884, Electrical Engineering for May 1934 was enlarged and issued as an Anniversary number, reflecting the highlights of Institute history.

Standards

During the past year, since April 30, 1933, it has been found necessary to call only 3 meetings of the standards committee. The time of the committee at those meetings was devoted almost entirely to matters of organization of committees and coordination of projects in hand or proposed.

Due to the many changes which have occurred in both membership of the Institute and the personnel of companies and organizations, a considerable number of new appointments of A.I.E.E. representatives on various sectional committees of the American Standards Association and on standardizing committees of other organizations have been made.

Several new propositions for standardization have been presented to the committee for consideration and recommendation as to disposition. Among these may be noted the following: Modification of standards for temperature limits of insulation; standardization of depreciation in electrical machinery and apparatus; and development of a color code for control wiring. In addition, a number of

suggestions for revision of existing A.I.E.E. standards and American standards were received and transmitted to the committees concerned.

Seven standards have received the approval of the A.S.A. either as "American Standards" or "Tentative Standards." Four of these were standards appearing in the A.I.E.E. series and 3 were developed by a sectional committee of which the Institute was a joint sponsor. The standards approved were as follows: Constant Current Transformers; Graphical Symbols for Electric Power and Wiring, for Radio, and for Electric Traction, including Railway Signaling; Capacitors; Electric Arc Welding Apparatus; Resistance Welding Apparatus. In November 1933, the sectional committee on Rotating Electrical Machinery issued its first report on "Proposed American Standards for Rotating Electrical Machinery." This report, when it eventually reaches the status of a standard, will replace the 5 present A.I.E.E. rotating machinery standards which were used largely as the basis of the report.

U.S. National Committee of the I.E.C.

The work of the International Electrotechnical Commission has been somewhat hampered during the past year by world economic conditions. Only one meeting of the U.S. National Committee has been necessary to take care of participation by the United States in I.E.C. work.

Progress was made on specific technical projects during the year as follows:

1. *International Electrotechnical Vocabulary.* A meeting of the international advisory committee which has in preparation a comprehensive electrotechnical vocabulary in French and English was held in Paris in October. It is now proposed that the French portion of the vocabulary will be prepared first and it is hoped that it will be possible to submit this part to the I.E.C. within the next year. After this is done the English edition will be prepared through coöperation with the British and U. S. National Committees.

2. *Electric and Magnetic Magnitudes and Units.* A meeting of this section of advisory committee No. 1 on nomenclature was held in Paris in October under the chairmanship of Dr. A. E. Kennelly. Recommendations in regard to unit names, unit symbols, definitions of the cgs units and the conventional direction of inductively reactive power in diagrams were arrived at and will be submitted later to all of the national committees of the I.E.C. A complete statement of the status of this work is contained in Electrical Engineering for March 1934, p. 402–5.

3. *Electric Traction Equipment.* At a meeting of the committee of action of the I.E.C. held in Paris in October it was decided to publish the revised rules for electric traction equipment. Such publication was objected to by the U.S.N.C. on the grounds that the rules as proposed were contrary to the best engineering opinion in this country and would result in unfavorable changes in both cost and efficiency. The first page of the publication contains a statement to the effect that the rules have been objected to by the U.S.N.C. The document is designated as "I.E.C. Publication No. 48—Rules for Electric Traction Motors" (1st edition 1933).

During the year technical advisors were appointed for the 2 advisory committees organized the preceding year, F. M. Farmer as technical adviser on the subject of electric cables (I.E.C. committee No. 20) and Dr. George W. Vinal as technical adviser on accumulator batteries (I.E.C. committee No. 21).

The meeting of advisory committee No. 19 on internal combustion engines, scheduled for last September in this country, was not held because of the fact that so many of the foreign national committees found it impossible to send delegates.

The plenary meeting of the I.E.C. which had been scheduled for 1934 in Prague has been postponed until 1935. No definite time has been set and no place decided upon but the suggestion has been made that it would be well to hold the meeting in Brussels during the universal exhibition which will take place in 1935.

Coördination Committee

In accordance with past practice, the committee corresponded with District and Section officers to obtain their views regarding any national conventions and District meetings desired in their respective Districts during the calendar year 1935. On account of economic conditions, the committee recommended to the board of directors, at its meeting held on January 22, 1934, that the adoption of a schedule of 1935 meetings be postponed to the May meeting of the board, and this recommendation was approved.

The committee considered and reported to the board of directors upon various matters which had been referred to it.

Committee on the Economic Status of the Engineer

The activities of this committee were largely referred to and handled by the Institute's delegation on Engineers' Council for Professional Development, which was organized in 1932.

Committee on Safety Codes

No meetings of the committee were called this year, as no matters were presented either from within the committee or from outside organizations to warrant calling a meeting.

The Institute was represented by delegates from the committee on safety codes at the meetings of the National Fire Waste Council, in Washington, and the National Fire Protection Association, in Milwaukee.

The chairman of the committee worked with the National Safety Council on their recently revised "Safe Practices Pamphlet No. 29 on Electrical Equipment in Industrial Plants," and carried on correspondence in connection with arranging for speakers for the annual safety congress of the National Safety Council held in Chicago in 1933.

The chairman of the committee on safety codes of the A.I.E.E. has continued to function as the chairman of a special committee of the electrical committee of the National Fire Protection Association on the use of bare neutral in interior wiring systems. It was desirable to have an engineering representative as chairman of this special committee and, if possible, an individual with central station, manufacturing, and actual wiring experience. This subject has been an active one and has involved considerable correspondence and activity for the

chairman and the special committee. The subject is still active and continuing. In its ramifications it involves the function of water mains, and services, in connection with the grounding of distribution and house wiring systems. Considerable material has been gathered, but no report has as yet been rendered.

Technical Committees

The technical committees continued their activities in the stimulation of the preparation of desirable papers in their respective fields and in the review of papers submitted to the Institute for presentation and publication. Information on meetings, papers, and publications is given on other pages of this report.

Membership Committee

The membership committee with a complete District and Section organization has been working diligently to obtain applications for membership, to bring Students into Associate membership, and to urge and help members to reinstatement. The results are shown in the accompanying tables.

Table IV gives the annual membership statistics in the usual form.

Table IV—Membership Statistics for the Fiscal Year Ending April 30, 1934

	Honorary	Fellow	Six-Year Member	Associate	Associate	Total
Membership on April 30, 1933	9	729	3,864	6,671	5,747	17,020
Additions:						
Transferred	6	25	134	750		
New members qualified		1	46	11	654	
Former members reinstated		1	15	48	21	
Total	15	756	4,059	7,480	6,422	18,732
Deductions:						
Died		26	34	29	13	
Resigned		3	77	315	188	
Transferred		3	35	126	761	
Dropped		10	230	861	801	
Membership on April 30, 1934	15	714	3,693	6,149	4,659	15,230

Table V shows the number of applications received from enrolled Students and from all others during each of the past 4 fiscal years. Fewer Students' applications are being received for Associate membership, and the number of applications received from all others during the past year was larger than for the preceding year.

Table V—Number of Applications Received From Enrolled Students and From All Others

Year Ending	From Students	From All Others	Total
April 30, 1934	467	498	965
April 30, 1933	674	305	979
April 30, 1932	779	612	1,391
April 30, 1931	533	964	1,497

Table VI shows that the number of enrolled Students has been decreasing. It is of major importance to the Institute that the Student enrollment be maintained for future membership. While Student enrollment is under the auspices of the committee on Student Branches, the membership committee is responsible for obtaining applications from enrolled Students for admission to the Associate grade.

Table VI—Number of Enrolled Students

April 30, 1934	3,186 (1,548)
April 30, 1933	3,260 (1,494)
April 30, 1932	3,700 (1,624)
April 30, 1931	3,813 (2,218)

(Following the number of Students reported for April 30th of each year is indicated, within parentheses, the number of new applications received during that year; the difference between this number and the reported total, of course, reflects the number of renewals of Student enrollment for the corresponding period.)

Considerable effort of the membership committee has been devoted to encouraging and helping members in arrears for dues, and thereby subject to suspension, to be reinstated to active membership. The figures of Table VII show the results of this effort. In these results, the committee feels there is cause for satisfaction.

Table VII—Number of Members in Section Territory Reinstated

August 1, 1933, to April 30, 1934	603
Year beginning August 1, 1932	277
Year beginning August 1, 1931	327
Year beginning August 1, 1930	375

The membership committee has received verbal and written communications urging leniency in carrying members faced with unfavorable financial circumstances. Table VIII shows the figures in this regard.

Table VIII—Membership of the Institute, April 30, 1934

Of the 15,230 membership reported for April 30, 1934, 11,028 are fully paid to April 30, 1934. The balance of 4,202 is divided into the following groups:

1. Members owing dues to May 1, 1933.	
Total number of members who have not acted upon resolution of board of directors adopted in January 1934 providing an extension of time for payment of these dues (including 836 members of 6 years' standing or longer who were entitled, upon application, to dues cancellation if unemployed during corresponding fiscal year)	1,874
Total number of members who obtained dues cancellation to May 1, 1933, because of unemployment reasons (80), or who have received an extension of time (48), but who have not yet renewed active membership on pro rata basis for current year, as provided in resolution of board of directors adopted in January 1934	128
	2,002
2. Members owing dues to May 1, 1934	2,200
(During the period May 1 to 22, 1934, 353 members have paid dues to May 1, 1934, reducing the total to 1,847.)	

The large number of letters sent out by headquarters staff pursuant to the resolutions of the board of directors, together with many answers from members afford convincing proof that the attitude has been liberal. If occasions arise where it apparently has not seemed liberal, they are, undoubtedly, due to misunderstandings.

As a comparison, the figures of Table IX are of interest:

Table IX—Memberships Fully Paid

	Membership as of April 30	Number of Members Fully Paid as of April 30	Per cent Fully Paid
1934	15,230	11,028	72.4
1927 (year of maximum membership)	18,344	16,247	88.5

Deaths

The following deaths have occurred during the year:

Fellows: Harold DeForest Arnold, Ernest J. Bechtel, Frederick N. Bosson, Byron T. Burt, Alexander Churchward, Charles F. Conn, Harry C. Cushing, Jr., Minor M. Davis, Clarence E. Doolittle, Giuseppe Faccioli, William J. Hammer, William S. Lee, James Lyman, Kempster B. Miller, John H. Morecroft, Everett Morss, Niels L. Mortensen, Farley Osgood, Frank W. Peek, Jr., Norman N. Ross, Edson O. Sessions, H. A. Sinclair, George O. Squier, J. Franklin Stevens, Calvert Townley, George M. Yorke.

Members: Albert E. Alkins, Frank H. Bernhard, Lee Boyer, Burton H. Brooks, Arthur A. Brown, William A. Bucke, T. Herbert Clegg, G. Herbert Condict, Harry A. Curtis, Henry H. Cutler, Harry T. Edgar, Augustine R. Everest, Charles L. Fortier, Albert L. Harvey, Murray J. Idail, Herbert E. Kaighn, Louis F. Leurey, Cyril F. Mackness, Walter C. Mangels, Norman Marshall, George J. Newton, C. W. Nitschke, Francis L. O'Bryan, Joseph D. Peters, William B. Potter, Thorburn Reid, Charles H. Schum, Robert Shand, Carleton W. Smith, Harold W. Smith, John E. Sumpter, Charles S. Thompson, Roberto J. Urie, George C. Ward.

Associates: R. Narayana Aiyangar, Charles G. Beckwith, John C. Benjamin, Norman McD. Crawford, Herbert H. Dewey, Paul Dewitt, Jetha N. Diwan, William A. Ferguson, James G. Finley, Leon H. Frank, Otto T. Gierisch, Maurice Grunfield, J. Henry Hackett, Grenville A. Harris, Herman T. Hauser, Paul H. Jaehnig, E. C. Joho, Charles F. Kaesemeyer, Shizuo Katoh, William W. Ker, Myles B. Lambert, William F. Lamme, Charles V. Lenehan, Robert Lindsay, Marion B. Lines, Daniel R. Lyden, George B. McElheny, Charles A. McGeehan, Charles F. Medbury, Edward A. Mellinger, Veator D. Mendenhall, Vance W. Miller, Edward F. Morrill, Edson L. Morris, Ord Myers, M. Alfonso Porras, Frederick J. Rasmussen, Walter D. Ryan, Clare N. Stannard, Horace W. Steinhoff, Emanuel W. Sundberg, Paul S. Sussan.

Board of Examiners

The board of examiners held 9 meetings during the past year, averaging about 2.5 hr, and considered 2,277 cases, divided as shown in Table X.

Table X—Applications for Admission and Transfer

Applications for Admission:			
Recommended for grade of Associate	771		
Not recommended	5		
		776	
Recommended for grade of Member	48		
Not recommended	12		
		60	
Recommended for grade of Fellow	1		
Not recommended	2		
		3	
Recommended for enrollment as Students			1254
Applications for Transfer:			
Recommended for grade of Member	154		
Not recommended	3		
		157	
Recommended for grade of Fellow	25		
Not recommended	2		
		27	
			2277

Institute Prizes

Five national prizes and 9 District prizes for papers presented in 1932 were announced on p. 424 of the June 1933 issue of Electrical Engineering. The national prizes were presented at the summer convention in Chicago, and the District prizes were presented at various meetings in the respective Districts.

Scholarships

The governing bodies of Columbia University have placed at the disposal of the Institute each year a scholarship in electrical engineering for each class. The awards are made annually by an Institute committee. Each scholarship pays $350 toward annual tuition, with provision for reappointment.

Complete details governing prizes and scholarships may be obtained by applying to the national secretary of the Institute.

Edison Medal

The Edison Medal, founded by associates and friends of the late Thomas A. Edison, is awarded annually by a committee consisting of 24 members of the Institute "for meritorious achievement in electrical science, electrical engineering, or the electrical arts." The medal for 1933 was awarded to Dr. Arthur E. Kennelly, "for meritorious achievements in electrical science, electrical engineering, and the electrical arts as exemplified by his contributions to the theory of electrical transmission and to the development of international electrical standards." The medal was presented at the winter convention of the Institute, January 24, 1934.

John Fritz Medal

The John Fritz Medal board of award, which is composed of representatives of the national societies of civil, mining, mechanical, and electrical engineers, awarded the thirtieth medal to John Ripley Freeman, posthumously.

Lamme Medal

The Lamme Medal was founded as a result of a bequest of the late Benjamin G. Lamme, chief engineer of the Westinghouse Electric and Manufacturing Company, who died on July 8, 1924. The bequest provides for the award by the Institute of a gold medal (together with a bronze replica thereof) annually to a member of the A.I.E.E. "who has shown meritorious achievement in the development of electrical apparatus or machinery" and for the award of 2 such medals in some years if the accumulation from the funds warrants.

The Lamme Medal committee of the Institute awarded the sixth (1933) Lamme Medal to Dr. Lewis B. Stillwell, "for his distinguished career in connection with the design, installation, and operation of electrical machinery and equipment." Arrange-

ments are being made for the presentation of the medal at the annual summer convention at Hot Springs, Va., June 25–29, 1934.

Alfred Noble Prize

This prize, established in 1929, consists of a certificate and a cash award of $500 from the income from a fund contributed by engineers and others to perpetuate the name and achievements of Alfred Noble, past-president of the A.S.C.E. and of the Western Society of Engineers. It is made to a member of any of the coöperating societies, A.S.C.E., A.I.M.E., A.S.M.E., A.I.E.E., or W.S.E., for a technical paper of particular merit accepted by the publication committee of any of these societies, provided the author, at the time of such acceptance, is not over 30 years of age. The third award (1933) was made to C. Maxwell Stanley.

Commission of Washington Award

This award may be made annually "to an engineer whose work in some special instance, or whose services in general have been noteworthy for their merit in promoting the public good," by a committee composed of 9 representatives of the Western Society of Engineers and 2 each from the A.S.C.E., the A.I.M.E., the A.S.M.E., and the A.I.E.E.

Iwadare Foundation Committee

As this is the first report of the Iwadare Foundation committee, an outline of its work since its appointment and a brief statement of its functions are included.

In 1929 Mr. K. Iwadare of Japan established and generously endowed a Foundation under the trusteeship of the Denki-Gakkwai (The Institute of Electrical Engineers of Japan) with a 2-fold purpose:

1. To provide from the income the means for enabling promising Japanese students to reside in the United States for a period of one year for the purpose of carrying on studies in electrical engineering colleges, the plants of electrical industries, and government institutions; and

2. To provide from the income the means for bringing to Japan from time to time noted American electrical engineers to deliver a series of lectures on American advances and practices in the electrical arts.

As the Japanese Institute naturally looked to our Institute for guidance in carrying out this program in the United States, the Iwadare Foundation committee was appointed by the President of the American Institute of Electrical Engineers in December 1931, to assist the Japanese Institute in carrying out the provisions of the Iwadare Foundation.

The committee appointed consisted of F. B. Jewett, chairman, W. I. Slichter, and Gerard Swope. This committee served until August 1, 1933, at which time Professor Slichter's term expired. At that time, Dr. C. E. Skinner was appointed to this committee, and the present membership consists of F. B. Jewett, chairman, Gerard Swope, and C. E. Skinner.

The first purpose of the Iwadare Foundation has been handled in the main by the Japanese Institute of Electrical Engineers. From time to time, recipients of such fellowships have come to our country and, under the guidance of our national secretary, have been enabled to carry on work in the field of their choice. Five Fellows so far have visited this country, namely:

Masaharu Hoshiai, Assistant Professor of Electrical Engineering at Tokyo Imperial University.

Takeo Akahira, Research Engineer of the Institute of Physical and Chemical Research.

Tomoyoshi Hirota, Assistant Professor of Electrical Engineering at Waseda University.

Kichiro Sakakibara, Electrical Engineer.

Shintaro Uda, Assistant Professor of Electrical Engineering at Tohoku Imperial University.

The sixth Fellow,

Y. Takahashi of the Meidensha Elec. Works, Tokyo (Part-time lecturer at Imperial University)

called at Institute headquarters on April 25, 1934.

The second purpose of the Iwadare Foundation has not so far worked out entirely as intended. Dr. A. E. Kennelly of Harvard University was invited to lecture in Japan before the Iwadare Foundation committee was appointed. He went to Japan late in 1931. Since his visit, largely due to the depression, no other lecturer has visited Japan under a grant from this Foundation. The late General J. J. Carty, at one time vice-president of the American Telephone and Telegraph Company, and Dr. Frank J. Sprague, president of the Sprague Safety Control and Signal Corporation, both past-presidents of the American Institute of Electrical Engineers, and E. M. Herr, formerly president of the Westinghouse Electric and Manufacturing Company, had each accepted an invitation to go to Japan, but circumstances arose which precluded their final acceptance. A few other candidates of suitable caliber from industrial organizations, solicited by your committee, could not at the time leave the United States.

Last fall Dr. C. E. Skinner, past-president of the American Institute of Electrical Engineers, on the recommendation of your committee, accepted an invitation from the Japanese Institute to be the next lecturer from the United States, and he is now in Japan and plans to remain there during April 1934.

The Japanese Institute of Electrical Engineers has requested the American Institute through your committee to select another lecturer for next fall. Although it is the desire of the people in Japan in general to select 2 representatives from industry to one from university circles, it may be impossible this year to adhere strictly to this preference and it may be that your committee will make the next selection from university circles, although if possible the next appointee will be from the industrial field.

Advisory Committee to New York Museum of Science and Industry

The committee, during the past year, has been in conference with Dr. C. R. Richards, director of the

New York Museum of Science and Industry, and has made a survey of the exhibits of the Museum, particularly with reference to the developments in the generation, distribution, and application of electricity.

Employment Service

The Institute coöperates with the national societies of civil, mining, and mechanical engineers in operation of the Engineering Societies Employment Service with its main office in the Engineering Societies Building, New York. Offices are operated in Chicago and San Francisco also. In addition to the societies named, others coöperate in certain of the offices as follows: New York—Society of Naval Architects and Marine Engineers; Chicago—Western Society of Engineers; San Francisco—California Section of the American Chemical Society, and the Engineers Club of San Francisco.

The New York office has coöperated closely with the Professional Engineers Committee on Unemployment which was organized in the fall of 1931 by the local Sections of the A.S.C.E., A.I.M.E., A.S.M.E., and A.I.E.E.

The service is supported by the joint contributions of the societies and their individual members who are benefited. As in the past, it consists principally in acting as a medium for bringing together the employer and the employee. In addition to the publication of the employment service announcements monthly in Electrical Engineering, weekly subscription bulletins are issued for those seeking positions.

An analysis of this employment service is given in Table XI.

Table XI—Analysis of Employment Service

Month	Men Registered				Men Placed			
	New York	Chicago	San Francisco	Total	New York	Chicago	San Francisco	Total
1933								
May	122	46	66	234	35	35	28	98
June	156	33	52	241	50	12	25	87
July	128	51	57	236	33	9	22	64
August	144	45	74	263	42	11	21	74
September	126	43	46	215	48	4	10	62
October	100	24	31	155	62	8	21	91
November	77	17	26	120	63	11	44	118
December	75	4	38	117	52	5	25	82
1934								
January	67	1,002	44	1,113	60	644	17	721
February	66	74	37	177	38	80	9	127
March	61	33	60	153	48	23	10	81
April	93	49	48	190	54	15	17	86
Total	1,235	1,421	588	3,244	585	857	249	1,691

American Engineering Council

The "object" of the American Engineering Council, as stated in its Constitution, is "to further the public welfare wherever technical and engineering knowledge and experience are involved, and to consider and act upon matters of common concern to the engineering and allied technical professions."

The Council includes in its membership about 20 national, state, and local engineering societies. Under the plan of reorganization recently adopted for the purpose of making further reductions in the operating expenses of the Council, the assembly and the administrative board were combined, and the number of representatives reduced. The A.S.C.E., A.S.M.E., and the Institute now have 5 representatives each, 2 other societies have 1 each, and there are 6 regional representatives for state and local societies. In addition, past-presidents serve for 6 years after the expiration of their terms as president without being accredited to any member organization. L. W. Wallace, who had served as executive secretary since the organization of the Council, resigned in January 1934, and was succeeded by F. M. Feiker.

The wide variety of types of activities in which the Council engages is illustrated by the titles of the special committees which have been continued for 1934, as follows: administration of public works; air transport service in foreign commerce; communications; competition of governmental agencies with engineers in private practice; engineers water power policy; flood control; naval towing tank; patents; relation of consumption, production, and distribution; state engineering councils; telephone directory classification of engineers; water resources; and committee to appear before coordination committee of founder societies.

The many important developments in progress or contemplated which will have strong influences upon the engineering profession and upon the public welfare in matters directly involving engineering have placed heavy demands for assistance upon the Council during the past year. It is endeavoring to serve as effectively as possible the engineering profession and through it the public welfare.

United Engineering Trustees, Inc.

This organization, formerly United Engineering Society, was set up by the 4 national societies of civil, mining, mechanical, and electrical engineers to hold in trust and to administer for them the Engineering Societies Building, in which their headquarters are located, certain funds, and the library. Its charter gives it broad powers for the advancement of the engineering arts and sciences.

Extracts from the annual report of the United Engineering Trustees, Inc., were published on p. 633 of the April 1934 issue of Electrical Engineering.

Engineering Foundation

This department of United Engineering Trustees, Inc., was established in 1914 by the national societies of civil, mining, mechanical, and electrical engineers "for the furtherance of research in science and in engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind." It was conceived by Ambrose Swasey, of Cleveland, Ohio, and he has made 4 gifts toward its endowment. The fund has been generously increased through the gifts of the late Edward D. Adams and others, and also through a bequest of the late Henry R. Towne.

Appropriations have been made for various research projects, and coöperation has been extended in others.

During the past few years the Foundation has supplied substantial financial assistance for 2 researches sponsored by the A.I.E.E. committee on electric welding, one at the Massachusetts Institute of Technology and the other at Lehigh University. The former was completed, and the latter is to be continued during 1934.

Engineering Societies Library

The library is administered as a free public library under the direction of the library board of United Engineering Trustees, Inc., this board being composed of representatives of the national societies of civil, mining, mechanical, and electrical engineers.

The library contains about 132,712 books and pamphlets. It receives regularly about 1,200 technical periodicals in many languages, and many additional publications issued irregularly.

A staff of technically trained searchers and translators is maintained. The staff is prepared to furnish the following types of service: photoprints, abstracts, translations, bibliographies, searches, etc. Special arrangements have been made for lending books.

Engineers' Council for Professional Development

A conference on certification composed of representatives of the national societies of chemical, civil, electrical, mechanical, and mining engineers, the Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners approved, in 1932, a plan for joint action of these organizations for the enhancement of the professional status of the engineer, and recommended the formation of the Engineers' Council for Professional Development. The participating bodies ratified the plan, and the organization of E.C.P.D. was effected in the fall of 1932. The council consists of 21 members, 3 representing each of the participating bodies.

The first annual meeting of E.C.P.D. was held October 10, 1933, and certain recommendations and matters of policy were approved. The principal recommendations deal with accrediting of engineering schools, minimum definition of an engineer, and suggested greater uniformity of grades of membership among the professional societies. These matters are now under consideration by the participating bodies.

Representatives

The Institute has continued its representation upon various national committees and other local and national bodies with which it has been affiliated in past years. A complete list of representatives was published in the September issue of Electrical Engineering, and in the 1934 Year Book.

Finance Committee

During the year the committee has held meetings frequently, has passed upon the expenditures of the Institute for various purposes, and otherwise performed the duties prescribed for it in the constitution and by-laws.

Haskins and Sells, certified public accountants, have audited the books, and their report follows.

Respectfully submitted for the board of directors,

H. H. Henline,

National Secretary

May 25, 1934

HASKINS & SELLS
CERTIFIED PUBLIC ACCOUNTANTS

22 EAST 40TH STREET
NEW YORK

May 18, 1934

American Institute
of Electrical Engineers,
33 West 39th Street,
New York.

Dear Sirs:

We have made an examination of your accounts for the purpose of verifying the stated financial condition at April 30, 1934, and have made an examination of your records of cash receipts and disbursements for the year ended that date. We submit the following exhibits and schedule:

Exhibit

A—Balance Sheet, April 30, 1934.
Schedule 1—Property Fund and Restricted Funds—Securities, Cash, and Accrued Interest Receivable.

B—Statement of Cash Receipts and Disbursements of General Fund for the Year Ended April 30, 1934.

C—Statement of Cash Receipts and Disbursements of Property Fund and Restricted Funds for the Year Ended April 30, 1934.

In our opinion Exhibit A sets forth your financial condition at April 30, 1934, and Exhibits B and C set forth your receipts as recorded and your disbursements during the year ended that date.

Yours truly,

Haskins & Sells

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Balance Sheet, April 30, 1934

Exhibit A

ASSETS

Property Fund Investments:		
One-fourth interest in real estate and other assets of United Engineering Trustees, Inc., exclusive of Trust Funds	$496,948.48	
Equipment:		
Library—Volumes and fixtures	37,296.37	
Office furniture and fixtures (less reserve for depreciation, $31,124.09)	11,456.91	
Works of art, etc.	3,001.35	
Securities and cash—Schedule 1	10,065.00	
Total property fund investments		$558,768.11
Restricted Fund Investments—Schedule 1:		
Securities—At cost (less reserve for bonds of doubtful value)	$167,179.02	
Cash	7,848.52	
Accrued interest receivable	223.33	
Total restricted fund investments		175,250.87
Current and Working Assets:		
Cash	$ 29,824.74	
Accounts receivable:		
Members—For dues	38,082.79	
Advertisers	60.00	
Miscellaneous	3,687.27	
Accrued interest on investments	2,243.59	
Inventories:		
"Quarterly Transactions"	4,714.25	
Text and cover paper	5,888.93	
Badges	618.39	
Total current and working assets		75,119.86
Total		$809,138.84

LIABILITIES

Property Fund Reserve		$558,768.11
Restricted Fund Reserves:		
Reserve Capital Fund	$154,528.25	
Life Membership Fund	10,290.37	
International Electrical Congress of St. Louis Library Fund	4,711.39	
Lamme Medal Fund	4,685.78	
Mailloux Fund	1,035.18	
Total restricted fund reserves		175,250.87
Current Liabilities:		
Accounts payable	$ 9,450.66	
Dues received in advance	2,684.45	
Entrance fees and dues advanced by applicants for membership	480.50	
Subscriptions for "Quarterly Transactions" received in advance	88.00	
Miscellaneous	66.65	
Total current liabilities		12,770.26
Surplus		62,349.60
Total		$809,138.84

Notation: In accordance with the usual practice of the Society, no provision has been made for dues which may prove to be uncollectable.

Property and Restricted Funds—Securities, Cash, and Accrued Interest Receivable, April 30, 1934

Exhibit A, Schedule 1

	Number of Shares of Stock or Face Value of Bonds	Property Fund (Equipment Replacements)	Restricted Funds: Reserve Capital Fund	Restricted Funds: Life Membership Fund	Restricted Funds: International Electrical Congress of St. Louis Library Fund	Restricted Funds: Lamme Medal Fund	Restricted Funds: Mailloux Fund	Total
SECURITIES								
Railroad Bonds:								
Baltimore & Ohio Railroad Company 6% refunding and general mortgage series C, due 1995	$12,000.00	$	$ 8,940.00			$4,330.00		$ 13,270.00
Central of Georgia Railway Company 5% consolidated mortgage, due 1945	3,000.00		1,477.50					1,477.50
Chicago, Burlington & Quincy Railroad Company 4%, due 1958	5,000.00			$ 4,868.75				4,868.75
Chicago, Burlington & Quincy Railroad Company 5% first and refunding mortgage series A, due 1971	1,000.00		1,010.00					1,010.00
Chicago & Erie Railroad Company 5% first mortgage, due 1982	1,000.00		1,105.00					1,105.00
Chicago & Northwestern Railway Company 6½%, due 1936	9,000.00		7,202.50					7,202.50
Chicago, Terre Haute & Southeastern Railway Company 5% first and refunding mortgage, due 1960	8,000.00		7,940.00					7,940.00
Florida East Coast Railway Company 5% first and refunding mortgage series A, due 1974 (certificates of deposit)	10,000.00		9,818.75					9,818.75
New York Central Railroad Company 5% refunding and improvement mortgage series C, due 2013	6,000.00		5,742.50					5,742.50
Pennsylvania Railroad Company 4¼% general mortgage series A, due 1965	5,000.00		5,130.00					5,130.00
St. Louis-San Francisco Railway Company 5% prior lien mortgage series B, due 1950 (certificate of deposit)	6,000.00		5,497.50					5,497.50
Southern Railway Company 5% first consolidated mortgage, due 1994	1,000.00		980.00					980.00
Western Pacific Railroad Company 5% series A, due 1946	15,000.00		7,225.00					7,225.00
Total railroad bonds—(Forward)			$ 62,068.75	$ 4,868.75		$4,330.00		$ 71,267.50

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Property and Restricted Funds—Securities, Cash, and Accrued Interest Receivable, April 30, 1934

Exhibit A, Schedule 1

	Number of Shares of Stock or Face Value of Bonds	Property Fund (Equipment Replacements)	Restricted Funds: Reserve Capital Fund	Life Membership Fund	International Electrical Congress of St. Louis Library Fund	Lamme Medal Fund	Mailloux Fund	Total
SECURITIES—Continued								
TOTAL RAILROAD BONDS—(Forward)			$ 62,068.75	$ 4,868.75		$4,330.00		$ 71,267.50
Public Utility Bonds:								
Consolidated Gas Company of New York 5½% debentures, due 1945	$ 5,000.00		$ 5,187.50					$ 5,187.50
Duquesne Light Company 4½% first mortgage series A, due 1967	3,000.00		2,970.00					2,970.00
Hydro-Electric Power Commission of Ontario 3½%, due 1952	4,500.00		4,500.00					4,500.00
New York Telephone Company 4½%, due 1939	2,000.00				$ 878.75		$1,000.00	1,878.75
Pacific Gas & Electric Company 5½% first and refunding mortgage series C, due 1952	5,000.00		5,137.50					5,137.50
Philadelphia Company secured 5% series A, due 1967	10,000.00		10,000.00					10,000.00
Shawinigan Water & Power Company 4½% first mortgage and collateral trust sinking fund series A, due 1967	5,000.00		4,581.25					4,581.25
Texas Electric Service Company 5% first mortgage, due 1960	4,000.00		3,910.00					3,910.00
United Light & Power Company 5½% first lien and consolidated mortgage, due 1959	5,000.00		4,975.00					4,975.00
Total public utility bonds			$ 41,261.25		$ 878.75		$1,000.00	$ 43,140.00
Industrial Bonds:								
American Smelting & Refining Company 5% first mortgage series A, due 1947	$ 9,000.00		$ 9,085.00					$ 9,085.00
Bethlehem Steel Company 5% purchase money and improvement mortgage sinking fund, due 1936	5,000.00		5,033.75					5,033.75
Cleveland Union Terminals Company 5% sinking fund series B, due 1973	4,000.00	$4,010.00						4,010.00
Fidelity Union Title and Mortgage Guaranty Company first mortgage certificates (on property 75–79 Prospect Street, East Orange, N. J.) 5½%, due 1933	$14,663.00	977.53	13,685.47					14,663.00
International Match Corporation 5% convertible debentures, due 1941 (certificate of deposit)	3,000.00		2,880.00					2,880.00
New York Steam Corporation 6% first mortgage, due 1947	10,000.00		10,837.50					10,837.50
United States Rubber Company 5% first and refunding mortgage series A, due 1947	2,000.00		1,915.00					1,915.00
Western Electric Company 5% debentures, due 1944	10,000.00		9,818.75					9,818.75
Youngstown Sheet and Tube Company 5% first mortgage sinking fund series A, due 1978	10,000.00		10,137.50					10,137.50
Total industrial bonds		$4,987.53	$ 63,392.97					$68,380.50
Municipal Bonds:								
New York City 4½% corporate stock, due 1957	2,000.00				$2,204.05			$ 2,204.05
Capital Stocks:								
Commonwealth Edison Company	12 shares		$ 2,892.00					$ 2,892.00
Consolidated Gas Company of New York, $5.00 cumulative preferred	30 "	$ 3,060.00						3,060.00
Public Service Corporation of New Jersey, $5.00 preferred	30 "		2,958.75					2,958.75
United Gas Improvement Company, $5.00 preferred	30 "	1,995.00	997.50					2,992.50
Total capital stocks		$ 5,055.00	$ 6,848.25					$ 11,903.25
Total securities		$10,042.53	$173,371.22	$ 4,868.75	$3,082.80	$4,330.00	$1,000.00	$196,895.30
Less Reserve for Bonds of Doubtful Value:								
Central of Georgia Railway Company 5% consolidated mortgage, due 1945	$ 3,000.00		$ 1,477.50					$ 1,477.50
Florida East Coast Railway Company 5% first and refunding mortgage series A, due 1974	10,000.00		9,818.75					9,818.75
International Match Corporation 5% convertible debentures, due 1941	3,000.00		2,880.00					2,880.00
St. Louis-San Francisco Railway Company 5% prior lien mortgage series B, due 1950	6,000.00		5,497.50					5,497.50
Total reserve for bonds of doubtful value			$ 19,673.75					$ 19,673.75
Total Securities, Less Reserve		$10,042.53	$153,697.47	$ 4,868.75	$3,082.80	$4,330.00	$1,000.00	$177,221.55
Cash		22.47	630.78	5,388.29	1,560.90	255.78	12.88	$ 7,870.99
Accrued Interest Receivable				33.33	67.50	100.00	22.50	223.33
Total property fund securities and cash		$10,065.00						$ 10,065.00
Total restricted fund investments			$154,328.25	$10,290.37	$4,711.29	$4,685.78	$1,035.18	$175,250.87

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Statement of Cash Receipts and Disbursements of General Fund for the Year Ended April 30, 1934

Exhibit B

Cash on Deposit, May 1, 1933, With the National City Bank of New York		$ 15,648.46
Receipts:		
Dues (including dues allocated to members "Electrical Engineering" subscriptions)	$162,285.88	
Advertising	17,036.74	
"Electrical Engineering" non-member subscriptions	10,375.18	
"Quarterly Transactions" subscriptions	9,436.64	
Miscellaneous publications, etc.	3,321.32	
Students dues	8,109.50	
Entrance fees	3,460.00	
Badges	1,188.50	
Transfer fees	834.46	
Interest on investments and bank balances	8,567.92	
Miscellaneous	35.56	
Total receipts		224,651.70
Total		$240,300.16
Disbursements:		
Publication expenses:		
"Electrical Engineering"	$ 65,248.35	
"Quarterly Transactions"	10,895.37	
Technical papers	2,792.22	
Year book	5,965.10	
Miscellaneous	1,024.40	
Administrative expenses	41,280.10	
Institute Sections	23,572.10	
Institute meetings	8,814.30	
Institute Branches	2,082.04	
American Engineering Council	9,250.00	
Forward	$171,923.98	$240,300.16
Total—(Forward)		$240,300.16
Disbursements—(Forward)	$171,923.98	
Traveling expenses:		
Board of Directors	2,585.60	
Branch Counselors	1,444.19	
Geographical districts:		
Executive Committees	1,117.75	
Vice-Presidents	440.85	
National Nominating Committee	1,207.90	
President's Special Appropriation	1,012.25	
United Engineering Trustees, Inc.:		
Library assessment	7,926.03	
Building assessment	2,966.40	
Standards Committee	4,406.87	
Membership Committee	5,188.29	
Employment service	3,535.44	
American Standards Association	1,333.33	
Badges	948.98	
Loss on exchange	500.85	
Retirement salary	2,700.00	
Finance Committee	400.00	
United States National Committee of International Commission on Illumination	300.00	
Geographical District prize—Best Branch paper	135.00	
Technical Committees	200.31	
Headquarters Committee	17.00	
Code Committee	60.00	
Edison Medal Committee	144.31	
Total disbursements		210,475.42
Cash on Deposit, April 30, 1934, With the National City Bank of New York		$ 29,824.74

Statement of Cash Receipts and Disbursements of Property Fund and Restricted Funds for the Year Ended April 30, 1934

Exhibit C

	Total	Property Fund (Equipment Replacements)	Restricted Funds: Reserve Capital Fund	Restricted Funds: Life Membership Fund	Restricted Funds: International Electrical Congress of St. Louis Library Fund	Restricted Funds: Lamme Medal Fund	Restricted Funds: Mailloux Fund
Cash on Deposit May 1, 1933, With East River Savings Bank and National City Bank of New York	$8,036.80		$316.25	$6,019.50	$1,459.59	$235.78	$ 5.68
Receipts:							
Principal of mortgage certificates—Partial collection	$ 837.00	$22.47	$314.53				
Interest on bonds	620.00			$ 200.00	$ 135.00	$240.00	$45.00
Interest on bank balances	166.15			166.15			
Total receipts	$1,123.15	$22.47	$314.53	$ 366.15	$ 135.00	$240.00	$45.00
Total	$9,159.95	$22.47	$630.78	$6,385.65	$1,594.59	$475.78	$50.68
Disbursements:							
Annual withdrawal authorized in by-laws	$ 997.36			$ 997.36			
Bronze and gold replicas of Lamme Medal	220.00					$220.00	
Other disbursements	71.60				$ 33.60		$38.00
Total disbursements	$1,288.96			$ 997.36	$ 33.60	$220.00	$38.00
Cash on Deposit, April 30, 1934, With East River Savings Bank and National City Bank of New York	$7,870.99	$22.47	$630.78	$5,388.29	$1,560.99	$255.78	$12.68

The Expulsion Oil Circuit Breaker

In the expulsion type of oil circuit breaker the arc occurring on circuit interruption is "expelled" from the contact chamber by a high velocity gas blast. Breakers of this type have demonstrated their capability of consistently interrupting short circuits on a typical large electric power system within 1 or 2 cycles of arc. In this paper the theory of this type of breaker is presented and its performance is analyzed.

By
A. C. SCHWAGER
MEMBER A.I.E.E.

Pacific Elec. Mfg. Co.
San Francisco, Calif.

THE CONTINUALLY growing capacity of high voltage electric power systems and the resultant demand for fast circuit interruption has brought about in the last few years the development of greatly improved circuit interrupters. The duration of the short-circuit time has been shortened by eliminating part of the mechanical time lag of the opening motion and by reducing the arcing time. The plain circuit breaker has been substituted by devices bringing about a more rapid and smooth interruption of the arc. This paper is limited to the electrical problem of arc interruption.

Interruption in a circuit breaker with not more than $^1/_2$ cycle of arc is obviously the ultimate goal to be accomplished. This requirement has been met for moderate voltages by several new devices; for higher voltages the arcing time is consistently longer and often still excessive. The reduction in arcing time brings about a reduction in arc energy sometimes to 5 per cent of the value obtained under identical conditions with a plain oil circuit breaker. It is well known, however, that a vacuum switch can interrupt currents with an arc energy of extremely small magnitude when compared with the best oil circuit breakers. The question, therefore, arises as to whether it is possible to build an arc rupturing device for an oil circuit breaker that approaches the performance of the vacuum breaker and what minimum value of arc energy would be required for interruption. In this paper such a design is shown to be feasible. A high-voltage high-capacity expulsion type oil circuit breaker has demonstrated its capability of consistently interrupting short circuits on a typical large electric power system under various conditions over a range from 1 to 100 per cent of maximum rated short-circuit current with from 1 to 2 cycles of arc. Arc energy and gas generation have been reduced to values heretofore not reached, with oil deterioration and carbonization practically eliminated. Interruption up to full rated capacity occurs with no other external sign than that resulting from the motion of the operating mechanism.

Full text of a paper recommended for publication by the A.I.E.E. committee on protective devices, and scheduled for discussion at the A.I.E.E. Pacific Coast convention, Salt Lake City Utah, Sept. 3–7, 1934. Manuscript submitted May 9, 1934; released for publication June 8, 1934. *Not published in pamphlet form.*

Theory of the Expulsion Circuit Breaker

For many years, it has been realized that an arc is deionized more effectively in an atmosphere of hydrogen than in any other gas. This accounts for the short arc lengths obtained in the conventional plain-break oil circuit breaker, which burns essentially in a hydrogen atmosphere, when compared with the large distances to which an arc has to be drawn in air to effect interruption. Recent investigations show that an arc in hydrogen burns at much smaller *diameter* than an arc in air, for identical currents (Kesselring, *Elektrotechnische Zeitschrift*, v. 55, p. 92). The diameter of the arc is one of the primary factors influencing the speed of deionization in the vicinity of the current zero period: the smaller the arc diameter, the more rapid the deionization. An arc in air can be forced to burn at a smaller diameter by subjecting it to a high velocity air blast, a fact that has been made use of for several decades in air blast devices. The smallest diameter and the most effective deionization of an arc for a certain current finally can be obtained by a combination of the foregoing 2 conditions, that is, by subjecting it to a blast of hydrogen gas. No detailed account will be given here of the factors responsible for this performance, such as diffusion, recombination, and specific heat; for a more detailed analysis the reader is referred to the excellent paper by Slepian on "The Extinction of Long A.C. Arcs" (A.I.E.E. Trans., v. 49, 1930, p. 421–30).

An arc under oil produces hydrogen by decomposition and it is not difficult to provide a device for forcing the hydrogen at high velocity through the arc. The conventional explosion chamber is but one example; however, its performance is not satisfactory with regard to arcing time, arc energy, and capacity to interrupt small currents. An ideal gas blast device should fulfill the following specifications:

1. Interruption should take place at the first current zero.
2. It should be equally effective for large and small currents (including charging currents of long transmission lines).
3. The amount of gas generated should be limited to the minimum necessary for definite interruption.

In the following paragraphs is described a gas blast device that should meet the foregoing specifications. Figure 1a illustrates the conventional explosion pot in the process of interruption with the movable contact in a position at which the first current zero occurs. The arc is burning in a stationary atmosphere of hot gases, gas blast action is entirely absent and reignition occurs. Only after the blade has left the throat is there a localized gas blast through it

which produces sufficient deionization to prevent reignition. On high voltages, interruption by means of such an explosion chamber requires 4 cycles of arc or more. As shown in Fig. 1b, the free escape of the deionizing gas stream is impeded seriously by the large volume of oil in the chamber. The high pressure gas bubble within the chamber forces a definite quantity of oil through the throat and causes the cross section of the gas blast to be small and erratic for the various duties under which it must operate. Figure 1c shows another well-known arrangement of an explosion pot, a hole being provided back of the fixed contact through which the gases can escape into the surrounding oil. Provided the gas pressure is high and the mass of the oil piston formed by the oil volume within the opening is sufficiently small, a gas blast is initiated in a very short time, causing interruption at an early current zero. This chamber has the additional advantage that, should the arc last until the movable contact has left the throat, it would become doubly effective because 2 oppositely directed gas blasts would be established as shown in Fig. 1d. However, the large amount of oil contained in such a chamber interferes with the free escape of the gas blast and makes the performance highly unsatisfactory.

To improve the operation of this contact it is necessary above all to establish a gas blast unimpeded by oil. This can be accomplished by a radical reduction in oil volume such as is shown in the construction represented in Fig. 2. The movable contact is withdrawn in a close fitting tube. Upon formation of the arc, the oil piston within the fixed contact is expelled and a free gas blast is established. The total oil volume of such a chamber easily can be limited to a few cubic inches, an amount greatly in excess of that decomposed and vaporized during the interruption. This contact in its appearance, as well as in its action of first expelling a piston of oil followed by a gas stream, has more similarity to the well-known expulsion fuse than to an explosion chamber and for this reason it is called an "expulsion contact"; a circuit breaker equipped with this contact is called an "expulsion circuit breaker."

The expulsion contact schematically represented in Fig. 2 has certain undesirable features, inherent also to the contact shown in Fig. 1c. All contact fingers are of the same length and burning can take place on any of them; in addition, upon establishing a gas blast the arc is deflected into the contact and made to burn on parts that in the closed position of the breaker act as current carrying surfaces, thereby reducing their carrying capacity and causing undue heating. The cross section of the expulsion chamber opening is fixed by the dimensions of the movable blade and therefore is not readily variable to a value that might prove more suitable for most efficient operation. A design such as that shown in Fig. 3 eliminates these disadvantages. An arcing tip projecting beyond the length of the main contacts is provided and an insulating tube the cross section of which can be selected independently of the cross section of the moving blade is located adjacent to this arcing tip. The oil volume is reduced to a small value by means of a filler as indicated in Section *AA*. This contact can be simplified in its construction by eliminating the tube, a cylindrical opening being formed by the wall of the chamber and the oppositely located spring of the arcing tip, as shown in Fig. 4. If a copper plate extending from the arcing tip to the outside of the chamber be provided to cover the spring, an additional highly desirable feature is obtained. The arc root establishing on the arcing tip, under the influence of the high velocity gas stream will be moved outward along the copper plate,

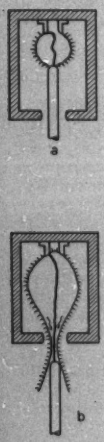


Fig. 1 (a and b). Conventional explosion pot during interruption

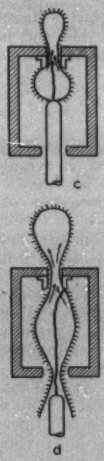


Fig. 1 (c and d). Explosion pot with end opening during interruption

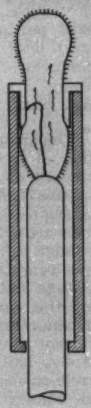


Fig. 2. Expulsion chamber in operation

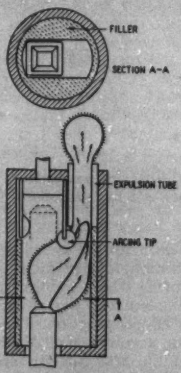


Fig. 3. Expulsion chamber with tubular blow-out opening

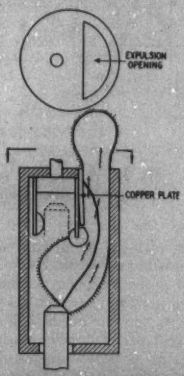


Fig. 4. Expulsion chamber with blow-out opening formed by arcing contact and main chamber tube

drawing the arc to a length several times the distance of contact separation and thereby greatly increasing the rate of deionization.

Performance of the Expulsion Contact

In the following paragraphs the performance of the expulsion contact shown in Fig. 4 under circuit interruption will be analyzed. Immediately upon contact separation an arc is formed between the arcing tip and moving blade, decomposing and vaporizing the surrounding oil and forming a high pressure gas bubble inside the chamber. Since the opening through the tube presents the only avenue of relief, the oil in the tube is accelerated and after a short period completely removed, whereupon a high velocity gas blast is established; this acts as a deionizing agent on the arc path, thereby preventing reignition at the next current zero. Therefore, *interruption or failure to interrupt should be related to the existence or absence, respectively, of a gas blast at current zero.*

The time to produce a gas blast is affected by various factors, principally by the quantity of gas generated and by the volume of oil to be removed from the expulsion tube. If the rate of gas generation be known it is possible to calculate the motion of the oil in the tube (hereafter called the oil piston) and to determine the time required for complete removal. Before proceeding with these calculations the most favorable time for removal will be discussed. As stated before, interruption is desired in $^1/_2$ cycle; therefore, if the oil piston is of such dimensions that it is not removed completely in that time, performance is unsatisfactory. If, however, the oil piston be removed in about $^1/_{10}$ cycle, the gas blast

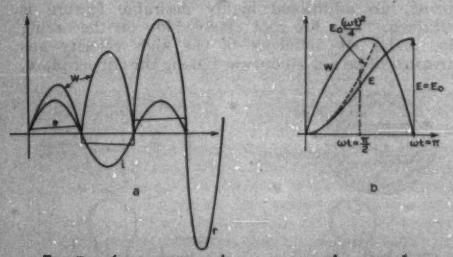
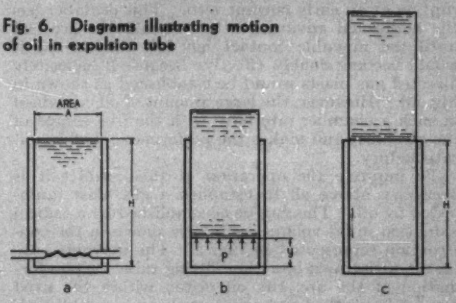


Fig. 5. Arc current, voltage, watts, and energy for an interruption taking place in 3 half cycles

is initiated at a time when interruption is neither possible nor desirable. In addition, a large quantity of gases escape in a period during which they could be accumulated for release immediately before current zero to produce a more effective action. The ideal performance requires the accumulation of the gases as nearly as possible at the first current zero in order that the formation of a fully effective gas blast may be accomplished at that instant. If the contacts separate at a current zero, the time for accumulation of gases is close to $^1/_2$ cycle; however, if separation take place at a current maximum, the gas blast should be established within $^1/_4$ cycle. To take care of these various conditions it seems advisable to set up the following requirement: Gas generation and dimensions of the oil piston shall be correlated in such a manner that a gas blast is established in $^1/_4$ cycle.

In the following calculations various assumptions have been necessary in order to obtain a solution; accordingly, the results should be taken qualitatively rather than quantitatively. For each assumption, an attempt has been made to choose conditions that would bring about a more rapid production of a gas blast, in order that the final result might formulate the conditions for the production of a gas blast

Fig. 6. Diagrams illustrating motion of oil in expulsion tube



in $^1/_4$ cycle. The gas blast is therefore more likely to exist previous to $^1/_4$ cycle and is very unlikely to start later than $^1/_4$ cycle after separation of the contacts.

Arc Energy

The amount of gas generated during the interruption of a short circuit is related directly to the amount of arc energy liberated. Figure 5a shows schematically an oscillogram of an interruption taking place in 3 half cycles; i represents the current, e the arc voltage, and r the first half cycle of recovery voltage. A curve showing instantaneous arc watts was computed as the product of current times arc voltage and is labeled W. Over each half cycle of arc this curve approximates a sine curve with its maxima displaced to the right of the maxima of the current wave and increasing rapidly with each successive half cycle. Considering only the first half cycle as shown in Fig. 5b and assuming a constant arc voltage e, the arc watts vary purely sinusoidally and are given by $W = eI_{max} \sin(\omega t)$, where $\omega = 2\pi f$. The arc energy up to the time t then follows:

$$E_t = \frac{eI_{max}}{\omega}(1 - \cos \omega t) \qquad (1)$$

and is plotted in Fig. 5a, curve E. Denoting by $E_0 = \frac{2eI_{max}}{\omega}$ the arc energy during $^1/_2$ cycle, the

Table I—12-Kv Tests on Expulsion Contacts

Contact No.	Dimensions of Expulsion Opening A, Sq Cm	Dimensions of Expulsion Opening H, Cm	Current Interrupted, Amp	Line Voltage, Kv	Kva Interrupted	Arc Times, Cycles	Total Gas Volume Cold, Cu Cm	$\frac{V_0}{4}$ Cu Cm	$\frac{V_0}{AH^2}$	P (Kg per Sq Cm) During First Half Cycle	Arc Energy During First Half Cycle Kw-sec	Total Arc Energy Kw-sec
1	5	13	3,530	12.1	42,500	1	1,300	350	0.13	15	4.2	16
2	1	2	3,600	12.3	44,000	0.25	350	350	173	13	4.2	4.2

energy E_t can be represented also by $E_t = \frac{E_0}{2}(1 - \cos \omega t)$ giving (see Fig. 5b) for small values of t

$$E_t \cong E_0 \frac{(\omega t)^2}{4} \quad 0 < \omega t \leq \frac{\pi}{2} \tag{2}$$

Gas Generation

For a long time it has been established that a direct proportion exists between the arc energy and the amount of gas generated, one kilowatt-second of arc energy producing in the neighborhood of 50 cu cm of gas, measured at atmospheric pressure and temperature (see "Hochspannungsforschung und Hochspannungspraxis," by O. Mayr, Springer, 1931). Since the average temperature of the decomposed gases during interruption is not less than 500 deg C, their volume at atmospheric pressure practically is doubled. In addition, a considerable amount of oil is vaporized but not decomposed; when this is taken into consideration, the minimum total volume of hot gases produced per kilowatt-second is about 200 cu cm. Substituting this value into eq 2 gives the following for the volume of hot gases reduced to atmospheric pressure generated up to the time t:

$$V_t = 0.05 E_0 (\omega t)^2 \quad \text{in which } 0 < \omega t < \frac{\pi}{2}$$

Denoting with $V_0 = 0.2E_0$ the volume of gases generated in one-half cycle,

$$V_t \cong V_0 \frac{(\omega t)^2}{4} \quad 0 < \omega t < \frac{\pi}{2} \tag{3}$$

Since, in general, the expansion of the gas bubble under oil is accompanied with changes in its pressure, information as to the mode of expansion, that is, whether isothermal or adiabatic is necessary. Because of the continuous liberation of energy by the arc, isothermal expansion is most probable and is confirmed by tests. Up to the point where a gas blast starts Boyle's law can be applied.

Motion of Oil Piston

Knowing the rate of gas generation it will be possible to determine the motion of the oil piston in the expulsion tube. In Fig. 6a such a tube is shown separately, consisting of a cylindrical vessel of cross section A and height H, closed at the bottom and open at the top. If gases are generated by an arc in the vicinity of the bottom, the entire oil piston will be accelerated. For simplicity of calculation, the entire oil piston shall be assumed to be solid and its removal shall take place according to Figs. 6b and 6c; the external pressure as well as the work done in lifting the piston shall be neglected.

Denoting the travel of the piston by y, its velocity by v, the pressure of the gas by p, the specific gravity by σ, and the acceleration due to gravity by g, it follows:

$$A \cdot H \cdot \frac{\sigma}{g} \cdot \frac{d^2y}{dt^2} = Ap \tag{4}$$

$$\frac{V_t}{p} = A \cdot y \tag{5}$$

Substituting eq 3 into eq 5, solving the differential equation, and assuming $\sigma = 0.0009$ kg per cubic centimeter and $f = 60$ cycles

$$y = 1.4 \times 10^3 \sqrt{\frac{V_0}{A \cdot H}}\, t^2 \text{ cm} \tag{6}$$

$$v = 2.8 \times 10^3 \sqrt{\frac{V_0}{A \cdot H}}\, t \text{ cm per second} \tag{7}$$

$$p = 0.25 \sqrt{\frac{H V_0}{A}} \text{ Kg per square centimeter} \tag{8}$$

giving the following condition for initiation of a gas blast within $^1/_4$ cycle:

$$\frac{V_0}{A \cdot H^2} \geq 0.17 \tag{9}$$

all of the last 4 formulas applying for centimeters, kilograms, and seconds.

The motion of the oil piston is accelerated uniformly, y increasing with t^2, v with t, and p being constant—a fact that is particularly interesting since it justifies previous assumptions of an isothermal condition in the gas volume during the expulsion period. The quantities A and H are given by the particular design of expulsion contact and can be varied arbitrarily. However, V_0 is unknown, but is dependent directly on the arc energy liberated during the first half cycle. If V_0 were known it would be possible to select A and H according to eq 9 in order to produce interruption at the first current zero. Information covering a great many tests on oil circuit breakers shows that an arc energy of 0.5 kw-sec per 1,000 kva interrupted is as low a value as can be expected. In the following paragraphs an attempt shall be made to design an expulsion chamber capable of interrupting 40,000 kva (maximum capacity of testing station) at 12 kv in $^1/_2$ cycle. An interruption of 40,000 kva would liberate 20 kw-sec, producing a volume $V_0 = 4{,}000$ cu cm. Area A was made 5 sq cm and height H 13 cm, giving a value $\frac{V_0}{AH^2} = 0.36$ which is in excess of the required value of 0.17 necessary to produce interruption.

Fig. 7. Oscillogram showing the interruption of 3,530 amp at 12.1 kv with expulsion contact as shown in Fig. 4

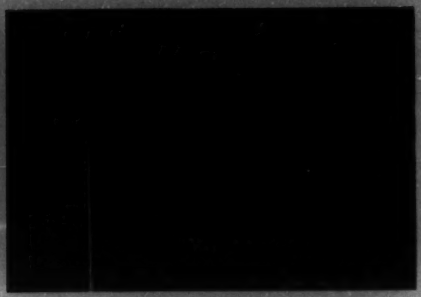


Fig. 7a. Oscillogram showing interruption of 3,600 amp at 12.2 kv with expulsion contact in 0.25 cycle

A single expulsion chamber according to Fig. 4, called contact No. 1, with dimensions of the expulsion piston as indicated in the preceding paragraph was built and tested. Figure 7 shows an oscillogram of an interruption which took place in 1 cycle instead of the expected $^1/_2$ cycle. The quantity of gas generated during the interruption was measured, allotted to each half cycle by means of the oscillographic record of the respective arc voltages, the values obtained being given in Table I.

The arc energy liberated during the first half cycle is considerably smaller than that anticipated, V_0 amounting to only 1,400 cu cm instead of 4,000 cu cm giving a ratio $\frac{V_0}{AH^3} = 0.13$, and therefore insufficient for interruption. To produce interruption at such a small value of V_0, AH^3 has to be reduced radically. A second contact (No. 2) was built and tested with $A = 1$ sq cm and $H = 2$ cm, the test results being shown in Fig. 7a and tabulated in Table I. Interruption took place in $^1/_4$ cycle with an arc voltage hardly visible on the oscillogram. The quantity of gas generated was not measured, but an estimate on the basis of arc voltages (Figs. 5 and 6) gives a value not exceeding 350 cu cm; therefore, $\frac{V_0}{AH^3}$ amounts to 173 for this contact, a value approximately 1,000 times larger than necessary. It is realized that an exceedingly small value of V_0 is capable of bringing about a gas blast in $^1/_2$ cycle; for contact No. 2 $V_0 = 1.4$ cu cm would appear sufficient. Whether or not such a small volume of gas is capable of interrupting the arc is not known. In an oil circuit breaker in which the arc can burn only if the voltage across it exceeds a definite minimum value, the volume of gas generated is in excess of 1.4 cu cm and apparently is sufficient to cause interruption upon establishment of the gas blast. It is hoped that further investigations can be carried out to determine the range of extremely low gas volumes where eq 9 represents only a necessary but insufficient condition for interruption at the first current zero.

The large value of $\frac{V_0}{AH^3}$, not necessarily required for the interruption of large currents, provides a feature that is most desirable in interrupting small currents, where arc energy and gas generation are small. Whereas most of the present circuit breakers show a highly increased arcing time for currents ranging from 2,000 amp to very small values, the expulsion contact can be expected to bring about interruption in substantially the same time over the entire current range; there should be no great difference in performance between an interruption of 10,000 amp and one of 100 amp. Table II substantiates this statement for contacts Nos. 1 and 2 for currents ranging from 3,600 down to 960 amp.

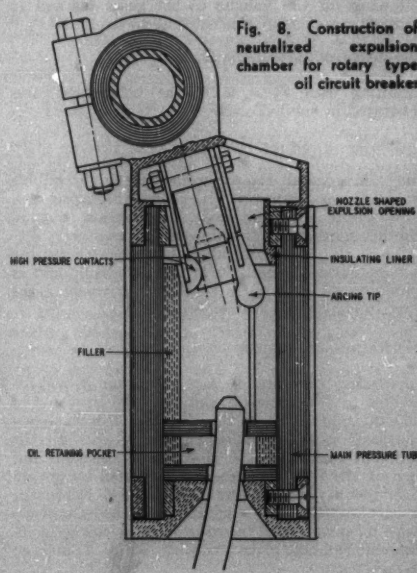


Fig. 8. Construction of neutralized expulsion chamber for rotary type oil circuit breaker

The tests from which the data of Table II were obtained have shown that it is possible to explain the interruption of an arc in an expulsion chamber on the presence of a gas blast. The theory developed allows the dimensions of the expulsion tube to be such that interruption is accomplished within $^1/_2$ cycle. An arc energy of 0.5 kw-sec per 1,000 kva, generally considered the best value attainable, by no means defines a circuit breaker of the best possible performance; values of 0.1 kw-sec and less are within easy reach with the expulsion chamber breaker.

Gas Blast

Having paid particular attention to the requirements for the removal of the oil piston from the expulsion tube and the subsequent initiation of a gas blast, the characteristics of the gas blast proper and in particular of its velocity of escape will be analyzed briefly. The gas blast escapes into a large body of oil surrounding the expulsion chamber, forming a rapidly expanding gas bubble. In general, the rate of escape of the gases due to accumulation over a part of the half cycle near the current zero will exceed the instantaneous rate of gas generation inside the chamber. It is well known that a gas stored at a pressure p_1 escapes through a cylindrical orifice with a velocity equal to the sound velocity of the gas under the prevailing condition of state, provided the external pressure p_2 does not exceed a value of approximately $^1/_2 p_1$.

Because of gas bubbles forming outside the expulsion tube, the motion of the oil in the tank is similar in principle to the motion of the oil in the expulsion tube already analyzed. If the height of oil above the gas bubble is identified by H and its cross section by A, eqs 4 and 5, can be applied. It is estimated that with the large value of A prevailing in the conventional oil circuit breaker tank the pressure p_2 set up by an extremely high rate of gas generation will not reach a value of $^1/_2 p_1$; the gases, therefore, escape at the velocity of sound, that is, at 660 m per second (2,300 ft per second) or more. Velocities exceeding sound velocity are obtained if the cylindrical opening be replaced by an outwardly flared nozzle; such a construction favors rapid deionization and carries the arc root farther along, and is incorporated in the final contact design.

Fig. 10. Set-up for 110-kv field tests

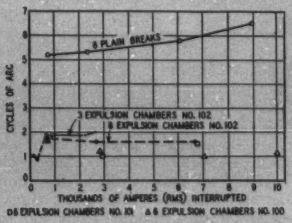


Fig. 9. Relation between current interrupted and arcing cycles for different types of contacts on 110-kv tests

Table II—Arcing Time of Expulsion Contacts for Small Currents

Contact No.	Amperes Interrupted at 12 Kv	Arcing Time, Cycles
1	960	1.2
	1,980	1.3
	3,530	1.0
2	980	0.4
	1,730	0.4
	3,600	0.25

Mechanical Forces During Interruption

A conventional explosion chamber, as shown in Fig. 1a, is known to exert large and sometimes harmful reactions upon the supporting entrance bushing. This is because the pressure produced by the accumulation of gases over several cycles acts upon different wall areas on the top and bottom of the chamber. A gas blast escaping into a body of oil also produces a reaction upon the chamber if active independently of any other force, although its value is small with an expulsion chamber because of the early relief and the subsequent moderate internal pressure. It is evident that the reaction upon an ordinary explosion chamber can be neutralized when it is combined with a gas blast of proper momentum and direction. It has been found that an expulsion chamber in which the throat area is approximately equal to that of the expulsion tube produces close equalization. For practical applications on circuit breakers of 600- and 1,200-amp capacity, a piston according to contact 1, Table I, has been found to give better results than one according to Contact 2. This contact, therefore, has been chosen for the

Fig. 11. Oscillogram showing interruption of 10,000 amp, single phase to ground, on 110-kv system with expulsion contacts No. 100

Fig. 12. Contact No. 102 after series of tests

following practical applications in spite of the fact that $^1/_2$ cycle of arcing time thereby is sacrificed.

Figure 8 shows the detailed construction of a neutralized expulsion chamber as it is used on a rotary type oil circuit breaker. Besides the neutralization of pressures, the following features are incorporated:

1. Main expulsion chamber of small volume, obtained by arc resisting fillers.
2. Nozzle shaped expulsion opening.
3. Arcing tip and adjacent copper plate provide means for elongating arc.
4. High pressure line contacts enable the blade to leave the arcing tip after a very short travel; no burning occurs on these contacts.
5. Oil retaining pocket providing reservoir for decomposing oil, should the arc be carried through throat.

Application of Expulsion Contacts to High Voltage Circuit Breakers

Because of the poor deionization of the arc path during the current zero period, the arc in a plain oil circuit breaker has to be drawn to considerable length to effect interruption; the arc in such a breaker is re-established along the old insufficiently deionized path, although the surrounding gas is capable of withstanding the recovery voltage. In proceeding to the well deionized arc path of the expulsion contact, conditions are found to be different, a breakdown being more likely to occur through the gaseous atmosphere between the arcing tip and the movable contact. Restriking along the old arc path, which is drawn to a length many times the distance of contact separation and cooled over its entire length, is not probable.

Tests on contact No. 1 at 12 kv showed interruption of 3,600 amp in $^1/_4$ cycle with only $1^1/_4$-in. contact separation. If the same current were applied at 60 kv, deionization would be equally effective, but the breakdown distance of $1^1/_4$ in. would be insufficient to prevent reignition. The dielectric strength of the gas bubble has a definitely limited value, prevention of breakdown through it at 60 kv requiring a break distance of approximately 10 in. If this chamber were to interrupt currents at such a high voltage in $^1/_2$ cycle, a contact speed in excess of 50 ft per second would be required, a value which is not feasible because of the excessive mechanical forces required to bring about such velocities. Even the use of the conventional 2-break switch at half that velocity is impractical. The multiple break switch, however, has the advantage of introducing the insulating gas at a much higher rate for blade velocities in general use, and for electrical as well as mechanical reasons represents the ideal arrangement. It has the additional advantage that the total resulting break distance is so large that interruption can be obtained when operating with plain contacts, giving a factor of safety not common on 2-break switches.

Field Tests at 110 Kv

Plain-Break Oil Circuit Breaker. A 115-kv 6-break rotary type circuit breaker provided with plain contacts was submitted first to interrupting capacity tests. Since single-phase-to-ground short circuits constitute the most common faults and produce maximum short circuit currents, tests were made with this connection. At the Newark (Calif.) substation of the Pacific Gas and Electric Company's transmission system short circuits ranging from 700 to 9,000 amp were interrupted by a single phase of the

Table III—Results of 110-Kv Field Tests on a 6-Break Rotary Type Oil Circuit Breaker With Plain Contacts

Test No.	Duty Cycle	Amperes Interrupted	Recovery Kv	Cycles of Arc	Pressure in Tank, Lb per Sq In.	Oil Throw, Gal	Oil Dielectric Strength After Test	Interrupted Single-Phase Kva	Equivalent 3-Phase Kva
1	OCO	745	53	5.2		None	Above 27	39,500	120,000
2	OCO	2,350	59	5.3	7.5	None	Not tested	138,000	415,000
3	OCO	6,050	60	5.8	55	$1^1/_2$	Not tested	362,000	1,080,000
4	OCO	8,950	56	6.5	125	3	Above 27	501,000	1,500,000

Table IV—Results of 110-Kv Field Tests on an Oil Circuit Breaker Equipped With No. 102 Expulsion Contacts (See Fig. 8)

Test No.	No. of Breaks	Breaker Cycle	Breaker Duty	Current, Amp Initial	Current, Amp Interrupted	Recovery Kv	Interrupted Single Phase Kva	Equivalent 3-Phase Kva	Cycles of Arc	Total Cycles for Breaker to Clear	Tank Press, Lb per Sq In.	Gas Volume at 20° C and Atmospheric Pressure, Cu Cm
1	6	OCO	Short circuit		700	63	45,000	135,000	1.7	5.2	0	Less than 4,000
2	6	OCO	Short circuit	3,800	2,800	65	182,000	546,000	1.6	5.2	0	8,000
3	6	OCO	Short circuit	7,700	6,200	63	390,000	1,170,000	1.6	5.3	0	8,000
4	6	CO	Charging current		145	75	9,000	27,000	1.0	4.4	0	Less than 4,000
5	6	CO	Charging current		265	94.5	17,000	51,000	0.9	4.3	0	Less than 4,000
6	3	OCO	Short circuit		700	62	43,000	129,000	1.6	5.0	0	Less than 4,000
7	3	OCO	Short circuit	5,000	2,700	62.5	169,000	500,000	1.9	5.2	0	Less than 4,000
8	3	OCO	Short circuit	6,400	2,300	62	143,000	430,000	2.0	5.4	0	8,000

test breaker. The results are tabulated in Table III. The relation between arcing time and short-circuit current is shown in Fig. 9.

Expulsion Oil Circuit Breaker. A 115-kv breaker identical in size to the plain breaker tested first was equipped with 3 different types of expulsion contacts, varying in design features, but all being based upon the expulsion principle. For the purpose of identification they will be denoted as contacts Nos. 100, 101, and 102, respectively. Contact No. 100 is shown in Fig. 3, No. 101 in Fig. 1c, and No. 102 represents the final design shown in Fig. 8. Figure 10 shows the field set-up of the test breaker to which these contacts alternately were applied. Single-phase short circuits on the 110-kv system, ranging from 770 to 10,000 amp (rms interrupted current) applied to contacts Nos. 100 and 101 were cleared with less than 2 cycles of arcing time. In no case was a drop of oil thrown, and the dielectric strength of the oil remained unchanged. Figure 11 shows an oscillogram of an interruption of 10,000 amp by Contact No. 100 in 1.1 cycle; the arc voltage is hardly noticeable. Results of all individual tests on contacts Nos. 100 and 101 are plotted in Fig. 9. Since tank pressures on this test were too small to be recorded and no trace of gases escaping through the vent pipe was noticed, it was decided to measure the volume of gases generated during the tests of contact No. 102. The single-phase-to-ground current tests were supplemented by charging current tests. Table IV gives a summary of the test results.

One of the contacts after test is shown in Fig. 12. Except for a slight burning on the stationary and movable arcing contact tips there was no trace of the interruptions on any of the contacts. The oscillogram recorded during test No. 3 is shown in Fig. 13; the arc voltage is hardly noticeable. The charging current oscillogram shown in Fig. 14 is particularly interesting since it shows interruption taking place in one cycle. Additional tests 6, 7, and 8 on a breaker equipped with 3 contacts showed arcing times not in excess of 2 cycles and give an indication of the performance that can be obtained with 6 expulsion chambers on voltages of 220 kv and higher.

Fig. 13. Oscillogram showing interruption of 6,200 amp, single phase to ground, on 110-kv system with expulsion contacts No. 102

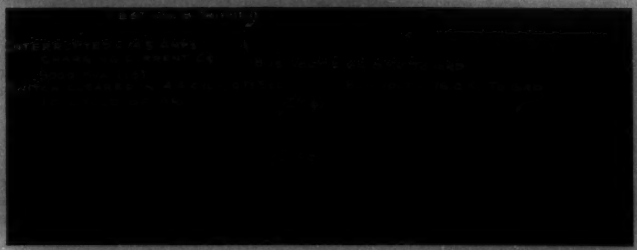


Fig. 14. Oscillogram showing interruption of charging current on 110-kv system with contacts No. 102

Counterpoise Tests at Trafford

Tests have been conducted on an experimental transmission line equipped with a counterpoise for reducing the tower footing surge impedance so as to give added protection against lightning. The results of these tests are presented herewith, and should prove valuable to engineers engaged in the design and operation of transmission lines. The desirability of further tests made under a variety of conditions is indicated.

By
C. L. FORTESCUE
FELLOW A.I.E.E.

F. D. FIELDER
ASSOCIATE A.I.E.E.

Westinghouse Elec. and Mfg. Co., East Pittsburgh, Pa.

THE COUNTERPOISE, introduced during the last few years for the protection of power transmission lines against direct strokes of lightning, consists of cables connected to the transmission line towers and buried in the ground. The theory of the counterpoise, a review of past developments, and an analysis of the different types of counterpoises were given in a recent paper (see "Counterpoises for Transmission Lines" by C. L. G. Fortescue, ELEC. ENGG., v. 52, Dec. 1933, p. 908–17).

During the winter of 1933–34 tests were made on an experimental line at the Trafford (Pa.) laboratory with the following objects:

1. To find if the relations between transmission line ground wire and counterpoise are susceptible of measurement using surge generators, cathode-ray oscillographs, and conventional laboratory measurements.

2. To determine, if possible, the effect of leakance on the mutual surge impedance between counterpoise and line and its relation to the depth of the ground plane and the resistivity of the soil.

3. To develop a simple technique of testing so that the electrical utilities may be encouraged to proceed with similar investigations on a larger scale with more diversity in soil conditions, with the hope that with a reasonable expenditure of money the counterpoise problem can be solved in a practical way.

A simple wood pole line was installed consisting of one 4/0 and one 2/0 copper wire on cross arms about 30 ft above the ground at the poles, but considerably higher than this at intermediate points on account of the irregular nature of the ground surface. The line is over 2,000 ft in length and forms a loop starting from the laboratory. A sketch of the plan of the line and its location with respect to the laboratory is shown in Fig. 1. The line was complete and ready for testing about the end of December 1933.

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. Pacific Coast convention, Salt Lake City, Utah, Sept. 3–7, 1934. Manuscript submitted May 18, 1934; released for publication May 28, 1934. *Not published in pamphlet form.*

TEST I. SURGE IMPEDANCE OF LINES AND MUTUAL IMPEDANCE BETWEEN LINES

These measurements were made by surging one line ungrounded and measuring the current input into the line and the induced potential between the second wire and ground. The measurements of surge impedance made in this manner were calculated at 0.5 μsec intervals (Fig. 3) and then averaged. In Fig. 2 are shown average measurements at different impressed voltages. This curve shows a variation from 450 to 550 ohms. The value of 500 ohms has been taken as fairly representative for the conditions under which the final measurements of the effect of the counterpoise were made.

In Fig. 4 is shown the voltage at pole 2 with both lines ungrounded and, therefore, gives the true coupling factor between the lines. The average of the coupling factors measured at the maximum point of the wave is approximately 0.25, so that if the surge impedance of the surged line is 500 ohms, the mutual surge impedance will be 500 × 0.25 or 125 ohms.

These tests afford a reliable means of obtaining the depth of the equivalent ground plane, and also of checking the value of the surge impedance. Assuming a speed of propagation equal to light, the surge impedance equals $60 \log_e \frac{2(h+d)}{r}$, where h is the height of the wire above ground, d is the depth

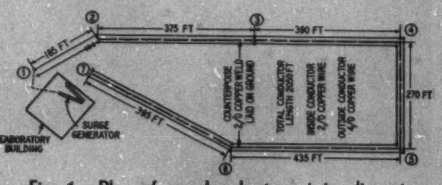


Fig. 1. Plan of wood pole transmission line at Trafford, Pa.

of the ground plane below the surface, and r is the radius of the conductor. Also, the mutual surge impedance for wires on the same horizontal plane a distance d_1 apart equals

$$60 \log_e \frac{2\sqrt{(h+d)^2 + d_1^2}}{d_1}$$

Thus if we know the surge impedance of one of the lines and r and h, d can be obtained. However, because of the presence of corona the effective value for r may be in doubt. For this line, h at pole 2 is

approximately 29.5 ft and d_1 is 10.5 ft. Substituting in the formulas:

$$60 \log_e \frac{2(h+d)}{r} = 500$$

$$\log_e \frac{2(h+d)}{r} = \frac{500}{60} = 8.33$$

$$\frac{2(h+d)(12)}{0.24} = 4{,}225$$

$$h + d = \frac{(4{,}225)(0.24)}{2 \times 12} = 42.25$$

$$d = 42.25 - 29.5 = 12.75$$

The mutual surge impedance was found to be 125 ohms.

$$\log_e \frac{2\sqrt{(h+d)^2 + d_1^2}}{d_1} = \frac{125}{60} = 2.08$$

$$2\,\frac{\sqrt{(h+d)^2 + d_1^2}}{d_1} = 8$$

$$\sqrt{(h+d)^2 + d_1^2} = 42$$

$$(h+d)^2 = 1{,}764 - 110 = 1{,}654$$

$$h + d = 40.6$$

$$d = 11.1 \text{ ft}$$

If the speed of propagation is less than that of light, then the ground plane depths will be greater.

The correspondence is close enough for practical purposes, and d may be taken as 13 ft in round figures. In the above example, if d_1 had been taken as 11 ft, we would have

$$\sqrt{(h+d)^2 + d_1^2} = 44 \text{ ft}$$

$$(h+d)^2 = 1{,}936 - 121 = 1{,}815$$

$$h + d = 42.6$$

$$d = 13.1 \text{ ft}$$

Hence, an error in d_1 of a few inches will spoil the check. The same is true of the effective radius of the wire. If it is assumed that the surge impedance is affected by the corona radius a correction would have to be made in r, depending upon the corona point of the wire. For example, if the effective radius were 10 per cent larger than in the first example, $(h + d)$ instead of being 42.25 would be 46.5 ft and d would be 17 ft instead of 12.75 ft for the same value of surge impedance.

Test II. Surge Impedance of Ground (Fig. 5)

One of the guy wires with its anchor was used as a footing ground. Its measured ground resistance by megger was 150 ohms. The apparent surge impedance was obtained by inserting a noninductive resistance in series with the ground and measuring the surge potential at the junction point of the resistance and ground, and at the junction point of the resistance and surge generator line. The difference between the 2 readings divided by the resistance gives the wave of the current in the ground, and the potential at the junction of the noninductive resistance and ground is the surge potential. At 0.25 μsec from the zero point of the wave (see Fig. 5) the apparent surge impedance is 240 ohms and at the end of 0.5 μsec it drops to 120 ohms. It is 100 ohms at 0.75 μsec, 90 ohms at 1 μsec, and has an average of about 75 ohms at the crest, from wh'ch point it reduces gradual y to about 50 ohms. The record of the test is given in the curve. This is in accord with observations made by other investigators who have made similar measurements with surge generators on high resistance grounds. It is possible that the proximity of large bodies, such as the Trafford laboratory building and the tracks of a branch line of the Pennsylvania Railroad, may be responsible for some of this effect.

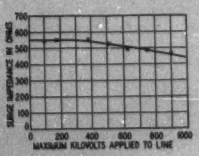


Fig. 2. Surge impedance of No. 4/0 line

(Positive waves)
Points are averages determined by method of Fig. 3

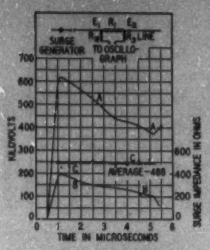


Fig. 3. Typical determination of line surge impedance

Curve A. Voltage applied to line (E_2)
Curve B. Voltage difference across R_1 ($E_1 - E_2$)
Curve C. Surge impedance = $\frac{E_2}{(E_1 - E_2)/R_1 - E_2/R_2}$

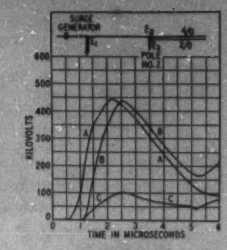


Fig. 4. Determination of coupling factors with open line

Curve A. Voltage at surge generator (E_1)
Curve B. Voltage on 4/0 line at pole 2 (E_2)
Curve C. Induced voltage on 2/0 line at pole 2 (E_3)

Test III. Surge Impedance of Counterpoise (Fig. 6)

The counterpoise consisting of solid $^3/_8$ in. copper weld wire was laid down for the full length of the line over the surface, and only a small portion of it near the pole at which tests were made was lightly covered with earth. This test was made by the same method used for measuring the surge impedance of the ground. The results of this test are shown in the curve of Fig. 6. It will be noted that the apparent surge impedance of the counterpoise is 145 ohms at the end of 0.25 μsec, 80 ohms at the end of 0.5 μsec, 60 ohms at the end of 0.75 μsec, and 45 ohms at the end of 1 μsec, and steadily decreases with time till at 1.75 μsec after the start of the wave it has a value of only 30 ohms. The megger measurement of the counterpoise was 6.0 ohms. The variation in the apparent surge impedance of the counterpoise is a further indication that the earth resistivity is comparatively low, the first indication being the

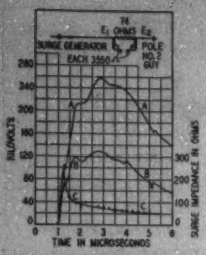


Fig. 5. Determination of surge impedance of pole No. 2 guy

Megger measurement 150 ohms
Curve A. Voltage before resistor (E_1)
Curve B. Voltage applied to guy (E_2)
Curve C. Surge impedance of guy

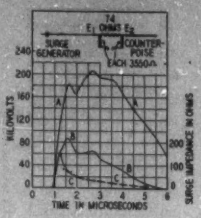


Fig. 6. Determination of surge impedance of counterpoise

Megger measurement 6.0 ohms
Curve A. Voltage before resistor (E_1)
Curve B. Voltage applied to counterpoise (E_2)
Curve C. Surge impedance of counterpoise

small depth of the equivalent ground plane. Under these conditions the effect of leakance cannot be ignored and it will be found that it has a dominating effect on the characteristics of the counterpoise.

Test IV. Coupling Factors (Figs. 7–9)

Test IV consisted of 3 parts, as follows:

(*a*). Line grounded to guy wire alone (Fig. 7).
(*b*). Line grounded to counterpoise alone (Fig. 8).
(*c*). Line grounded to both guy wire and counterpoise (Fig. 9).

These curves show the coupling factors between the line system which receives the surge and the free line, and it will be noted that the introduction of the counterpoise in place of the guy ground has had little influence on the value of the initial coupling factors. This is to be expected for 2 reasons. First, because the depth of the ground plane is very small; the ratio of the distance of the line image in the ground plane from the counterpoise to the distance of the line itself from the counterpoise is of the order of 1.9, the log of which is about 0.64. If the ground plane were at ground level the mutual surge impedance would be zero and as it approaches ground level the mutual surge impedance becomes smaller and smaller. Second, the low resistivity which is associated with a small depth of ground plane produces distributed leakance, which may be looked upon as producing positive reflections of current which have the effect of reducing the mutual surge impedance potential due to the positive current surges moving in the normal direction while at the same time they decrease the apparent surge impedance of the counterpoise.

Test V. Coupling Factor With Counterpoise Placed in Air (Fig. 10)

Test V is the same test as IV(*b*) with counterpoise raised 6 ft above ground level (see Fig. 10). This test was made to show the effect of placing a counterpoise in air. It will be noted that the presence of the counterpoise has increased the coupling, as was to be expected, because now the counterpoise is closer to the line wire and further from its image, also the effect of leakance is eliminated. The net result, however, is a distinct loss of effectiveness of the counterpoise, resulting in higher potentials of the ground wire and larger difference of potential between the line and ground wire. Theoretically, if the line wire could be completely enclosed with ground wires spaced fairly close together and connected together at frequent intervals, protection approaching the ideal in which line wires and ground wires would have the same potential under all conditions would be approached. This is, however, impossible to achieve in practice and it seems that

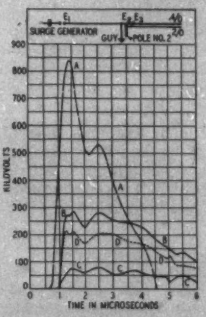


Fig. 7. Determination of coupling factors with guy connected

Curve A. Voltage at surge generator (E_1)
Curve B. Voltage on 4/0 line at pole 2 (E_2)
Curve C. Induced voltage on 2/0 line at pole 2 (E_3)
Curve D. Voltage difference between lines ($E_2 - E_3$)

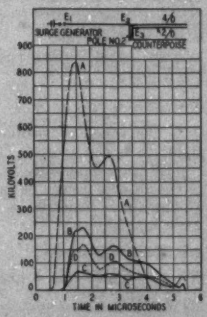


Fig. 8. Determination of coupling factors with counterpoise connected

See subcaption of Fig. 7 for meaning of curves

the best procedure is to take advantage of the lowered surge impedance obtained by burying the counterpoise in the ground.

Test VI. Experimental Tests With Parallel Wires Laid on the Ground to Determine Specific Resistance of the Soil

The results of these tests are given in Table I. To obtain the specific resistance from these values the formula for the resistance per unit length between 2 parallel conductors in homogeneous conducting mediums may be used. The approximate formula is

$$\text{Resistance per unit length} = \frac{1}{\pi}\rho \log \frac{2d}{r}$$

In this formula $2d$ is the distance between the centers

of the wires, r is the radius of the wires, and ρ is the specific resistance in the same units as are used for the measure of length; for example, if the length is in meters, ρ is in ohms per meter cube. In the case with which we are dealing the center line between conductors divides the 2 mediums, earth having a resistivity ρ, and air having infinite resistivity. This condition gives

$$\text{Resistance per unit length} = \frac{2}{\pi}\,\rho \log \frac{2d}{r}$$

Using this formula we obtain:

Test No. 1. ρ = 727.5 per foot cube
= 222 per meter cube

Test No. 2. ρ = 376 per foot cube
= 114.5 per meter cube

Test No. 3(*a*). ρ = 487 per foot cube
= 148 per meter cube

Test No. 3(*b*). ρ = 448 per foot cube
= 137 per meter cube

All these tests were made under different weather conditions. In test No. 1 the soil was comparatively dry. In test No. 2 it was thoroughly water soaked. In test Nos. 3(*a*) and 3(*b*) it was comparatively moist. End effects have been ignored in all cases.

The object of these tests was to determine whether this simple method of arriving at ρ for the top soil would give reliable results. The fact that tests 3(*a*) and 3(*b*) give comparable results is encouraging and suggests that further tests along these lines should be made. It is believed that in the lightning protection of transmission lines the actual penetration is relatively small, with the surge currents actually spreading over the surface of the earth, and it is this surface distribution that gives the effect of penetration. For this reason the resistivity of the surface soil may be of great importance. The values of ρ obtained may be classed as medium values. High values are of the order of 10,000 ohms per meter cube, and low values of the order of 2 or 3 ohms per meter cube.

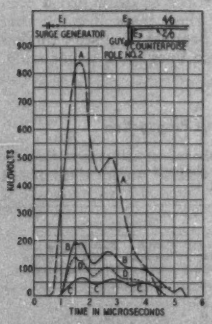


Fig. 9. Determination of coupling factors with counterpoise and guy connected

See subcaption of Fig. 7 for meaning of curves

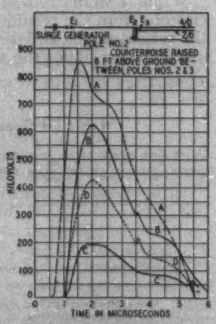


Fig. 10. Determination of coupling factors with counterpoise raised

See subcaption of Fig. 7 for meaning of curves

Test VII. The Use of the Surge Generator in Simulating a Lightning Discharge to a Line

Where a lightning stroke strikes a transmission line wire it has become the practice to consider the lightning channel to have a surge impedance Z_0 to which has been ascribed values varying from 200 ohms to 400 ohms. If the effective surge impedance of the line to the surge from the stroke is Z_1 and E_0 is the potential of the lightning surge and E_1 that of the surge on the line resulting from the stroke then

$$\frac{E_0}{E_1} = \frac{Z_0 + Z_1}{2Z_1}$$

In measuring the surge impedance of such a line a known noninductive resistance is placed in series with it and the surge generator, and the surge potential at the junction point of the line and resistor and at the other terminal of the resistor are measured. Let these values be E'_1 and E'_0, respectively, and let the value of the resistor be R_0. Then we have

$$\frac{E'_0 - E'_1}{R_0} = \frac{E_1}{Z_1}$$

or

$$\frac{E'_0 - E'_1}{E_1} = \frac{R_0}{Z_1}$$

$$\frac{E'_0}{E_1} = \frac{R_0 + Z_1}{Z_1}$$

In order, therefore, that the ratio of $\frac{E'_0}{E_1}$ shall represent actual surge conditions for a given value of Z_1

$$\frac{R_0 + Z_1}{Z_1} \text{ must equal } \frac{Z_0 + Z_1}{2Z_1}$$

or

$$R_0 + Z_1 \text{ must equal } \frac{Z_0}{2} + \frac{Z_1}{2}$$

or

$$R_0 \text{ must equal } \frac{Z_0}{2} - \frac{Z_1}{2}$$

For a composite circuit consisting of short lengths of transmission of different values of surge impedance

Table I—Ground Resistance Measurements Between Parallel Conductors Laid 2 In. Below Surface

	Volts	Amperes	Ohms Resistance
Test No. 1—Weather Fair; Conductors 25 Ft Apart, 127 Ft in Length			
Alternating current	110	4.1	26.8
Direct current	118	3.8	31.0
Test No. 2—After 12 Hr Rainfall; Conductors 25 Ft Apart, 127 Ft in Length			
Alternating current	104	7.5	13.9
Direct current	120	7.0	17.2
Test No. 3(a)—Weather Fair; Checking Conductors 25 Ft Apart, 127 Ft in Length			
Alternating current	104.5	5.8	18.0
Direct current	120.0	5.7	21.0
Test No. 3(b)—Weather Fair; Conductors 68 Ft Apart, 127 Ft in Length			
Alternating current	105	5.55	19.0
Direct current	127	5.8	21.9

Z_1 cannot be considered constant so that the value of R_0 must be determined for the value of Z_1 which is dominant at the instant of time in which we are interested.

Tests were made in accordance with this theory, the results of which are shown in Figs. 11 and 12. In analyzing these curves it must be remembered that the conductor used as a ground wire is only 30 ft above ground at the pole, whereas usually the height of most ground wires of steel tower transmission lines is from 80 to 100 ft above ground at the tower. The surge impedance of the steel tower itself is of the order of 100 ohms. In the experimental line, the down drop lead and the guy wire have

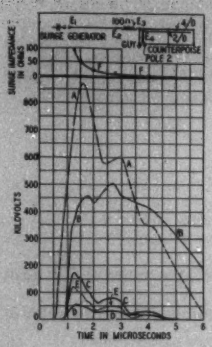


Fig. 11. Determination of coupling factors with 100 ohms series resistance

See subcaption of Fig. 12 for meaning of curves

probably a surge impedance of several times this value. This higher surge impedance does not compensate for the lower level of the ground wire except possibly in connection with the magnitude of the potential obtained, but on account of the low level the maximum magnitude will be reached in much less time, and this is what the curves indicate. For example, in Fig. 12 the crest of the ground wire potential is reached in 0.5 μsec although the wave E_3 is still increasing. However, on account of the high surge impedance of the down drop grounding lead it is probable that the crest value obtained is approximately the same as would exist on a normal tower after 1 μsec. The surge impedance values are therefore higher than would be recorded on a normal steel tower line and the rate of decrease is higher.

The resistance used is based upon the supposition that at the point of test the portion of the line affected is only one-half the portion that would be affected by a lightning stroke. In other words, the counterpoise and ground wires would normally extend in 2 directions, 2 guy wires would represent the normal ground, and there would be 2 down drop leads having a combined surge impedance equal to one-half of the lead used. Under these conditions Fig. 12 gives the values that would be obtained if the surge impedance of the lightning stroke were approximately 250 ohms at the start and became finally 200 ohms. There does not appear to be anything unreasonable in such an assumption if we wished to make it, but it is much easier to make calculations on the basis of a fixed value of Z_0 and 200 ohms has been generally used. On the basis of 200 ohms with conventional towers and a footing resistance of 15 ohms the calculated value of maximum tower top potential reached in 1 μsec with the same surge impressed as in A would be approximately 112 kv as against 117 kv shown by the test. However, at the end of 2 μsec after the start of the wave the calculated value will be 72 kv whereas the curve shows only 27 kv. The effect of the counterpoise appears to be to increase the attenuation of the tower top potential. The total currents indicated by the curve are of the right order; thus, for example, after 2 μsec the current is $\frac{540{,}000 - 27{,}000}{195}$ or 2,630 amp. In terms of 20,000 kv the current would be 97,500 amp, but this is the current in half the line only so that the total current at 20,000 kv would be 195,000 amp, which agrees with the maximum surge currents that have been observed in field tests. The energy in a 20,000-kv lightning stroke has about 5,500 times the energy of the surge shown in these curves. The values obtained from Fig. 12 extrapolated to 20,000 kv are probably pessimistic.

It would be very instructive if the tests given in these curves could be duplicated on an actual transmission line. Small scale models are not appropriate as there is no way of scaling down the velocity of propagation of surges in proportion to the scale of the model; this fact has been lost sight of in the past and many erroneous ideas have resulted from laboratory tests on models. Tests made on selected locations would be of incalculable benefit to the electrical industry as they would undoubtedly clear up all of the puzzling inconsistencies that have been encountered in the past; newly built lines could be tested and their performance predicted before they were put in service, poorly behaving old lines could be diagnosed and in many cases corrected.

While it would not be proper to draw broad conclusions from the results of these tests, it is felt that the results are of sufficient promise to justify further investigation along the same lines on a larger scale.

Table II—Speed of Propagation

Using line open at far end and shorted at surge generator with sphere gap which causes a steep chopped wave. Length of line 2,190 ft

Oscillogram	Microseconds: Time for first reflection	Time for second reflection	Time for third reflection	Time for fourth reflection
1. One complete reflection	5.0			
2. One complete reflection	5.0			
3. Three reflections	5.0	5.1	5.9	
4. Three reflections	5.0	5.0	5.0	
5. Four reflections	5.0	5.0	5.6	5.4
6. Four reflections	4.8	4.6	5.0	5.0
Average	5.1			

Speed $= \frac{(2{,}190)(2)}{5.1} = 860$ ft per microsecond (87.5 per cent of speed of light)

Test VIII. Velocity of Propagation of Waves Over Line

A check of the velocity of propagation over the line was made by using a chopped wave which traveled back and forth along the line. Positive reflections occurred at the open receiving end, and negative reflections at the grounded sending end. Oscillograms recorded the period of these double reflections (see Table II). The average of the values obtained from these tests indicated a velocity of propagation 87.5 per cent of that of light. This difference is probably explained by the fact that the line is very low and the resistivity and dielectric constant of the earth have an appreciable effect. With higher resistivity soil this effect might be expected to be more pronounced.

Discussion of Tests

The first fact that was encountered when Test I was carried out was the small depth of the equivalent ground plane. This was not at all what was expected from the geological nature of the site on which the transmission line was installed. However, Test VI seems to confirm the results of Test I by indicating that the top soil has comparatively low resistivity and for further confirmation the surge impedance of the guy anchor ground and the character of the impedance of the counterpoise are what would be expected with comparative low soil resistivity.

In considering the adequacy of the ground used as a reference from which to measure potentials and that of the actual ground for the surge generator, we must consider to a certain extent the mechanism of the lightning stroke. The cloud and the earth form 2 capacities and the earth may be considered infinite and practically at zero potential so long as there are no discharges. An electric field exists between the cloud and the earth which is affected by any discharge from cloud to earth. The charges on the earth's surface due to the charge on the cloud may be considered as caused by the charges in the cloud and their image in the surface of the earth. This would give the correct distribution if the earth were a perfect conductor, but since this is not so, the field of the cloud penetrates into the earth some distance and while the surface distribution will generally preponderate, any change in the charge of the cloud will produce a volume distribution penetrating some distance into the earth, the depth of penetration being greater the greater the resistivity of the earth in the region affected by the cloud field. When the cloud starts to discharge to earth, displacement currents take place in the cloud and similar conduction and displacement currents take place in the earth, which are associated with the charge in the field of the cloud caused by the streamer. When the streamer reaches the earth, charge rushes in from all parts of the earth causing changes in surface and volume distributions to annul the charge conveyed by the lightning channel and these movements of the charge distribution constitute the conduction and displacement currents in the earth and from the earth to cloud, and the complete circuit formed thereby carries a total current equal to the lightning discharge current at the earth's surface.

From the above it will be evident that there will be considerable difficulty in obtaining a ground for the surge generator that will give the same distribution of earth currents that is obtained with a natural lightning discharge. On the other hand, if the surge generator ground impedance is low, the current passing through it may be considered as derived from a very large area which may be comparable with that through which the movements of charges in the earth associated with a lightning stroke take place. The

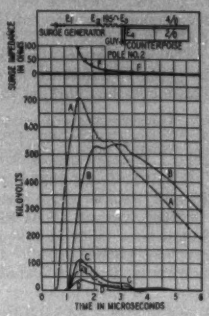


Fig. 12. Determination of coupling factors with 195 ohms series resistance

Curve A. Voltage at surge generator (E_1)
Curve B. Voltage at pole 2 before series resistance (E_2)
Curve C. Voltage on 4/0 line at pole 2 (E_3)
Curve D. Induced voltage on 2/0 line at pole 2 (E_4)
Curve E. Voltage difference between lines ($E_3 - E_4$)
Curve F. Surge impedance of line, guy, and counterpoise

laboratory ground used in these tests is connected to the water mains supplying the building, to the metallic structure of the building itself which has a large capacity, and also to the large oil tanks which are connected to the oil drainage system. It covers an area, therefore, of large surface contact with the earth and having high capacitance, and fulfills fairly well the conditions for distribution of the surge current in the earth. It should be remembered also that the high potentials existing in the earth due to a lightning stroke are highly localized and even at a distance of a hundred feet or so the potentials are reduced to relatively small values. It does not seem likely that where the resistivity of the soil is very high the direction of flow of the earth currents will influence to any great extent the propagation of the surges in the counterpoise wire itself. With low resistivity soil the magnitude of the currents in the earth may become large and if their direction is opposite to that of the propagation in the counterpoise they may have a considerable effect on its apparent behavior. In considering the results of these tests, therefore, weight must be given to the possible effects of the location of the laboratory with respect to the line and the position of the surge generator ground.

Let us consider Tests IV(*a*), (*b*), and (*c*); these were made under the same weather conditions and therefore are comparable. It should also be noted that the line used for the ground wire is grounded only at pole No. 2, being open at the far end. The fact that the line is open at the far end need not concern us as the reflection will not have any effect until

after 5 μsec from the start of the wave. However, with no ground at poles 1,000 ft distant the potential recorded is higher after 2 or 3 μsec than it would have been had the line been grounded at a distance of 1,000 ft from pole No. 2. First of all, it should be noted that the wave impressed at the generator terminals is practically identical in the 3 tests. Next it will be noted that the coupling factor for (*a*) is about 29 per cent, for (*b*) about 32 per cent, and for (*c*) about 34 per cent. The results for (*b*) and (*c*) appear to be inconsistent as far as coupling factor is concerned, but this easily may be accounted for by the point on the wave at which the values were read. In general, it will be seen that the inclusion of the counterpoise has affected the coupling factor a very little.

The next thing to observe is the maximum value of the potential difference between line and ground wire. This shows the following values:

(*a*). With guy wire ground alone, 212.5 kv.
(*b*). With counterpoise alone, 170.0 kv.
(*c*). With both guy and counterpoise, 142.0 kv.

It will be noted that the counterpoise shows considerably (20 per cent) better than the guy wire and the 2 together are about 16 per cent better than the counterpoise alone and 33 per cent better than the guy wire ground alone. But there is considerably more gain than is indicated by the maximum values alone. In the first case (*a*) the difference of potential at the end of 2 μsec duration of the wave is about 93 per cent of the maximum, and at the end of 3 μsec the difference is 77 per cent of maximum; with the counterpoise alone (*b*) at the end of 2 μsec of wave the value of the potential difference is only about 58 per cent of the maximum, and at the end of 3 μsec it is about 31 per cent of its maximum. With both guy and counterpoise (*c*) at the end of 2 μsec of the wave the value is 57 per cent of the maximum and at the end of 3 μsec of wave it is 31 per cent of the maximum. Thus it is evident that the counterpoise has attenuated the wave of potential difference to a great amount compared with the guy ground, with corresponding improvement in protection.

In spite of the fact that the soil resistivity is quite low, a condition which is not particularly favorable to the counterpoise, it has shown a decisive gain. It is probable, however, that the same results might have been obtained by the use of several driven grounds. On the other hand, it is probable that 200 ft of counterpoise would have given just as good results as the full length which was used. With higher resistivity soil the counterpoise will show up more effectively due to the greater depth of the ground plane and lower leakage, which will give a high mutual surge impedance between counterpoise and ground.

Further Investigation

The results of these tests show that a technique has been worked out which it is believed will give approximately the characteristics of counterpoise grounds under any soil conditions. There is urgent need for more data on the performance of counterpoises under varying soil conditions. After such data have been obtained it will be an easy matter, knowing the soil resistivity, to design a counterpoise system which will be adequate. On the other hand, some method must be developed for finding out whether a counterpoise is needed or whether the same results may be obtained more economically by the use of driven grounds. It is believed the proper procedure for obtaining the required data is to build a section of wood pole line 2,000 or 3,000 ft long of similar construction to that at the Trafford laboratory, except that better arrangements for grounding one of the lines should be provided, so that lower surge impedance of the grounding lines may be obtained. The work would be done at the center of the line so that a grounded tower 1,000 ft away on either side will be available. In order to obtain results more or less directly comparable with actual lines, 3 wires are suggested so that 2 of them may be used for overhead ground wires, while the third will be the line wire and left free for mutual coupling measurements. The counterpoise may be made up of any suitable material in suitable lengths, say 200 or 100 ft, and provision can be made for connecting links so that it may be laid down as a single parallel counterpoise over the whole length of the line, or by removing a section the counterpoise may be made to extend on either side of the tower 100 or 200 ft or they may be laid down to form a double parallel counterpoise or cross counterpoise.

On account of the fact that the test should be made at the middle of the line instead of at one end as was done in the Trafford test, an extra large surge generator should be used because the load on the surge generator will be twice as great as in the Trafford tests. A 2,000-kv generator of 0.025-μf capacity would be satisfactory. Difficulty may be experienced in obtaining a reference ground for the surge generator of sufficiently low surge impedance where the resistivity of the soil in the test location is high. This problem will have to be worked out in the field for each location. Once this ground is established there will be no difficulty in carrying out the necessary tests on the line. A program of the kind discussed above is very essential if the art of transmission of power is to progress.

Conclusions

The following conclusions appear to the authors to be justified from these tests.

1. Measurements can be made from which the surge impedance of ground wires, counterpoise wires, grounds, and the mutual coupling factors between these and line wires can be derived for use in calculations.

2. The depth of the equivalent ground plane may be deduced from some of these measurements.

3. The results of these tests indicate that small depth of ground plane and low resistivity of the soil are related characteristics. They reduce the coupling factor between counterpoise and line.

4. The relation between coupling factors of counterpoise and line as affected by the depth of the ground plane seems clear, but the effect of leakance due to low earth resistivity will require more data with diverse soil conditions.

5. Leakance appears to be the dominant quantity in determining the effectiveness of counterpoises when the soil resistivity is low.

Further investigation of like character will be required to determine at what values of soil resistivity counterpoises instead of driven grounds are indicated.

6. The tests indicate that counterpoises even in comparatively low resistance soil are effective not so much by reducing the maximum value of the tower top potential as by reducing the tail of wave in a very marked manner so that the energy in the wave is very much reduced.

7. A method of obtaining the resistivity of the top soil has been derived and gives what appears to be satisfactory results.

8. A method of testing a complete line to simulate the effect of a lightning stroke over a channel having a given value of surge impedance was tried out. This method although not rigorous holds great promise as a means for comparing the advantages of different types of grounding, and comparing them with known types. It also may be used in testing new lines to determine their probable future behavior.

9. A more comprehensive program of testing should be carried out at locations having different soil conditions to determine the characteristics of counterpoises and other grounding means.

Field Tests on Conductor Vibration

Field tests on transmission conductor vibration as affected by dampers and suspension clamps have been made in an attempt to find a solution to the important problem of stopping such vibration in an economical manner. This paper presents some data in regard to number and spacing of the "Stockbridge" type damper. The question of whether vibration is transmitted through or stopped by various types of suspension clamps also is discussed, and actual records of frequencies on both sides of suspension clamps shown.

By
E. M. WRIGHT
MEMBER A.I.E.E.

J. MINI, JR.
ASSOCIATE A.I.E.E.

Pacific Gas and Elec. Co., San Francisco, Calif.

MUCH valuable information has been obtained, both from the laboratory and field, on vibration of transmission line conductors. The theory, cause, effect, and methods of preventing trouble from conductor vibration has been presented from many angles over a number of years. This paper will not attempt to discuss the theory or cause of vibration, but will present records, taken on an operating line over a period of several months, with and without damping equipment, in the hope that these records will help some of the many engineers now studying this problem to understand better what actually occurs in the field.

The tests were made:

1. To determine the damping effects of different numbers and spacings of the same type of damper in any one span.

2. To get records of the actual frequency and amplitude of the vibration occurring on the conductor.

3. To get simultaneous records of the actual frequency and amplitude occurring in adjacent spans.

4. To compare the action of trunnion and non-trunnion type clamps on the bending of the conductor, by taking simultaneous frequency and amplitude records equidistant on each side of the clamp.

The tests were made on a 165-kv circuit of 795,000-cir-mil aluminum conductor steel reinforced, having 54 strands of aluminum, 0.1214 in. diam., and 7 strands of steel, 0.1214 in. diam. The circuit was operating on one side of a twin circuit steel tower line having a normal span of from 750 to 800 ft. (229 m to 244 m). The tension in the conductor was approximately 4,100 lb (1,860 kg) at 60 deg F.

Instruments

Many instruments have been made to record amplitude of vibration, by attaching them directly to a "dead" line, or by connecting to a "hot" line with an insulating string, but this method requires bulky equipment and tends to confine the test to one locality or restricts the number of records obtained. With portability and a large number of records in mind, an instrument shown in Fig. 1 quite similar to a smaller one used by the Aluminum Company of America, was adapted for the purpose. This instrument in its original form was used to record time of operation of motor vehicles and consisted of

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. Pacific Coast convention, Salt Lake City, Utah, Sept. 3–7, 1934. Manuscript submitted April 30, 1934; released for publication May 24, 1934. *Not published in pamphlet form.*

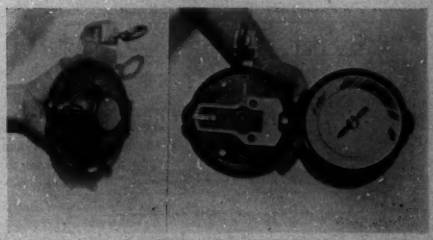


Fig. 1. Two views of recorder "A," used to record time and amplitude of vibration

a light pendulum with a stylus attached to it. This stylus recorded the movement of the pendulum on a 6 in. (15.2 cm) diam. circular waxed chart which was driven by means of a clock. For recording vibration, the instrument was rotated 90 deg in the plane of the pendulum and the latter held in a horizontal position with a light spring. The instrument was then hung on a mechanically vibrated conductor and the weight of the pendulum and distance of the stylus from the axis of the pendulum altered until the chart record represented the vibration amplitude to very near actual scale at all frequencies from 3 to 30 cycles per second. By making all but the clock parts out of aluminum, the weight was kept down to 3.5 lb (1.59 kg). Seven of these instruments were made and were put on and taken off the conductor with a "hot stick" 12 ft (3.66 m) long. Several checks made in the field showed the amplitude of vibration recorded to be remarkably close to the actual. This instrument will be referred to as recorder *A*.

Another instrument was adapted to record frequency and amplitude for 3 independent motions

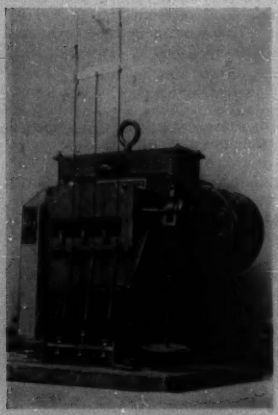


Fig. 2. Recorder "B" with alternate low and high speed chart drive

Simultaneous vibration records taken from 3 different points. Note beam between the 2 outside strings with center point attached to center recording arm for recording the resultant of the 2 outside motions

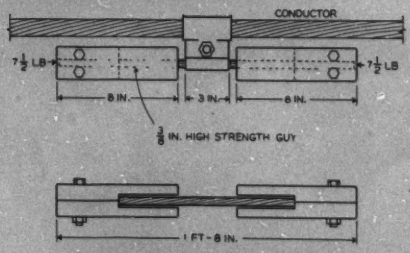


Fig. 3. "Stockbridge" type damper used in test, showing above, elevation of damper, and below, plan of damper without clamp

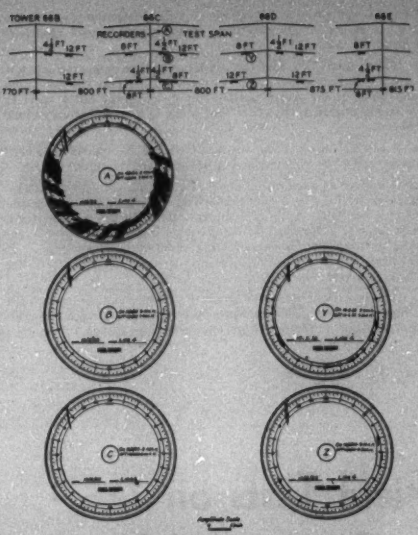


Fig. 4. Charts from recorder "A" showing amplitude of vibration on conductors with 2 arrangements of 2 dampers per span

	A	B	C	Y	Z
On, 10/5/33, a.m.	8:40	8:40	8:45	9:05	9:10
Off, 10/6/33, a.m.	9:00	9:00	9:00	9:20	9:20

simultaneously on one rolled strip chart. Three small cranks, with equal length arms, were mounted on the face of an Esterline Angus quick-trip high-speed motor-driven recorder as shown in Fig. 2. The horizontal sections of 2 of these arms were attached directly to the conductor with a special waxed twine, at positions within 20 ft (6.1 m) of each other. The end of the vertical section of the crank arms held a stylus which recorded the movement of the end of the arms on the moving chart. The chart was standard paper roll which had been sprayed with a black crackle enamel. Marks made by the steel stylus could be seen easily by light reflection. Moderate speed clock drive, and fast electric motor speed drive were used alternately for long periods of operation. Amplitude was recorded continuously at both speeds but readable frequency also was recorded at the fast speed for short periods only every half hour. This instrument was designed primarily to obtain simultaneous readings of vibration in the conductor on each side of the suspension clamp. A small aluminum beam was connected between the 2 outside strings, and the center of this beam was attached to the middle crank arm to obtain the resultant of the 2 outer string vibrations. The resultant is equal to one-half the algebraic sum of the 2 vibration motions. This instrument will be referred to as recorder *B*.

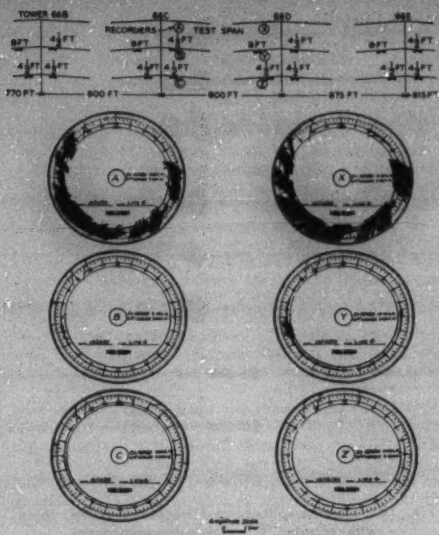


Fig. 5. Charts from recorder "A" showing amplitude of vibration on conductors with 2 arrangements of 2 dampers per span

	A	B	C	X	Y	Z
On, 10/19/33, a.m.	9:50	9:45	9:40	10:05	10:10	10:15
Off, 10/20/33, a.m.	9:05	9:05	9:05	9:35	9:35	9:35

Damper Tests

Many preliminary records were taken on the line to determine the frequency and amplitude of vibration. During these tests, covering approximately 1,000 continuous hours, it was found that vibration occurred over 80 per cent of the time at amplitudes from 0.1 in. (5 mm) to at least 0.9 in. (2.38 cm) which was the maximum travel limit for recording of the stylus in the recorder *A*. As a result of these preliminary tests, an exposed position of approximately 6 miles (9.67 km) near Sacramento, Calif., was chosen for the vibration damper tests. At this place, the line location is almost due north and south, and about 20 miles (32.2 km) from the eastern side of the southern end of the Sacramento Valley. The valley is about 60 miles (96.7 km) wide at this point. Prevailing winds were generally from the west across the line toward the Sierra Nevada mountains, during the time of test between June and October.

The damper chosen for test was the "Stockbridge" type, as shown in Fig. 3.

Experiments were made in the year 1932 on another line having the same type of conductor, and as a result 4 dampers per span, spaced 4.5 ft (1.37 m) and 12 ft (3.66 m) from the suspension clamp on one end, and 8 ft (2.44 m) and 15 ft (4.57 m) from the suspension clamp on the other end of the same span were installed.

The purpose of the present tests was to determine the best position and the minimum number of dampers which could be used in each span to sufficiently damp the vibrations.

In the tests described in this paper, several damper installations were made along the line, each being separated from the others by at least 3 undamped spans. All combinations of the above spacings were installed, and at each location, one conductor, usually the top, was left undamped, while the middle and bottom wire were damped with the experimental arrangement. Recorders type *A* were placed on the undamped wire at one end, and on the middle and bottom wires at both ends 6.0 ft (1.84 m) from the suspension clamps. The undamped wire record was

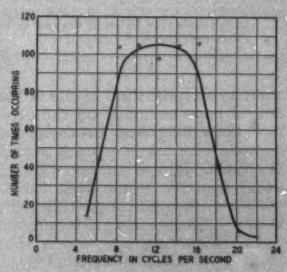


Fig. 7. Frequency curve, showing number of times any frequency occurred over a long period of time

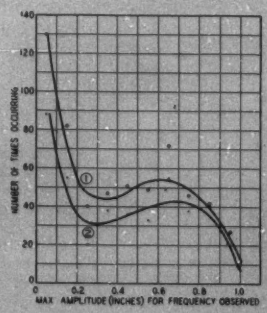


Fig. 8. Amplitude curves, showing number of times any amplitude occurred

Curve 1. Number of times occurring during test
Curve 2. Number of times occurring at frequencies 8 to 16 cycles per second

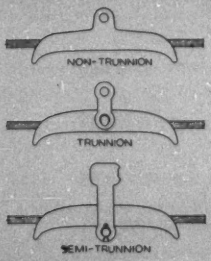


Fig. 6. Three types of suspension clamps used in test

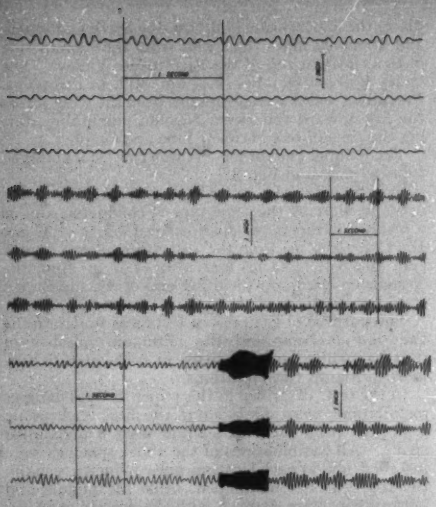


Fig. 9. Three amplitude and frequency charts, taken with recorder "B" on trunnion type clamp

Top and bottom curves of each chart from opposite sides of the clamp 5 ft out
Middle curve of each chart is the resultant. (See Fig. 2)
Solid sections taken at clock speed for 30 min
Frequency curves taken at motor speed (shown by the horizontal scale) for 12 sec at the end of each half hour
Amplitude shown by vertical scale

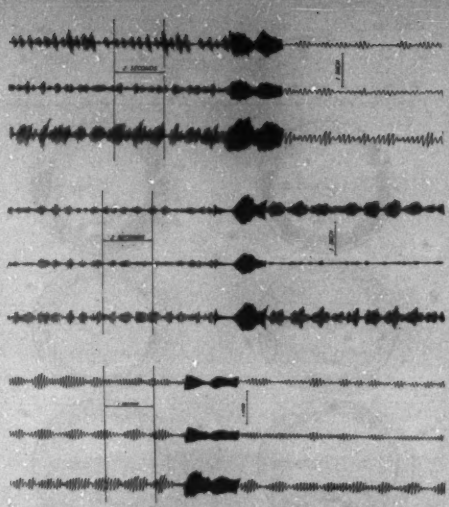


Fig. 10. Three amplitude and frequency charts, taken with recorder "B" on semi-trunnion clamp

See subcaption of Fig. 9 for meaning of curves

used as an indication of the probable vibration which would have occurred on the other 2, if dampers had not been attached to them. From 4 to 8 24-hr records were taken on each installation. The records from the damped wires were compared with each other and by elimination the better arrangements were set up again, this time with dampers installed in the adjacent spans, to prevent interference from those heretofore undamped spans. Records taken from 2 of the better arrangements are shown in Figs. 4 and 5. These records were taken from several of the same type and are distinctly representative.

Suspension Clamp Tests

The purpose of this test was to get a large number of simultaneous records of frequency and amplitude of conductor vibration on both sides of 3 different types of suspension clamps. The clamps used were standard makes of the non-trunnion, trunnion, and semi-trunnion types shown in Fig. 6. The insulator string consisted of 14 10-in. (25.4-cm) ball and socket, 5.75-in. (14.6-cm) spaced cap and pin type insulators. Records were all taken with the recorder B installed in the tower approximately 15 ft (4.57 m) below the bottom conductor. Waxed strings were attached to the conductor on each side of the suspension clamp at points 5 ft (1.52 m) out from its center. These strings were dropped vertically to the end of high strength aluminum tubes supported horizontally, and from the end of these over small ball bearing aluminum sheaves through the tube to the recorder B. A short distance above the recorder B, a light metal beam was connected between the 2 strings, and its middle point connected with a light stiff wire to the middle crank arm. The amplitude of the vibration recorded by this middle crank stylus point indicated quite accurately whether the vibrations in one span were or were not synchronous and in phase with those in the adjacent span.

The records taken on the above set-up also furnished some very useful information as to the frequencies actually occurring on the conductor over a long period of time; the comparative frequencies and vibration amplitude occurring in adjacent spans; and the effect, if any, of the different type of clamps on frequency and amplitude.

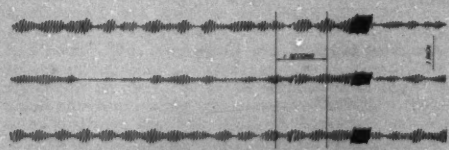


Fig. 11. Amplitude and frequency charts, taken with recorder "B" on non-trunnion clamp

See subcaption of Fig. 9 for meaning of curves

The frequency occurring on the conductor for all records taken is shown in Fig. 7, and indicates quite a broad range on this particular conductor. Most of the records were taken between 5 p.m. and 8 a.m. as but little vibration occurred during the remainder of the time. In Fig. 8 are shown 2 curves of amplitude plotted against number of times occurring. The amplitude referred to is that occurring at a point 5 ft (1.52 m) from the suspension clamp.

The frequency occurring in adjacent spans was generally about the same, being in almost all cases within 1 or 2 cycles per second of each other. In a few cases the frequency in one span was approximately one-half that in the other. Some cases were observed, however, where there was little or no vibration recorded in one span, while the adjacent span was quite active, reaching amplitudes of 0.5 in. (1.27 cm) or over at times. In general, the amplitude and frequency characteristic of one span was similar in some respect to that in the adjacent span.

Charts shown in Figs. 9, 10, and 11 are representative sections taken from the records on the 3 types of clamps. The top and bottom curves represent the vibration of the conductors from opposite sides of the clamp. The middle curve is the resultant or half the algebraic sum of the top and bottom curves, as indicated by the motion of the middle point of the beam shown in Fig. 2. The records were taken at various speeds of the clock, or motor drive, but may be studied by means of the scales shown. A comparison of the wave form of the conductor vibration for any instant taken from either side of the clamp will indicate what the resultant vibration should be. For all cases studied closely, this checked exactly with that recorded. A study of all records taken gave no indication of any consistent effect given by any certain type of clamp. All the records of frequency and amplitude, regardless of type of clamp, showed a consistent inconsistency. Most of the records studied showed an indication that the vibration in one span tended to break up the vibration in the adjacent span regardless of the type of clamp used. This was shown by the occasional sudden change in the uniformity of cyclic wave.

Several records were taken with recorder *B* on a suspension clamp which had a spring working in compression, connected between the clamp and the insulator string. Simultaneous records were taken on the bottom conductor, at each side of this clamp. A few tests were also taken on the middle wire and the bottom wire, at the same time, with the recorder attached to opposite sides of their respective clamps. There seemed to be a marked vibration interference on both sides of the clamp, as both of the wave forms were very irregular and broken up. When comparing the vibrations of the middle wire which was supported on a standard clamp, with the vibrations in the bottom wire hung in the special compression spring clamp, the latter generally showed less amplitude, but nothing definite can be said about this, due to the few records taken.

Conclusions

The following conclusions were reached after a close study of all the records taken, and apply only to the type of conductor, the particular location, span, and tension used. It is quite probable that the same general conditions would be found in other conductors regardless of size, tension, and span.

1. For the particular type conductor and damper tested, one damper installed on the conductor approximately 4.5 ft (1.37 m) from the suspension clamp at each end of the same span will sufficiently limit vibration under all conditions, and is better from a damping standpoint than an additional number.

2. The most prevalent frequencies are between 8 and 16 cycles per second, and hence the calculated loop lengths are between 17 ft (5.2 m) and 11 ft (3.36 m) for the conditions under which the test was made.

3. The frequency in one span is generally within one cycle of that in the adjacent span, but is rarely the same.

4. No difference was noticeable between the effect produced by the use of the trunnion and non-trunnion type of clamps on the amplitude or frequency of vibration, or the tendency to either retard or aid the transmission of vibration waves from one span to the adjacent one.

5. Uniform amplitude does not occur for periods of more than one second and the frequency often changes 1 or 2 cycles per second within a few seconds.

May Be Visited During Pacific Coast Convention

"Temple of Osiris" in Bryce Canyon, in southwestern Utah, will be visited by many of those attending the Institute's Pacific Coast convention in Salt Lake City, Sept. 3–7, 1934. Bryce Canyon is a "box" canyon filled with a countless array of fantastically eroded pinnacles, and is generally considered to be the best exhibit of vivid coloring of the earth's materials

News
Of Institute and Related Activities

Plan Your Vacation to Include the Pacific Coast Convention at Salt Lake City

THE PACIFIC COAST convention this year will be held September 3–7, 1934, in Salt Lake City, Utah, which offers to many members unusual possibilities to combine a few vacation days with the convention trip. Yellowstone National Park is but a night's ride by rail from Salt Lake City. Within the boundaries of Utah and in Northern Arizona there are located such scenic wonders as the Grand Canyon, Zion, and Bryce Canyons. For those who are interested in the wonders of engineering as well as the wonders of western scenery there is a possibility of combining a trip to Boulder Dam (now at its most interesting construction stage) with the convention trip through the Utah parks. In addition the committee has arranged the schedule of technical sessions during the mornings, except on the opening day, so as to leave the afternoons free to enjoy sightseeing trips, inspection tours, or recreation in the form of golf or bathing at some one of the many delightful recreational centers within an hour's ride of Salt Lake City. Convention headquarters will be in the Hotel Utah.

Technical Program

A technical program of broad scope and current interest has been developed to appeal particularly to western engineers. A session on communication has been scheduled on Monday afternoon. On the mornings of the following days sessions will be held on the subjects of management, protective devices, lightning, transmission, and selected subjects. In addition, student sessions will be held on the afternoons of Tuesday and Wednesday, September 4 and 5, respectively.

The transmission session should have unusual appeal as it deals with some of the latest studies in stability, vibration, corona, and insulation, and some of the papers are related to the Boulder Dam transmission projects.

Entertainment Features

On Monday evening, September 3, there will be a reception in the ballroom of the Hotel Utah followed by dancing. This will be one of the most important entertainment features of the convention and it is hoped there will be a full attendance by members with their wives and guests.

On Thursday evening, September 6, following the golf tournament, the principal banquet of the convention will be held at the Salt Lake City Country Club. The awarding of the golf prizes will take place at this banquet and it will be followed by dancing.

The ladies have not been neglected in the entertainment arrangements. Sightseeing tours and social events are being planned and the details will be announced later.

Sports

On the afternoon of Thursday, September 6, there will be a golf tournament at the Salt Lake City Country Club. The John B. Fisken Cup competition, open only to members of the Pacific Coast Sections, will take place at this time. There will of course be competition for other prizes which will be open to all registered members and guests attending the convention.

Trips

On Friday afternoon, September 7, it is expected that those who intend to make a tour of the Utah National Parks and the Grand Canyon will start on their trips. The Boulder Dam inspection trip will also begin on Friday afternoon.

Technical Program

All papers are scheduled for publication in ELECTRICAL ENGINEERING prior to the convention. For the papers which already have been published reference to the issue and page is given after each title in the list which follows. The remaining papers are scheduled for publication in the August issue. Members who wish to follow the presentation in detail and discuss the papers are urged to take the necessary issues to the convention.

Monday, September 3

2:00 p.m.—Communication

TELEVISION, A. H. Brolly, Television Laboratories, Ltd.

RESONANT LINES IN RADIO CIRCUITS, F. E. Terman, Stanford University. July, p. 1,046–53

WIDE-BAND OPEN-WIRE PROGRAM SYSTEM, H. S. Hamilton, American Tel. & Tel. Co. April, p. 550–62

LINE FILTER FOR PROGRAM SYSTEM, A. W. Clement, Bell Telephone Laboratories. April, p. 562–6

Tuesday, September 4

9:00 a.m.—Management and Protective Devices

THE THEORY OF INCREMENTAL RATES AND THEIR PRACTICAL APPLICATION TO LOAD DIVISION, PARTS I AND II, M. J. Steinberg and T. H. Smith, Brooklyn Edison Co. March, p. 432–45; April, p. 571–84

JOINT USE OF POLES WITH 6,900-VOLT LINES, W. R. Bullard, Electric Bond and Share Co., and D. H. Keyes, American Tel. & Tel. Co. Dec., p. 890–8

SOME RECENT RELAY DEVELOPMENTS, Lloyd F. Hunt and A. A. Kroneberg, Southern California Edison Co., Ltd. April, p. 530–5

DISTANCE RELAY ACTION DURING OSCILLATIONS, E. H. Bancker and E. M. Hunter, General Electric Co. July, p. 1,073–80

THE EXPULSION OIL CIRCUIT BREAKER, A. C. Schwager, Pacific Electric Mfg. Corp. July, p. 1,108–15

Wednesday, September 5

9:00 a.m.—Lightning

LIGHTNING INVESTIGATION ON TRANSMISSION LINES—IV, W. W. Lewis and C. M. Foust, General Electric Co.

LIGHTNING INVESTIGATION ON 220-KV PENNSYLVANIA POWER AND LIGHT COMPANY SYSTEM 1931–1933, Edgar Bell, Pennsylvania Power & Light Co.

COUNTERPOISE TESTS AT TRAFFORD, C. L. Fortescue and F. D. Fielder, Westinghouse Electric & Mfg. Co. July, p. 1,116–23

LIGHTNING PERFORMANCE OF 132-KV LINES, Philip Sporn and I. M. Gross, American Gas & Electric Co.

FIELD TESTS ON THE COUNTERPOISE, L. V. Bewley, General Electric Co.

Thursday, September 6

9:00 a.m.—Transmission

FIELD TESTS ON CONDUCTOR VIBRATION, E. M. Wright and Joseph Mini, Jr., Pacific Gas & Elec. Co. July, p. 1,123–7

CORONA LOSSES FROM CONDUCTORS OF 1.4-INCH DIAMETER, Joseph S. Carroll, Stanford University, Bradley Cozzens, and T. M. Blakeslee, Dept. of Water and Power, City of Los Angeles, California. Dec., p. 854–60

POWER LIMITS OF 220-KV TRANSMISSION LINES, Alex. A. Kroneberg, Southern Calif. Edison Co., Ltd., Los Angeles, and Mabel Macferran, Metropolitan Water District of Southern California, Los Angeles. Nov., p. 756–66

POWER LIMITS OF SYNCHRONOUS MACHINES, Edith Clarke and R. G. Lorraine, General Electric Co. Nov., p. 780–7

The Insulator String, R. W. Sorensen, California Institute of Technology.

Properties of Contaminated Glass and Porcelain Surfaces, W. A. Hillebrand, University of California.

Friday, September 7

9:00 a.m.—Selected Subjects

Simplified Measurements of Sound Absorption, A. L. Albert and T. B. Wagner, Oregon State College.

A Glow Discharge Anemometer, F. C. Lindvall, California Institute of Technology. July, p. 1,068–75

Electrical Figures on Plates in Air, J. Gibson Pleasants, California Institute of Technology. Feb., p. 300–7

Ignition of an Arc at Low Pressures, S. S. Mackeown, J. D. Cobine, and F. W. Bowden, California Institute of Technology. July, p. 1,081–5

Insulator Arcover in Air, F. W. Maxstadt, California Institute of Technology. July, p. 1,062–8

Rules on Presenting and Discussing Papers

At some of the technical sessions, a few papers may be presented only by title. This will permit the devotion of more time to discussion. At other sessions, papers will be presented in abstract, 10 min being allowed for each paper unless otherwise arranged, or the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion. Authors will be notified officially in each case about one month in advance.

Any member is free to discuss any paper when the meeting is thrown open for general discussion. Usually 5 min are allowed to each discusser for the discussion of a single paper or of several papers on the same general subject. When a member signifies his desire to discuss several papers not dealing with the same general subject, he may be permitted to have a somewhat longer time.

It is preferable that a member who wishes to discuss a paper give his name in advance to the presiding officer of the session at which the paper is to be presented. Each discusser is to step to the front of the room and announce, so that all may hear, his name and professional affiliations. Three typewritten copies of discussion prepared in advance should be left with the presiding officer.

Other discussion to be considered for publication *must* be submitted, typed double spaced, in triplicate to C. S. Rich, secretary of the technical program committee, A.I.E.E. headquarters, 33 West 39th St., New York, N. Y., on or before Sept. 21, 1934. Discussion received after this date will not be accepted.

Committees

The general convention committee for the 1934 Pacific Coast convention consists of the following members: B. C. J. Wheatlake, *chairman;* R. W. Sorensen, *vice-chairman;* W. R. Barrett, *treasurer;* and W. M. Allen, A. P. Hill, G. L. Hoard, A. H. Hull, F. O. McMillan, H. T. Plumb, W. C. Smith, L. B. Stacey, J. A. Thaler, and V. B. Willey. The chairmen of the various subcommittees working with the general convention committee are as follows: technical program, A. LeRoy Taylor; finance, J. A. Kahn; transportation, C. A. Malinowski; hotels and registration, L. E. Brown; reception, C. R. Higson; entertainment, W. L. Winter; golf, J. A. Hale; publicity, L. B. Fuller; student activities, J. Hugh Hamilton; and ladies' entertainment, Mrs. L. B. Fuller.

The famous Temple Square in Salt Lake City. In the center is the temple of the Mormon Church, the large building at the left being the tabernacle. Salt Lake City, the scene of the Institute's Pacific Coast convention, Sept. 3–7, 1934, affords these and many other points of outstanding interest to visitors

Summer Convention to Be Reported in Next Issue

The 50th annual summer convention of the Institute held in Hot Springs, Va., June 25–29, 1934, with headquarters in The Homestead, was in progress as this issue went to press. A detailed report of this convention, including the annual business meeting with presentation of prizes and medal; 50th anniversary meeting; conference of officers, delegates, and members; directors' meeting; technical sessions; and inspection trips and entertainment features is scheduled for publication in the August issue of Electrical Engineering.

Technical Committee Reports Postponed

The annual reports of those technical committees of the Institute which have compiled reports for the past year were stated in the June issue of Electrical Engineering to be scheduled for publication in the present issue. However, publication of these annual reports has been indefinitely postponed pending recommendation of the Institute's technical program committee.

A.I.E.E. Directors Meet in New York

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute headquarters, New York, N. Y., on Friday, May 25, 1934.

Present: *President*—John B. Whitehead, Baltimore, Md. *Past-president*—H. P. Charlesworth, New York, N. Y. *Vice-presidents*—J. Allen Johnson, Buffalo, N. Y.; and E. B. Meyer, Newark, N. J. *Directors*—L. W. Chubb, East Pittsburgh, Pa.; A. B Cooper, Toronto, Ont.; A. E. Knowlton, New York, N. Y.; Everett S. Lee, Schenectady, N. Y.; L. W. W. Morrow, New York, N. Y.; A. C. Stevens, Schenectady, N. Y.; and H. R. Woodrow, Brooklyn, N. Y. *National treasurer*—W. I. Slichter, New York, N. Y. *National secretary*—H. H. Henline, New York, N. Y.

The board adopted a resolution in memory of past-president William S. Lee, who died on March 24, 1934. (The resolution appears elsewhere in this issue.)

The annual report of the president of United Engineering Trustees, Inc., was presented in person by Harold V. Coes, president, U.E.T.

Minutes were approved of a meeting of the board of directors held January 22, 1934, and of the executive committee held March 9, 1934.

Reports of meetings of the board of examiners held April 11 and May 23, 1934, were presented and approved. Upon the recommendation of the board of examiners, the following actions were taken: 2 applicants were transferred to the grade of Fellow; 6 applicants were elected and 13

were transferred to the grade of Member; 200 applicants were elected and 1 was reinstated to the grade of Associate; 242 Students were enrolled.

Future AIEE Meetings

Pacific Coast Convention,
Salt Lake City, Utah, Sept. 3–7, 1934

Winter Convention,
New York, N. Y., Jan. 22–25, 1935

South West District Meeting,
Oklahoma City, Okla., Apr. 26–28, 1935

Summer Convention,
Ithaca, N. Y., June 24–28, 1935

Pacific Coast Convention,
Los Angeles vicinity, Fall 1935

Great Lakes District Meeting,
Indianapolis—Lafayette Section territory (Date to be determined)

The finance committee reported disbursements as follows: March, $15,118.38; April, $20,510.97; May, $21,439.72. Report approved.

The national secretary reported 1,842 members in arrears for dues for the fiscal year which ended April 30, 1934. It was voted to transfer the names of these members to a "suspended" list after the distribution of the June and July issues of ELECTRICAL ENGINEERING, and to extend the time for the payment of the dues in arrears until further action by the board.

President Whitehead reported on his visits to various Sections of the Institute.

Sec. 58 of the By-Laws was canceled, thus eliminating the provision for subscription to ELECTRICAL ENGINEERING at the reduced rate of $3 per year by students who are not enrolled in the Institute. As the changes in the Institute's publication plan have nearly doubled the amount of technical material previously supplied in ELECTRICAL ENGINEERING, the expense involved seemed to make it undesirable to continue to supply the publication at $3 per year to students not enrolled in the Institute, and since the recent adoption of amendments to the By-laws extending the privileges of enrollment to students in evening courses, there seemed to be less need for the provision of Sec. 58.

Upon the recommendation of the committee on coördination of Institute activities, the following schedule of meetings for 1935 was adopted:

Winter convention, New York, January 22–25, with sessions on Tuesday, Wednesday, and Thursday, and inspection trips only on Friday.
Summer convention, Cornell University, Ithaca, N. Y., June 24–28.
Pacific Coast convention, Los Angeles vicinity, in the fall, exact location and dates to be determined later.
District meetings:
(1) Great Lakes District (No. 5), Indianapolis—Lafayette Section territory, location and dates to be determined later.
(2) South West District (No. 7), Oklahoma City, Okla., April 26–28.

Upon request of the Birmingham Section, the board authorized a change in its name to "Alabama Section" and the extension of its territory to include the entire state of Alabama.

Upon request of the New Orleans Section, its territory was increased by the addition of the part of the state of Mississippi south of the northern boundaries of the following counties: Issaouena, Sharkey, Yazoo, Madison, Leake, Neshoba, and Kemper.

The annual report of the board of directors to the membership for the fiscal year which ended April 30, 1934, as prepared by the national secretary, was approved for presentation at the annual meeting of the Institute on June 25, 1934.

The annual report of the national treasurer was presented and accepted.

Annual reports of the general standing committees (exclusive of the technical committees), abstracts of which were incorporated in the annual report of the board of directors, were received.

The report of the committee on award of Institute prizes of the awards of national prizes for papers presented during 1933 was presented and accepted. (The report was published in the June 1934 issue of ELECTRICAL ENGINEERING, p. 1026.)

The appointment of a national secretary for the administrative year beginning August 1, 1934, was made in accordance with Sec. 37 of the Constitution. National secretary H. H. Henline was reappointed.

Bancroft Gherardi was appointed a representative of the Institute upon the John Fritz Medal board of award, to fill the unexpired term, ending in October 1934, of W. S. Lee, deceased.

Report was made of an invitation to the Institute to be represented at the National Conference on Street and Highway Safety, Washington, May 23–25, and of the designation by President Whitehead of F. M. Feiker as the Institute's representative at this conference.

An invitation from the Institution of Engineers, Australia, to the officers and members of the Institute to take part in the proceedings of an engineering congress to be held in Melbourne, Australia, March 11–16, 1935, in connection with the proposed celebrations of Melbourne's Centenary, 1934–1935, was accepted, and the president was authorized to appoint the Institute's representatives.

The following resolution was adopted:

RESOLVED: That the board of directors expresses its appreciation of the excellent work of the fiftieth anniversary committee and the publication committee in commemorating the fiftieth anniversary of the Institute.

Other subjects were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

An Address On "Human Engineering Problems"

AN ADDRESS on "Human Engineering Problems" was prepared by Dr. Michael I. Pupin (A'90, F'15, HM'28, member for life, and past-president) to be delivered on April 26, 1934, at a general meeting of the Institute's New York Section, in the auditorium of the Engineering Societies Building, New York. Doctor Pupin's talk was scheduled as an important part of this meeting, which was also a commemoration by the New York Section, of the 50th anniversary of the founding of the Institute.

This address, which in the absence of Doctor Pupin was read by Dean J. W. Barker (M'26, F'30) elicited much favorable comment. The text of Doctor Pupin's address is presented herewith:

"I wish to call your attention this evening to some of the engineering problems which are seldom discussed at the meetings of the engineering societies. I call them the 'Human Engineering Problems,' in order to distinguish them from the technical engineering problems. When I was a college student engineering education was devoted exclusively to the training of young engineers in the art of solving purely technical engineering problems. Their training in the art of solving human engineering problems was unknown. You are undoubtedly puzzled by this title: 'Human Engineering Problems.' Permit me to explain its meaning by an illustration:

"Sixty years ago when my immigrant ship landed me in New York, I took a walk on lower Broadway and saw what looked to me like a cobweb of wires stretching across the housetops of Broadway. I wondered what it meant. I was told that these wires carried electrical signals between New York and the various places in the United States. My untutored mind could not quite grasp what that meant and I made many efforts to unravel the mysteries of electrical signaling. That was the beginning of my interest in electrical communications. Two years later, that is in 1876, I saw the first telephone exhibited at the Centennial Exposition in Philadelphia. Its performance looked to me like a miracle. A month or so later I was told by a scoffer that it was a silly toy only. But in a little over half a century this toy has given us a gigantic industry which is the result of the creative work of the American engineer. Since 1876, when Bell first exhibited his great invention, the telephone industry has grown from what the scoffer considered a silly toy, to an industry capitalized at 5 billion dollars. It has been absorbing about 100 million dollars annually during the last 50 years, and one would be inclined to expect that so rapid a growth would be a mushroom growth.

"But listen to what I once heard the experts say about it. Twenty years ago a commission of 12 German engineers came over, in order to study our industrial organization. At the start of their return trip to Germany I met them here in New York and heard them speak as follows: 'Your American industries are not better organized than our German industries,

and we did not have much to learn. Your telephone industry, however, is a great exception. Nothing in Germany can approach the wonderful organization of your telephone industry.' This confession of the Germans thrilled me, and I said, jokingly: 'Your Kaiser said on a certain occasion that there are only 2 great organizations in the world. The first is the German army, and the second is the Roman Catholic Church. Tell him when you return, that the first is the American Telephone industry and nobody cares which is second.' The Germans saw the joke and said: 'We shall do so if we have a chance. But remember that at German Court receptions there are no engineers. Politicians and soldiers are the ornaments of the German Court; the engineers are never seen there, not even in the back seats.' We hope that American engineers stand higher in the social scale.

"I wonder what these German engineers will say when they hear that the great American Telephone industry which thrilled them so much is being investigated by a Federal commission consisting of politicians and that the chairman of this commission in his latest report asks the following questions:

'How much more should it cost to place a long distance call from Washington to San Francisco than from Washington to Baltimore?'

'.....If 20 cents be a reasonable charge for such service from Washington to Baltimore, may it not be possible to place a call with any exchange in any American city at approximately the same cost?'

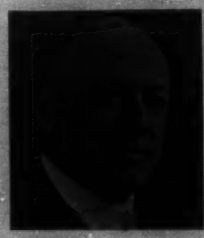
"No question ever asked displayed a more lamentable lack of expert knowledge, and it was framed by the chairman of the Federal investigating commission. A Federal investigating commission consisting of politicians who are totally ignorant of the technical arts which they are expected to investigate will certainly bring discredit upon American science and engineering. To prevent the appointment of such commissions is one of the human engineering problems of our profession.

"Just one more illustration. When 60 years ago my immigrant ship entered New York harbor my untutored peasant mind was bewildered by the sight of this great metropolis. Today, my mind, although incomparably more experienced than on that memorable day, is even more bewildered when I contemplate the great changes which American engineering has created in this marvelous town. The picture of New York of 60 years ago looks like a picture of a little village when put alongside of the picture of New York of today. Just think of its sky-high steel palaces served by speedy electrical elevators, by incandescent lighting, and by telephones which connect them with every point of the terrestrial globe; think of the many bridges, subways and tunnels which have transformed the modest Manhattan Island into greater New York, the greatest population center in the world; just think of the hundreds of millions of dollars which flow annually into the City treasury for the support of its complex administration; just think of all these things which were not even dreamed of 60 years ago and you will see clearly the great achievements of American engineering which is represented by the awe inspiring structure called Greater New York. No other civic center ever offered to man a greater opportunity for an administration of splendid engineering efficiency. And yet this wonderful home of organized American engineering is on the verge of bankruptcy. Engineers look on helplessly at the destructive work of the greedy politicians, but as a civic body they do nothing to stop the barbarous abuse of political power. It is indeed one of the greatest missions of our profession to gain for the engineer a greater share in the administration of the American cities which owe their existence to his creative work. But our profession cannot perform that mission unless it is trained in the art of solving human engineering problems."

Illuminating Engineering Society Meeting. The 28th annual meeting of the Illuminating Engineering Society is to be held in Baltimore, Md., Oct. 1–4, 1934. The convention this year offers the following outstanding features: The 10th lighting service conference—a vigorous, forceful meeting; the lighting equipment exposition—greatly expanded—a real feature; the technical and business sessions—covering a wide range of interests; and social events and inspection trips of unusual character. The many interesting things that have happened in the lighting industry and in I. E. S. circles during the past year will be reviewed at this convention.

American Transit Association to Meet. The 53rd annual convention of the American Transit Association will take place in the New Exhibition Hall of the Cleveland Public Auditorium, Cleveland, Ohio, Sept. 24–28, 1934. In connection with this convention, the operating and manufacturing members of the association will hold an exhibition of equipment, appliances, and manufactured articles of interest to executive and operating officials of the urban and interurban transportation companies.

In Memoriam



WILLIAM STATES LEE

IN THE death, on March 24, 1934, of William States Lee, the American Institute of Electrical Engineers lost its forty-third president and one of its most energetic and influential leaders.

Beginning his practical engineering career in 1897, after a brief period as instructor at the Citadel, from which he had been graduated in 1894, he rose rapidly from the positions of resident engineer of the Anderson (S. C.) Light and Power Company and the Columbus (Ga.) Power Company to become chief engineer of the latter in 1902, and vice-president and chief engineer of the Catawba Power Company, Charlotte, N. C., in 1903. In succeeding years, he served several power companies as vice-president, chief engineer, and director, the W. S. Lee Engineering Corporation as president, and the Piedmont and Northern Railway Company as president and chief engineer. He attained an enviable reputation as an executive in charge of many large power development and construction projects.

Throughout his career, his ability as an engineer, his keen perception of the controlling factors in any situation encountered, and his constant attention to the human values involved made him an outstandingly effective and a highly respected leader of men. His genial personality and wide range of information won him a multitude of friends.

Mr. Lee joined the Institute in 1904, and generously gave his time and energy to its activities in various capacities: as director 1911–14, and 1929–30, and president 1930–31; as member of a considerable number of committees, and as a representative of the Institute upon several joint organizations. He stood firmly at all times for the highest ideals of the Institute and ranked among its foremost leaders. As president of the American Engineering Council, during the years 1932 and 1933, he worked intensively and enthusiastically to make the engineering profession as helpful as possible in all problems involving engineering and affecting the public welfare.

RESOLVED: That the board of directors of the American Institute of Electrical Engineers hereby expresses, upon behalf of the membership, its deepest regret at the death of Mr. Lee and its sense of great loss sustained by the Institute and by the entire engineering profession, and be it further

RESOLVED: That these resolutions be entered in the minutes and copies be transmitted to members of his family.

—A.I.E.E. Board of Directors, May 25, 1934

Student Conference Held by North Central District

THE SEVENTH annual conference of student Branches of the A.I.E.E. in the North Central District (No. 6) was held at the South Dakota State School of Mines, Rapid City, S. Dak., April 13–14, 1934. This conference was a very successful one as indicated by both the number in attendance and the lively interest taken in all the sessions. It was a continuation of successful student conferences which have been held by this District.

Attendance

In attendance at the conference were 2 District officers: R. B. Bonney, vice president, District No. 6; and W. G. Rubel, secretary, District No. 6. Nine counselor-delegates were present, as were 9 chairmen of student Branches. In addition, 79 others were registered, bringing the total attendance to 99. The counselor-delegates present were:

J. O. Kammerman	S. Dak. State School of Mines
R. E. Nyswander	University of Denver
F. W. Norris	University of Nebraska
H. S. Rush	N. Dak. Agricultural College
H. F. Rice	University of North Dakota
W. C. DuVall	University of Colorado
C. W. Caldwell	University of South Dakota
G. H. Sechrist	University of Wyoming
W. H. Gamble	S. Dak. State College

The chairmen of student Branches who also were present as delegates were:

G. I. Welch	S. Dak. School of Mines
G. E. Bronson	University of Denver
Walker Cordner	University of Nebraska
Kenneth Brandby	N. Dak. Agricultural College
Orville T. Mundt	University of N. Dak.
Newell Parker	University of Colorado
Roy Sletvold	University of S. Dak.
George Gilleard	University of Wyoming
George Carefoot	S. Dak. State College

Friday Afternoon Session

The opening session, Friday afternoon, was called to order by Prof. J. O. Kammerman, chairman of the District committee on student activities, who introduced Dr. C. C. O'Hara, president of the South Dakota State School of Mines. Following a brief speech of welcome, R. B. Bonney took charge of the conference. In addition to the following schedule of papers and discussions which were presented, a number of lively discussions took place:

What Lies Ahead for the Engineering Graduate of Today? Prof. F. W. Norris, University of Nebraska.

Discussion, O. T. Mundt, chairman, University of North Dakota Branch.

Should Engineers Enter the Political Field? Prof. W. H. Gamble, South Dakota State College.

Discussion, K. Brandby, chairman, North Dakota Agricultural College Branch.

How Can Interest in the Student Branches Be Stimulated? Prof. H. F. Rice, University of North Dakota.

Discussion, Prof. C. W. Caldwell, University of South Dakota; George Gilleard, chairman, University of Wyoming.

New Problems Confronting Student Branches, Dr. R. E. Nyswander, Denver University.

Discussion, G. E. Bronson, chairman, University of Denver.

Banquet Held

The delegates to the conference and some 75 others were entertained at a banquet and program arranged by the student Branch of the South Dakota School of Mines and held in the ballroom of the Alex Johnson Hotel in Rapid City. G. I. Welch was toastmaster. The program follows:

Developments in Communications, T. L. Frank, head of department, building and equipment, Northwestern Bell Telephone Company, Omaha, Neb.

Motion Pictures, George Low, State School of Mines.

Introduction of Guests, Prof. J. O. Kammerman, State School of Mines.

The District Student Conference, R. B. Bonney, vice president, District No. 6, A.I.E.E.

Appreciation, Dr. C. C. O'Hara, president, State School of Mines.

Before the second session of the conference on Saturday, a number of the delegates and guests enjoyed an early morning ride to the Rushmore Memorial, about 30 miles from Rapid City, where the face of George Washington has been carved in the solid granite of Mt. Rushmore, by the famous sculptor, Gutzen Borglum.

Saturday Morning Session

The Saturday morning session was called to order by R. B. Bonney, and the following papers and discussions were presented:

Gold Mining in the Black Hills, Dr. J. P. Connolly, vice president, State School of Mines.

Report on Annual Convention of A.I.E.E. at Chicago, Prof. J. O. Kammerman, State School of Mines.

What Can Branches Do to Promote Institute Membership? Prof. G. H. Sechrist, University of Wyoming.

Discussion, N. Parker, chairman, University of Colorado Branch.

The Engineering Council for Professional Development, Prof. W. C. DuVall, University of Colorado.

Discussion, G. Carefoot, chairman, South Dakota State College Branch.

How Far Should Engineering Schools Be Held Responsible for Finding Employment for Graduates? Prof. H. S. Rush, North Dakota Agricultural College.

Discussion, W. M. Cordney, chairman, University of Nebraska.

Following this program, a resolution was unanimously adopted by the conference, congratulating the South Dakota School of Mines Branch upon its efficient management of the conference, and thanking Doctor O'Hara and Professor Kammerman for their hospitality.

Counselors' Meeting

Immediately following the Saturday morning session, a brief meeting of the student counselors was held. This was called to order by Professor Kammerman who stressed the desirability of rotating the meeting place of the student's conference. On the invitation of Professor Rush, the North Dakota Agricultural College, at Fargo, was selected for the 1935 conference. Professor Rush also was elected chairman of the District committee on student activities for the ensuing year, and was selected automatically as delegate to the Institute's 1934 summer convention.

The selection of student counselors was discussed, and the counselors were requested by the secretary to begin the consideration as early as possible of papers to be submitted during 1934 for the District prize.

Five-Year Course Added at M. I. T. A new departure in technological training to meet a growing demand for engineers with a thorough understanding of the social and economic implications of their profession was announced recently by Karl T. Compton (F'31) president of Massachusetts Institute of Technology, Cambridge, in a statement that this institution will offer a new 5-year course which will include advanced studies in the social sciences and economics. The new course, which in no way affects the regular 4-year courses in science and engineering at M. I. T., will be offered next Autumn in nearly all the professional fields of the curriculum.

Boulder Dam Power Transformers. Among the equipment recently placed on order by the federal government for Boulder Dam, Colo., are 11 power transformers, 7 of which are rated at 55,000 kva at 287,000 volts, and to be manufactured at the Pittsfield, Mass., works of the General Electric Company. Shipment of the transformers, valued at about $1,000,000, is scheduled in about a year. The larger transformers will be water cooled, will weigh over 200 tons each, and will be approximately 32 ft high, 20 ft wide, and 13 ft deep. The 4 smaller ones will be rated 13,333 kva at 138,000 volts, and will be forced-oil cooled.

Work Begins on Fort Peck Dam. Several hundred men are already engaged in the first stages of the work of building the Fort Peck Dam, the gigantic federal project on the Missouri River in Montana. This dam will be the largest earth filled barrier ever built, and will create a reservoir 175 miles long, and will cost some $72,000,000. Total length of the dam, including wings, will be nearly 4 miles. The dam will be 230 ft high, 100 ft wide at the top, and 2,658 ft thick at its base. Its purpose is to provide a 9-ft channel in the Missouri River throughout the year, aid in flood control, provide unemployment relief, and provide a site for power development. It is estimated that 4 years will be required for construction. A contract amounting to more than $500,000 has been awarded the Westinghouse Electric and Manufacturing Company for electrical substation equipment including high voltage switching equipment, 4 16,667-kva transformers, 2 20,000-kva synchronous condensers, and other equipment. Four pipe line dredges will utilize much of the power of the substation.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

History of Thomson-Houston Company Name

To the Editor:

"We have been reading with considerable interest the Jubilee Number of the official monthly journal and transactions of the A.I.E.E., dated May 1934. In the biographical section we were particularly interested in the notes regarding Professors Elihu Thomson and E. J. Houston.

"You are probably aware that the Thomson-Houston Company referred to therein, founded in Philadelphia in 1879, became a world wide organization; but in most countries the name has since been changed, and we believe we are right in saying that our company is the only one remaining which still bears the names of these 2 distinguished scientists."

Very truly yours,

H. A. PRICE-HUGHES
(The British Thomson-Houston Co., Ltd., Rugby, England)

Cable Failure and Dielectric Deterioration

To the Editor:

In his paper "Accelerated Aging Tests on High-Voltage Cable," appearing in ELECTRICAL ENGINEERING for June 1933, p. 371–7, D. W. Roper discusses the factors by which the quality of cables, as related to their life under service conditions, may be judged. He finds the primary criterion by which cables may be so judged to be the stability of the insulation during accelerated aging tests. That is, there should be no significant increase in power factor at maximum and minimum temperatures and no significant increase in ionization factor at room temperature (See conclusion XI, p. 376). These conclusions are in very close agreement with results obtained from accelerated life tests of cables conducted at the Harvard Engineering School.

This work was performed under the then Joint Cable Research Committee of the N.E.L.A., A.I.E.E., and A.E.I.C., of which Mr. Roper was chairman. Ten different samples in duplicate lengths from 6 different manufacturers were available for the accelerated life tests. Space permits the presentation of only a small proportion of the total results obtained. All cables were impregnated paper with 6/32 in. (4.76 mm) wall. Nos. 18 and 19T were 300,000 cir-mil copper; Nos. 23, 25, and 25T were 600,000 cir-mil copper. Nos. 25 and 25T were the duplicate lengths from one manufacturer. The samples were prepared so that the test length of sheath was 10 ft (3.05 m); in some cases it was necessary to reduce this because of failures in the sheath cuts which are necessary to give the end guards and shielding. In 2 important respects, our methods of testing were disadvantageous in comparison with Mr. Roper's. Our samples of 10 ft (3.05 m) and less are not nearly so representative as the 25 ft (7.6 m), 50 ft (15.2 m) and 1,000 ft (305 m) samples tested by him; we had no opportunity to correlate our tests with service conditions. On the other hand, it was possible for us to make complete electrical measurements at several voltages almost daily, so that electrical changes in the dielectric were followed closely. Also, the losses were separated into the solid-dielectric power and the ionization power ("Ionization Studies in Paper-Insulated Cables, II," by C. L. Dawes, H. H. Reichard, and P. H. Humphries. TRANS. A.I.E.E., v. 48, 1929, p. 382–95).

The entire 10 samples were first submitted to accelerated life tests, at room temperature only, at 42.5 kv, corresponding to an average gradient in the dielectric of approximately 225 volts per mil. Mr. Roper, under "Dielectric Power Loss," states that initial power factor tests on insulation made at the factory indicate no significant differences that can be correlated with the rate of deterioration. We found this essentially true. However, it appeared that those cables that had initially little or no ionization loss, or which reached this condition within a few hours, as a rule showed the longer lives. For example, in Fig. 1 the ionization power is plotted as a function of the life in hours. Cable 18 showed no ionization loss until after 150 hr, and its life of 785 hr by far exceeded those of the cables showing initially or subsequently substantial ionization loss.

The tests made at room temperature showed that failure might be preceded by an increase in solid dielectric power, and more frequently by an increase in ionization power. This effect is illustrated in Fig. 1

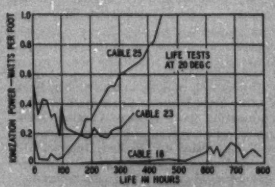


Fig. 1. Life tests at 20 deg C

which shows 3 typical ionization-power characteristics. Cable 18 showed no ionization power until after 150 hr; from 150 to 525 hr, the ionization power was very small; between 525 and 785 hr it increased in varying amounts, from 2 to 8 times its earlier values and then failed. Cables 23 and 25 had initial ionization factors of 0.43 per cent and 0.15 per cent. For some hours they both showed marked diminution in ionization power, and then rapid increase to failure.

Duplicate samples of these cables which had diverse initial characteristics were selected for accelerated life tests during which the temperature and the applied potential underwent weekly cyclic changes. The potential was varied from zero to 225 volts per mil, and the temperature from room temperature (about 20 deg C) to 60 deg C. Frequent measurements were made regularly at various temperatures during the cyclic changes, and also at various potential gradients. Although we were not able to classify our cables into low and high grades as does Mr. Roper, we found, as he did, large increase in dielectric loss sometimes varying over a wide range during the tests. This is illustrated by cable 25T in Fig. 2, which shows solid-dielectric loss per foot at 60 deg C as a function of time. We did find, however, with all the cables that survived the first few hours, a progressive increase in the solid-dielectric loss at all temperatures. The characteristic for cable 25T is given not only as an example of widely fluctuating losses, but also as an example of progressively increasing solid-dielectric loss. Cable 19T apparently was

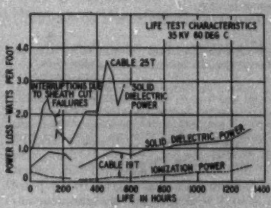


Fig. 2. Life test characteristics at 35 kv and 60 deg C

of high grade. It showed an initial ionization factor of 0.06 per cent, but a study of the ionization-power characteristic of Fig. 2 shows that this must have diminished up to 600 hr. However, this cable after 300 hr showed a progressively increasing solid dielectric loss up to the end of its life at 1,315 hr. The rate of increase of both the solid-dielectric loss and the ionization power increased as the cable approached the end of its life. All cables subjected to the cyclic temperature and voltage tests showed a progressive solid-dielectric power loss with time, whereas as a rule the increase in ionization power was not significant.

Mr. Roper mentions the rapid increase in local heating preceding failure. One of our cables failed while measurements were being made. The thermocouples on the sheath suddenly showed a rapid rise in temperature

which reached several degrees above the ambient temperature, and then failure occurred. The sheath was excessively hot over its entire length.

Mr. Roper mentions the recuperative properties of the insulation. This is illustrated in Fig. 2 for both cables, when failures in a sheath cut interrupted the life test of each cable for some hours.

It is interesting to learn that through exhaustive electrical tests it has become possible to predetermine whether or not cables can be expected to give satisfactory service performance; however, as Mr. Roper states, it is not yet possible to detect local defects before ultimate failure.

Very truly yours,

C. L. Dawes (A'12, M'15)
(Harvard University,
Cambridge, Mass.)

P. H. Humphries (A'26)
(Tulane University,
New Orleans, La.)

Rocking Indirect Arc Electric Furnaces

To the Editor:

In the January 1934 issue of Electrical Engineering, p. 132–8, is a very interesting article entitled "Rocking Indirect Arc Electric Furnaces" by E. L. Crosby. In reading this article several inaccuracies are apparent and we are taking the liberty of pointing these out. Our criticisms are as follows:

Deoxidizing Atmosphere

Under the heading "Deoxidizing Atmosphere" the statement is made that:

"In melting of nonferrous alloys such as brass or bronze, the indirect arc furnace ordinarily shows a net metallic loss in actual melting operation of only 10 to 25 per cent of the losses involved in the operation of fuel fired furnaces, which they have supplanted."

As the prospectus sheets of the Detroit Arc Furnace Company give metal losses as from 1 to 2 per cent on brass, the implication is that crucible furnaces show losses of from 4 to 20 per cent. This is certainly not the case and is quite a harmful exaggeration. Metal losses in crucible furnaces as taken from the article in *Metal Industry* (May, June, and July issues, 1933) which is an average cross section of a large amount of data on the subject, shows the true figure as being from 1 to 2.5 per cent, with extreme cases of 4 per cent for very high zinc brasses.

Under the same heading the statement is made:

"air may be introduced into this type of furnace under precise control, a feature that has been found valuable to many users."

It is not stated that when it has attempted to eliminate or reduce the objectionable carbon monoxide atmosphere with this expedient, electrode consumption may run as high as 12 to 15 lb per ton of metal melted, this adding materially to the melting cost.

Rocking Action

Under the heading "Rocking Action" the statement is made:

"it will be recognized immediately that this reaction (rocking) must effect improved thermal efficiency since it involves the transmission of refractory heat to the metal charge instead of through the refractory to be lost to the surrounding atmosphere. This insures lower power consumption."

It is true that such a rocking action produces a more efficient heat transfer, but to the reader it might wrongly imply sufficient efficiency to eclipse all other forms of melting—example figures in this regards may prove interesting:

At a consumption of 300 kwhr per ton of red brass the thermal input is 1,024,000 Btu as against 4,300,000 Btu to melt a ton of red brass with oil; however, with oil at 5 cents per gallon and electrical energy at 2 cents per kwhr the thermal cost per ton of metal melted for the oil fired crucible furnace is $1.50 versus $6.00 for the power for indirect arc furnaces.

From a metal qualitative standpoint, much objection may be raised to the generation of all the heat for melting from an arc as all the heat is liberated in a very constricted space at a temperature of plus or minus 6,000 deg F. This is not particularly harmful in the case of melting ferrous metals, but in the case of brasses and bronzes containing large percentages of low-boiling-point metals, a decided "burnt" condition may develop, which will result in a metal quality decidedly inferior for many types of foundry work.

Utilization

Under the heading of "Utilization" it is pointed out that this type of furnace enjoys very wide usage, which is quite true, but it is a fact that a large number of these furnaces have been abandoned in the brass and bronze field as per reasons given above. Valuable utilization information might be given your readers by pointing out that articles published in trade journals by the makers of this furnace acknowledge that melting costs for red and yellow brass run over $17 per ton, whereas crucible melting costs seldom exceed $10 per ton, and average under $8.

We again wish to point out that the article we are criticizing can be of considerable value to the electric power salesmen only if it does not try to encompass too many possibilities, and it is in the spirit of attempting to assist the future possibilities of electric power, as well as ourselves, that we place this information in the form of a criticism before you.

Very truly yours,

K. E. Buck
(Chairman, Technical Service
Committee, Plumbago Crucible
Assn., Philadelphia, Pa.)

To the Editor:

This letter is in reply to that by Mr. Buck of the Ross-Tacony Crucible Company representing the Plumbago Crucible Association, which was a criticism of the article by E. L. Crosby, on "Rocking Indirect Arc Electric Furnaces" appearing in the January 1934 issue of Electrical Engineering. Mr. Crosby was fatally injured in an automobile accident near Ludlow, Mass., on May 5, and it becomes my duty to answer the criticisms brought forth in this letter.

In presenting our answer we should like to do so with the utmost candor and friendliness but at the same time we wish to point out that many of Mr. Buck's statements are so far from accurate that our answer must necessarily be firm.

Metal Losses

Mr. Crosby's statement regarding metal losses was substantially correct as can be borne out by ample data available on comparative tests. The net metal losses when melting brass mixtures in Detroit Furnaces range from 0.25 per cent to 1 per cent depending upon composition, while the losses run from 2 per cent to 7 per cent in fuel fired furnaces depending upon furnace types and metal composition. We have demonstrated many times, the ability of this furnace to melt red brass in regular production with a net metallic loss of less than 0.5 per cent. We have scores of reports on comprehensive tests, made by many of our customers, showing from 0.25 per cent to 0.40 per cent metal loss. This fact has been thoroughly established over the past 15 years to the point that Mr. Crosby's statement is thoroughly justified.

Deoxidizing Atmosphere

Mr. Buck makes the erroneous assumption that the carbon monoxide atmosphere is objectionable for brass melting and that this is the reason for using air in the furnace at times. Many of the most competent brass foundry metallurgists would take hearty issue with Mr. Buck on this point. Furthermore, Mr. Crosby referred to the multiple uses of rocking electric furnaces in melting brass, bronze, cast iron, alloy steels, special alloys, and special chemical applications. In some cases it is desirable to introduce air for specific purposes and this can readily be accomplished in this furnace. Mr. Buck is further in error when he infers an electrode consumption of 12 to 15 lb per ton of brass melted. The use of air does increase the normal electrode consumption a definite amount depending upon the control established; but the highest figure that has come to our attention has been approximately half that mentioned by Mr. Buck. This was on a small furnace; on larger units the figure is still lower.

For Mr. Buck's information the conditions under which air is used in the furnace embody requirements which could not be met in crucible melting without a similar oxidizing treatment and we fail to see how, for the many specific applications we have in mind, this could be accomplished satisfactorily melting a stationary bath of metal in a crucible.

Rocking Action

I am unable clearly to follow Mr. Buck's line of reasoning in this regard. Mr. Crosby said exactly what he meant and he was correct in his statement. He intended making no hidden implications.

As to Mr. Buck's heat comparison on a British thermal unit basis, we fail to see the significance of this comparison. Looking

into his cost figures we find that he has quoted exceedingly low fuel cost figures—30 gallons of oil per ton of metal—approximately half the fuel consumption of many concerns with whom we are acquainted. On the other hand, the power cost quoted is somewhat high. Many concerns average substantially less than 300 kwhr per ton and less than the 2 cent figure quoted. This rate in Detroit, for example, is 1.2 cents per kilowatthour.

In objecting to the method of heat generation in the arc furnace, Mr. Buck overlooks the very basic design of the furnace, i. e., that the furnace is automatically rocked thus stirring the metal, effecting rapid and uniform heat distribution through the bath and thus avoiding the condition which he cites. In short, we feel that Mr. Buck was thinking back some years in terms of the Stassano or Rennerfelt or other stationary arc furnaces. Certainly there have been too many millions of pounds of metal melted in more than 400 installations of Detroit Rocking Electric Furnaces over the past 16 years and poured into castings of the highest quality to permit of any academic discussion regarding the feasibility of a method of melting which has been so thoroughly established and adopted by leaders of the industry.

Mr. Buck's cost figures should also be reversed or greatly modified. Many users of Detroit Electric Furnaces including the largest production foundries in their respective industries as well as many smaller jobbing shops are obtaining lower costs and better quality than from the fuel fired furnaces which they replaced. These economies accrue principally through

1. Lower metal losses
2. Lower labor costs
3. More efficient utilization of plant space
4. Frequent use of cheaper raw materials
5. The production of a higher percentage of finished perfect castings

Very truly yours,

A. E. Rhoads
(Vice president, Detroit Electric Furnace Company, Detroit, Mich.)

Standards

Report on Definitions in Electronics Field

While the Sectional Committee on Electrical Definitions has been actively at work since 1929, not until well along in 1933 was it deemed necessary to appoint a new subcommittee to cover the field of "electronics." This subcommittee was organized under the chairmanship of W. Wilson, of the Bell Telephone Laboratories, Inc.

In the official action creating the committee it was pointed out that literature in the electronics field is becoming somewhat muddled due to the fact that there is no standardization of nomenclature. In some cases several names (including trade names) are used to describe the same tube. It was therefore suggested that the subcommittee on electronics not only attempt the standardization of tube names, but suggest any other standardization of names and term definitions that seemed to them desirable.

The first report of this committee is now being issued in mimeographed form under a 60-day limit for comments and criticisms. It contains only that material upon which general agreement seemed to be obtainable without further delay. Other material may be added later. Only a limited number of copies of this preliminary report on "Electronics" is available. If particularly interested write H. E. Farrer, secretary, Sectional Committee on Electrical Definitions, A.I.E.E., 33 West 39th Street, New York, N.Y.

Standard Letter Symbols Under Revision

In February 1929 "Standard Letter Symbols for Electrical Quantities" was approved as American Standard by the A.S.A. This standard is now under revision. It is expected that additional symbols, for which there has been a call, will be added. At the same time there will be an additional column added to the listing of the quantities giving the names of the units.

Electrical Installations on Shipboard

A movement has recently developed abroad which may lead to an attempt to develop international rules for electrical installations on ships. The American Standards Association headquarters has been approached by General Secretary LeMaistre, of the International Electrotechnical Commission, as to the attitude of this country with regard to such an undertaking. A.S.A. referred the inquiry to the A.I.E.E. and it has been discussed both by the technical committee on applications to marine work and the standards committee. At the meeting of the latter committee on May 24, and following a report from the technical committee, an action was taken advising A.S.A. that in the opinion of the standards committee, if the work of international standardization of such rules is undertaken it should be under the auspices of the I.E.C. The Institute would be glad to offer A.I.E.E. Standard No. 45 "Recommended Practice for Electrical Installations on Shipboard" to the I.E.C. as a basis for the work. Incidentally, A.I.E.E Standard No. 45, which was developed under the auspices of the technical committee on applications to marine work is generally accepted by all the marine interests in the country, such as steamship owners, naval architects, shipbuilders, and classification and insurance associations.

Standards for Capacitors

In May 1930 the Institute issued in report form a proposed "Standard for Capacitors." This was offered to A.S.A. for approval as American Standard and on March 5, 1934, it was so approved. It is now available in pamphlet form as No. 18 in the A.I.E.E. series. Single copies can be obtained at a cost of 20 cents each, usual 50 per cent discount to A.I.E.E. members. Write H. E. Farrer, secretary, A.I.E.E. standards committee, 33 West 39th St., New York, N. Y.

Mercury Arc Rectifiers

The Sectional Committee on Mercury Arc Rectifiers in the fall of 1933 submitted a report on "Standards for Acceptance Tests of Metal Tank Mercury Arc Rectifiers." This report was approved by the Institute as sponsor in October 1933 for transmittal to A.S.A. with the understanding that the A.I.E.E. stood ready to issue it either as a report on a proposed standard or as an accepted standard in accordance with the decision of the electrical standards committee. This report came before the committee on scope and it was decided, because of the rapid changes taking place in the development of mercury arc rectifiers, to recommend that the work of the Sectional Committee be issued as a report. The report is now available in pamphlet form as A.I.E.E. Report No. 6. Copies may be obtained without charge by writing H. E. Farrer, secretary, A.I.E.E. standards committee, 33 West 39th St., New York, N. Y.

Noise Measurement Standards Developed

The work of the Sectional Committee on Acoustical Measurements and Terminology is rapidly taking form. The reports on nomenclature and on methods of measuring noise are now ready for letter ballot in the American Standards Association. The sectional committee is working under the sponsorship of the Acoustical Society of America and the chairman is Prof. V. O. Knudson, of the University of California. It was organized in January 1932, and since then 4 subcommittees have been actively working on the following subjects: Noise measurement; acoustical terminology; sound absorption and insulation; fundamental acoustical measurements. More complete details can be obtained from an article in the May 1934 issue of *Industrial Standardization* issued monthly by A.S.A.

Power Switchgear

The scope of the sectional committee on Power Switchgear (C37) has been extended to include a variety of apparatus in the general field of switchgear which was not included in the former scope. The work formerly covered included only oil circuit breakers, large air circuit breakers, disconnecting and horn-gap switches.

The new work includes high voltage fuses (above 750 volts) and the current limiting

resistors used with such fuses, metal-clad switchgear, relays directly associated with power switchgear, network protectors, switchgear assemblies including automatic switchgear, and power connectors of the type used with switchgear.

Engineering Foundation

Personnel Research Federation

In 1921 The Engineering Foundation and National Research Council jointly established the Personnel Research Federation. This organization has gained wide respect, but the slowness of comprehension by business executives of their human-relations problems, and the condition of business in general the last few years, have hindered the development of its usefulness. Now, the new conditions affecting intimate human relationships in industry and commerce are reaffirming the need for the kinds of service in which the Federation has been developing methods, inspiring research, demonstrating practical applications, and accumulating experience for 12 years.

A new president, C. G. Stoll, vice-president of the Western Electric Company, was elected in April 1934. Under his leadership steps already are being taken to strengthen the Federation for its large present opportunity.

The Federation, which has offices in the Engineering Societies Building, 33 West 39th Street, New York, N. Y., publishes the *Personnel Journal*, has a useful special reference library for members, and holds noteworthy meetings. It is believed that many engineers may find opportunities for new or enlarged services by making themselves competent to advise the clients in the human-relations field. Membership in Personal Research Federation should aid them in acquiring this knowledge.

New Secretary Elected by U.E.T.

The board of trustees of United Engineering Trustees, Inc., at its meeting of May 25, 1934, elected John Arms to be secretary to succeed Dr. Alfred D. Flinn, whose resignation was accepted at the same meeting. Doctor Flinn continues as director and secretary of The Engineering Foundation.

Mr. Arms has been general manager of United Engineering Trustees since December 9, 1933, and will continue to hold this office in addition to that of secretary. He is now the chief administrative officer for the board of trustees in caring for the Engineering Societies Building, Engineering Societies Library, and endowment funds which are held for the American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, and the American Institute of Electrical Engineers, jointly.

Mr. Arms is a member of the industrial engineering firm of Arms and Madeheim, and is a member of The American Society of Mechanical Engineers, Cornell Society of Engineers, Society of American Military Engineers, Army Ordnance Association, and The Engineers' Club of New York. He was born at Williamsport, Pa., in 1888, and now resides in East Orange, N. J. He served in the U.S. War Department, Selective Service Division, 1918.

American Engineering Council

Engineering Affairs at Washington

National projects of interest to engineers continue to follow each other with bewildering rapidity at Washington. During the last month engineers have been related to at least one field with which they have not been officially associated, namely, the Home Owners' Loan Corporation. This organization administers the distribution of some $200,000,000 to be used for modernizing and reconditioning homes. A group of 12 regional supervisors has been established, each in charge of men with background of architectural or engineering experience. Col. Paul Doty (A'04, M'12), president of The American Society of Mechanical Engineers, was appointed regional supervisor for the states of Alabama, Florida, Georgia, North Carolina, and South Carolina. Colonel Doty's headquarters will be at Atlanta, Ga. Under the regional supervisors, state organizations have been established for considering the equities involved in the applications for this remodeling development.

It is quite probable also that the broad program of housing, the details of which have not yet been made public, will bring opportunities for engineers and engineering in the follow through of the plans. This particular operation is under the general direction of Harry L. Hopkins, Federal Emergency Relief Administrator.

Secretaries of Engineering Societies Visit Washington

On Monday, June 4, 1934, at the invitation of F. M. Feiker, executive secretary of American Engineering Council, the secretaries of several national engineering societies spent the day in Washington, D. C., contacting the government department which had the most direct relations to engineers and engineering developments. George T. Seabury, American Society of Civil Engineers; A. B. Parsons, American Institute of Mining and Metallurgical Engineers; C. W. Rice and C. E. Davies, The American Society of Mechanical Engineers; and H. H. Henline, American Institute of Electrical Engineers, were present.

During the day there were visited in order, the Department of Labor, the Department of Interior, the N.R.A., the Russian Embassy, and the Department of Commerce. In addition, John Frey, vice-president of the American Federation of Labor, and member of the labor advisory board of the N.R.A., met with the secretaries; at the luncheon meeting, the Honorable Frederick A. Delano, chairman of the National Planning Board and Mr. Charles Eliot II, executive officer of the National Planning Board, were present; at dinner the presidents and secretaries of the local sections of the respective engineering organizations were in attendance. At the various meetings and in the departments of the government which were visited, individuals in authority and well acquainted with many phases of governmental activity, contributed valuable information to the secretaries. The day's visits with the administration officials were closed with a half hour's conference with Daniel C. Roper, secretary of commerce.

Many specific suggestions for the active utilization of engineering ability in the affairs of the government and of stimulating coöperation among engineers, were introduced.

Engineers Active at Meeting of U.S. Chamber of Commerce

At the recent annual meeting of the U.S. Chamber of Commerce, Harrison P. Eddy, president of the American Society of Civil Engineers, presented a paper entitled "An Engineering Analysis of the Public Works' Program" at the round table conference on problems and progress in regional and city planning. Several other men, prominent in engineering circles, participated in the program, and at the annual dinner, the engineers were recognized professionally in the persons of J. F. Coleman, president of American Engineering Council, and by Mr. Eddy. This is considered further evidence of the increasing public recognition of the engineer in relation to national policy and national development.

Referendum on Public Works Expenditures

During May 1934, at the request of J. F. Coleman, president of American Engineering Council, and as the result of a mail vote by the executive committee, 2 questions were submitted to Council concerning the policy of Council in regard to public works. The questions are as follows:

1. Do you approve of Council actively supporting in any legitimate way the various proposals to extend credit for the development of private construction enterprise based upon the requirement of adequate security?

   Yes.....31
   No.....2

2. Shall Council support a movement to obtain additional P.W.A. Funds?

   Yes.....20
   No.....13

Personal Items

K. S. Wyatt (A'32) research engineer, Detroit Edison Co., Detroit, Mich., with his co-authors E. W. Spring (A'26, M'32) and C. H. Fellows, has been awarded the 1933 A.I.E.E. national prize for initial paper for the contribution "A New Method of Investigating Cable Deterioration and Its Application to Service Aged Cable." Mr. Wyatt was born in Cambridge, Mass., in 1900. He first studied engineering at Mount Allison University, Sackville, New Brunswick. After completing the unified 2-year course, he majored in physical chemistry, obtaining the degree of B.A. in 1921 and the degree of B.Sc. with honors in chemistry in 1922, and was an instructor in physics in 1921. After a year of graduate work in physical chemistry at Harvard University he joined the Carborundum Company, Niagara Falls, N. Y., as assistant research chemist. In the fall of 1923 he accepted a scholarship from the National Research Council of Canada, and attended the University of Toronto, where he was engaged in research on "Supersaturation of Gases in Liquids." Mr. Wyatt joined the research department of the Detroit Edison Company in 1928, and has specialized in the study of the deterioration of high voltage insulation. Mr. Wyatt is a member of the Edison medal committee of the Institute, and is also a member of the American Chemical Society; he has prepared several papers for technical publications.

E. W. Spring (A'26, M'32) research engineer, Detroit Edison Co., Detroit, Mich., with his co-authors K. S. Wyatt (A'32) and C. H. Fellows, has been awarded the 1933 A.I.E.E. national prize for initial paper for the contribution "A New Method of Investigating Cable Deterioration and Its Application to Service Aged Cable." Mr. Spring was born in New Haven, Conn., in 1903. He graduated from the Sheffield Scientific School, Yale University, in 1924 with the degree of B.S. in E.E. He then entered the operating department of the Detroit Edison Company, and in 1929 joined the research department staff, taking charge of the electrical division of the research laboratory, where he has been particularly concerned with underground cable.

F. H. Gulliksen (A'29) an electrical engineer for the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been awarded the 1933 A.I.E.E. national prize for best paper in engineering practice. The title of his prize winning paper is "The Principle of Condenser Discharge Applied to Central Station Control Problems." He was born in Oslo, Norway, in 1901. In 1924 he graduated from the Norwegian Institute of Technology at Trondhjem, Norway, having worked for the hydroelectric commission of Norway during summers. He was employed at Elektrisk Bureau, Oslo, during 1925 as designer of radio and telephone apparatus. In December of that year he came to the United States and entered the graduate student course of the Westinghouse company, and in 1927 entered the regulator section of the supply engineering department. Since 1928 he has been in the regulator section of the control engineering department, engaged in the development and design of electronic regulators and industrial control equipment. A recent paper by Mr. Gulliksen, "Electronic Regulator for A-C Generators," is given on p. 877 of the June 1934 issue of Electrical Engineering.

J. Allen Johnson (A'07, F'27, and vice president) chief electrical engineer of the Buffalo, Niagara and Eastern Power Corporation, Buffalo, N. Y., has received honorable mention in the 1933 A.I.E.E. national prize awards for his paper in engineering practice, "Operating Aspects of Reactive Power." Mr. Johnson has been engaged in power generation work since his graduation from Worcester Polytechnic Institute in 1905, and was responsible for many important features of the electrical design of the Niagara developments following 1918. He was appointed to his present position in 1929. Mr. Johnson is president-elect of the Institute, and a more complete biography is given on p. 230 of the January 1934 issue of Electrical Engineering.

W. R. Smith (M'18, F'30) assistant chief engineer, United Engineers and Constructors, Inc., Newark, N. J., has been elected chairman of the New York Section of the Institute.

W. S. Gorsuch (A'07, M'17) engineer of economics, Interborough Rapid Transit Company, New York, N. Y., has been elected secretary-treasurer of the New York Section of the Institute.

R. H. Hughes (A'20, M'30) assistant vice president, New York Telephone Company, New York, N. Y., has been elected to membership on the executive committee of the New York Section of the Institute.

J. A. Scott (A'25) electrical engineer, General Electric Company, Schenectady, N. Y., represents the Institute on the new sectional committee on electrical insulating materials of the A.S.A.

Gabriel Kron (A'30) is now with the General Electric Company at Schenectady, in the engineering general department. He was formerly consulting engineer for the United Research Corporation, Long Island City, N. Y.

D. T. May (M'28) materials engineer, Bell Telephone Laboratories, Inc., New York, N. Y., represents the telephone group of the A.S.A. on its new sectional committee on electrical insulating materials.

D. L. Smith (M'27) electrical engineer, Chicago Rapid Transit Company, Chicago, Ill., represents the American Transit Association on the new sectional committee on electric insulating materials of the A.S.A.

H. L. Curtis (A'21, F'26) principal physicist, U.S. Bureau of Standards, Washington, D. C., was elected chairman of the new sectional committee on electric insulating materials of the A.S.A., and represents the Bureau of Standards.

R. J. Coe (A'30) has been appointed assistant electrical engineer of the New England Power Association, Boston, Mass.

A. L. Maillard (M'23) has been appointed head of the new air-conditioning department of the Kansas City Power and Light Company, Kansas City, Mo.

W. R. G. Baker (A'19) has recently been appointed vice president and general manager of the RCA-Victor Company, Harrison, N. J.

R. H. Dearborn (A'07, F'30) formerly head of the electrical engineering department of Oregon State College at Corvallis, has been appointed acting dean of the school of engineering.

K. S. WYATT

E. W. SPRING

F. H. GULLIKSEN

W. W. Lackie (F'16) will retire from the British Electricity Commission, London, England, in July 1934.

G. H. Dunstan (A'28) has been promoted from the position of instructor to assistant professor of general engineering at the University of Southern California, Los Angeles, Calif.

A. M. Chitty (M'22) has been appointed western district manager at Bremerton, Wash., for the Puget Sound Power and Light Company. He was formerly manager of the company's southwestern district.

G. H. Bucher (M'24) has been elected president of the Westinghouse Electric International Company and will continue in his duties as general manager. Since 1932 he had been vice president of the company.

Obituary

Paul Sussan (A'24) designer and draftsman for the New York Edison Company, died on April 17, 1934, in New York, N. Y. He was born in Riga, Latvia, April 8, 1880, and attended the Realgymnasium, Mitau, Russia, the University of Bern, Switzerland, and the Polytechnicum Cöthen, Germany, receiving the electrical engineering degree from the last named in 1903. He was assistant engineer in industrial installation work for Fischer and Company of Berlin from 1903 to 1904. From 1905 to 1917 he was engaged in designing of electrical apparatus for the General Electric Company at the Schenectady and Pittsfield works. From 1917 to 1920 he was employed by the Interborough Rapid Transit Company of New York City as draftsman, checker, and squad leader. From 1920 on he worked for the New York Edison company, preparing drawings and wiring diagrams for power houses and substations. In 1924 he was graduated from the Columbia University School of Optometry with the degree of doctor of optometry, and he practiced optometry for some years.

Murray J. Idail (A'19, M'24) manager of the engineering department of the Virginia Public Service Company at Charlottesville, Va., since 1929, died on March 10, 1934. He was born March 18, 1897, at Baltimore, Md., and was educated in the public schools there, and at the Preparatory School at Old Point Comfort, Va., and the Catholic University of America, Washington, D. C., receiving the B.S. degree in electrical engineering from the university in 1917. From 1914 to 1915 he took a student course in the gas and central stations departments of the Newport News and Hampton Railway, Gas and Electric Company at Hampton, Va. From 1918 to 1919 he was in charge of electrical design of all the Navy Department work which was assigned to Mr. F. R. Weller, consulting engineer. He did important work in designing power stations, heating plants, fuel oil plants and distribution systems for the navy yards at New Orleans, Norfolk, Philadelphia, New London, and Portsmouth. From 1919 to 1924 he was engineer in charge of the electrical department of Mr. Weller's concern. This work entailed designing and installing central stations, outdoor substations, transmission lines, etc. In 1924 he had charge of the design and construction of the first step of a 125-mile 110,000-volt tower line, with substations.

Grenville A. Harris (A'01) export manager, engineer, for Black Clawson Company, New York, N. Y., died January 31, 1934. He was born at Elizabeth, N. J., December 24, 1878. He attended Hackettstown Institute, Hackettstown, N. J., and Stevens Institute of Technology, receiving the M.E. degree from the latter. After taking the student course of the Westinghouse Electric and Manufacturing Company at Pittsburgh, Pa., he became construction engineer for the company and had charge of the erection of a number of important plants. From 1901 to 1916 he was resident engineer in charge of the electrical and mechanical work of Takata and Company, agents of the Westinghouse organization for Japan. From 1916 to 1921 he was chief engineer for the American Steel Export Company, having charge of the construction of steel plants. In 1921 he became export manager engineer, for Black Clawson Company, holding that position at the time of his death. During the Spanish-American War he was electrician, second class, on the U. S. S. Vixen, and he was awarded a war Medal for his services during the engagement of July 3, 1898. He was a member of The American Society of Mechanical Engineers.

Shizuo Kato (A'08) president of The Institute of Electrical and Mechanical Technology, Nishikicho, Nichome, Kanda, Japan, died recently according to word received at Institute headquarters from Michihiko Hatori (A'18), director of the Japanese institution. Mr. Kato was born November 8, 1880 at Tokyo, Japan, and was graduated from the electrical engineering department of the college of engineering of Tokyo Imperial University in 1904. After leaving college he became electrical engineer engaged in designing with the Nitsubishi Dockyard and Engine Works, manufacturers of electrical machinery, at Kobe, remaining with that firm for 11 years. In 1915 he became associated with The Institute of Electrical and Mechanical Technology, acting as editor, principal, director, trustee, and president.

Marion Brown Lines (A'31) engineer's assistant for The Mountain States Telephone and Telegraph Company, Colorado division, died April 9, 1934, in Denver, from injuries received in an automobile accident April 4. He was born at Neodesha, Kansas, January 26, 1902. In 1923 he graduated from the University of Kansas with a degree in mechanical engineering. In 1924 he began his work with The Mountain States Telephone and Telegraph Company in Colorado Springs in the construction and installation fields. In 1928 he was an assistant to the transmission and protection engineer for Colorado, becoming transmission engineer for The Mountain States Telephone and Telegraph Company in 1930. He was a first lieutenant of engineers of the Organized Reserves.

Minor Meek Davis (A'86, M'93, F'12, member for life) electrical engineer with the Postal Telegraph-Cable Company, New York, N. Y., for about 24 years, died on April 13, 1934. He was born March 28, 1858, at North Chatham, Mass., and attended the Coffin School at Nantucket, Mass. After a few years in the electrical departments of the Bankers and Merchants and United Lines companies, he entered the employ of the Postal Telegraph-Cable Company as assistant electrical engineer, becoming electrical engineer in 1907 and holding that position until 1920. He became a consulting engineer in 1920, retiring in 1925 at the age of 67.

Otto Tomas Gierisch (A'07) draftsman, died a few months ago, according to word received recently at Institute headquarters from his brother. He was born on August 13, 1882, in New York, N. Y., and was educated at Stevens Institute of Technology and at Brooklyn Polytechnic Institute. He was draftsman for a short time with the Safety Car Heating and Lighting Company, and draftsman with the Brooklyn Rapid Transit Company for a number of years following 1906.

Membership

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before July 31, 1934, or Sept. 31, 1934, if the applicant resides outside of the United States or Canada.

Allan, I. F., City Hall, Toronto, 2, Can.
Barlow, P. McG., Hygrade Sylvania Corp., Emporium, Pa.
Bianchi, P., N. Y. Tel. Co., N. Y. City.
Bowen, A. R., Bell Tel. Lab., N. Y. City.
Byrd, E. C., N. Y. Edison Co., N. Y. City.
Caughman, C. D., Federal Bank, Columbia, S. C.
Clare, C. F. (Member), Associated Elec. Lab. Inc., Chicago, Ill.
Dueley, R. L., Streamstown, Alberta, Can.
Dunn, J., Waite & Bartlett X-Ray Co., Cleveland, Ohio.
Dye, J. R., Phila. Elec. Co., Pa.
Edwards, L. T., R. & H. Chemical Co., Niagara Falls, N. Y.
Eggert, W. C., Public Utilities Commission, San Francisco, Calif.
Ekstrom, E. J., Hygrade Sylvania Corp., Clifton, N. J.
Evans, M. F., Wright-Hargreaves Mines, Kirkland Lake, Ont., Can.
Fleming, J. R., Univ. of Tennessee, Knoxville, Tenn.
Goldie, M. McL., 218 McDowall Bldg., Seattle, Wash.

Halloran, J. J., U. S. Engr. Office, Havre, Mont.
Hammond, R. H., Route 1, Box 530 National City, Cal.
Harvey, O. J., Milwaukee Elec. Railway & Light Co., Wis.
Howse, S. E., Westinghouse X-Ray Co., Los Angeles, Calif.
Kopf, F. J., N. Y. Edison Co., N. Y. City.
Kuder, A. S., Wash. Water Power Co., Spokane, Wash.
Latta, A., Stanton Operating Co., Pittston, Pa.
Lindberg, C. A., United Elec. Mfg. Co., Adrian, Mich.
Lomax, C. E. (Member), Associated Elec. Lab. Inc., Chicago, Ill.
Lynch, M. B., Bureau of Standards, Washington, D. C.
Mahoney, H. P. (Member), Associated Elec. Lab. Inc., Chicago, Ill.
McMaine, T. F., Western Union Tel. Co., Wichita Falls, Texas.
Nelson, M. L. (Member), Associated Elec. Lab. Inc., Chicago, Ill.
Newell, N. A. (Member), Bell Tel. Lab., N. Y. City.
Nunez, J. M., Hart Enterprise Elec. Co. Inc., New Orleans, La.
Patterson, R. T. L., Bell Tel. Lab. Inc., N. Y. City.
Pratt, M. H. (Member), Niagara Hudson System, Syracuse, N. Y.
Richards, E. L. (Member), Coyne Elec. School, Chicago, Ill.
Richards, L. J., East Bay Municipal Utility Dist., Oakland, Calif.
Salveson, S. R., N. Y. Hospital, N. Y. City.
Stallings, C. F., Amer. Tel. & Tel. Co., Atlanta, Ga.
Stinchfield, J. M., RCA Radiotron Co. Inc., Harrison, N. J.
Takahashi, Y., 63 W. 124th St., N. Y. City.
Teague, H. S. H., 34 West 138 St., N. Y. City.
Walker, J. E. L., 62 Stibbard Ave., Toronto, 12, Ont., Can.
Westland, F. J., Gen. Elec. X-Ray Corp., N. Y. City.
Williams, A. D., General Cable Corp., San Francisco, Calif.
Willick, F. J., 195 N. Vidal St., Sarnia, Ont., Can.
Zarcodny, S. J., 1984 Yale Station, New Haven, Conn.

48 Domestic

Foreign

Dey, R. B., Siemens Schuckert Werke, A. G., Berlin, Germany.
El-Kadhdry, M. A. B., Metropolitan Vickers Elec. Co. Ltd., Manchester 17, England.
Grobler, P. S., P. O. Box 16, Rustenburg, South Africa.
Krishnaswami, P. M. (Member), Andhra Engg. Co. Ltd., Vizagapatam, South India.

4 Foreign

Recommended for Transfer

The board of examiners, at its meeting of June 20, 1934, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Member

Althouse, Ernest E., div. operating supt., Central Hudson Gas & Elec. Corp., Kingston, N. Y.
Bardewyck, Arthur H., transm. and distr. engr., Cia. Interprovincial de Servicios Publicos, Buenos Aires, Arg., So. Am.
Bell, Delamar T., member of tech. staff, Bell Tel. Labs., Inc., N. Y. City.
Cannon, Wm. D., E.E., Western Union Tel. Co., N. Y. City.
Church, Oliver A., dist. mgr., Niagara Lockport & Ontario Pwr. Co., Batavia, N. Y.
Cramer, Clifford H., engr., Western Union Tel. Co., N. Y. City.
Faigle, Charles A., distribution engr., Central Hudson Gas & Elec. Corp., Poughkeepsie, N. Y.
Fishman, Solomon, asst. prof. of industrial engg., Newark Col. of Engg., Newark, N. J.
Fisk, Walter B., jr., asst. inside plant engr., Bklyn. Edison Co. Inc., Bklyn., N. Y.
Foss, H. Marcus, asst. engr. of equipment, Bell Tel. Co. of Pa., Pittsburgh.
Knapp, Floyd H., field engr., Bell Tel. Labs., Inc., New York.
Ku, Yu-Hsiu, dean of engg. college, National Tsing Hua University, Peiping, China.
Moffitt, Lamont E., asst. supt. of distribution, Bklyn. Edison Co., Bklyn., N. Y.
Poole, Robert R., member of technical staff, Bell Tel. Labs., Inc., New York City.
Salsbury, Raymond J., supt. of substation operations, Duquesne Light Co., Pittsburgh, Pa.
Sanford, Frank E., distribution engr., Union Gas & Elec. Co., Cincinnati, Ohio.
Skilling, Hugh H., instructor in elec. engg., Stanford University, Calif.
Watz, Erik J., sales engr., Gen. Elec. X-Ray Corp., New York City.

18 to Grade of Member

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Brayman, Chas. E., c/o J. J. Murphy & Son, 38 Ford St., Hartford, Conn.
Gilliam, Charles T., Power Cost Engg. Co., 742 Milam Bldg., San Antonio, Texas.
Goulding, Harold, 404 W. 116th St., New York, N. Y.
Gray, L. Tenney, Jr., 6452 Hillegas Ave., Oakland, Calif.
Henrichsen, E. E., Bell Tel. Labs. Inc., 463 West St., New York, N. Y.
McNitt, Donald P., 1009 First Natl. Life Bldg., St. Louis, Mo.
Miller, Frank D., Box 34, Yatesboro, Pa.
O'Hanlney, Joseph A. E., 57b—61st St., Bklyn., N. Y.
Patton, Edgar P., Standish Arms, 169 Columbia Heights, Bklyn., N. Y.
Tambuscio, G., 307 West 20th St., N. Y. City.
Thompson, B. F., Minas de Matahambre, Matahambre, Pinar Del Rio, Cuba.
Valier, Chas. E., Jr., 1804 Tel. Bldg., St. Louis, Mo.
Villegas, Tacoma General Hospital, Tacoma, Wash.

13 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

CALCULATION and DESIGN of ELECTRICAL APPARATUS. By W. Wilson. Lond., Sir Isaac Pitman & Sons, Ltd., 1934. 214 p., illus., 7x5 in., cloth, $3.00. Aims to provide a general, brief exposition of the principles that govern the calculation and design of switchgear, control gear, protective equipment, instruments and similar apparatus, as distinct from electrical machines and transformers. The work is presented in a practical manner.

DESIGN and USE of INSTRUMENTS and ACCURATE MECHANISM. By T. N. Whitehead. N. Y., Macmillan Co., 1934. 283 p., illus., 9x6 in., cloth, $3.50. While intended primarily for designers and users of instruments, many of the principles involved are applicable to mechanism as a whole, and especially to light machinery, such as carburetors and magnetos, governors, components of textile machinery and printing presses. The author discusses various types of errors which may be present, their causes and methods by which they may be remedied.

EINFÜHRUNG in die PHYSIK der GASENTLADUNGEN. By R. Seeliger. 2 ed. Leipzig, Johann Ambrosius Barth, 1934. 503 p., illus., 9x6 in., paper, 46 rm.; bound, 48 rm. A summary of our knowledge of the discharge of electricity in gases. Provides an account of the work done in this field, which is well designed to orient the worker concerning the latest discoveries.

(The) ELECTRIC HOME. By E. S. Lincoln and F. C. Smith. N. Y., Elec. Home Pub. Co., 1933. 454 p., illus., 9x5 in., paper $1.00; cloth, $2.00. A popular description of the ways in which electricity may be used in the home. Advice is given upon indoor and outdoor lighting, electric appliances, wiring, etc. The book suggests many uses that are unfamiliar to most laymen.

ELECTRICAL TECHNOLOGY. By W. J. Harwood. Phila., J. B. Lippincott Co., 1934. 347 p., illus., 8x5 in., cloth, $5.00. Designed to meet the requirements for the graduateship examination of the Institution of Electrical Engineers (Great Britain); and intended for students familiar with the elements of magnetism and electricity. The fundamental theory, particularly a-c theory, has been emphasized and special attention is given to the development and use of vector diagrams.

ENTSTAUBUNGS- und LÜFTUNGFRAGEN in der WERKSTATT. By R. Nagel. Berlin, VDI-Verlag, 1934. 31 p., illus., 8x6 in., paper 1.80 rm. Presents the fundamentals of factory ventilation and dust removal in a concise, practical way. It is intended to give the factory manager a general view of the subject which will enable him to devise methods for his own needs.

Great Britain. Dept. of Scientific and Industrial Research. INDEX to the LITTERATURE of FOOD INVESTIGATION. V. 5, No. 1, March, 1933, and No. 2, Sept., 1933. Lond. His Majesty's Stationery Office, 1934. 283 p., 10x6 in., paper, 5s. (Obtainable from the British Library of Information, New York, $1.43.) Approximately 100 periodicals are covered by this index, in addition to patents, books and reports. Brief abstracts and an author index are included, as well as an introductory review of developments during 1931 and 1932. The engineering section contains 366 references on temperature and humidity control, methods of food transport, insulation, refrigeration, air conditioning and gas producing.

Great Britain. Dept. of Scientific and Industrial Research. (Radio Research Report No. 14.) MAGNETIC MATERIALS at RADIO FREQUENCIES, by F. M. Colebrook. Lond., His Majesty's Stationery Office, 1934. 22 p., tables, 10x8 in., paper, 6d. (Obtainable from British Library of Information, N. Y., $17.) This brief survey covers present theoretical and experimental knowledge of iron-powder materials for coil cores. The available data about permeability, hysteresis, retardation loss and other losses are given, with a selected bibliography.

HANDBOOK of TECHNICAL INSTRUCTIONS for WIRELESS TELEGRAPHISTS. By H. M. Dowsett. 5 ed., rev. & enl. Lond., Iliffe & Sons, Ltd., 1934. 472 p., illus., 9x5 in., cloth, 15s. A theoretical course for students wishing to qualify for the certificate of proficiency granted by the postmaster general of Great Britain. The principles and practice of radio telegraphy are covered. While intended primarily for sea-going operators, the book will be useful to amateurs as well.

HISTORY of MATHEMATICS in AMERICA BEFORE 1900. (The Carus Mathematical Monographs No. 5). By D. E. Smith and J. Ginsburg. Chicago, published by Mathematical Assn. of Am. with the cooperation of the Open Court Pub. Co., 1934. 209 p., illus., 9x5 in., cloth, $2.00. A brief, readable survey of our mathematical achievements during the past, by a foremost American authority. The development of means for the study of mathematics, the influence of other countries, mathematical societies and periodicals and the achievements of prominent students are considered.

IMPACT TESTING of CAST IRON. Report of Subcommittee XV of Committee A-3 on Cast Iron. Phila., Am. Soc. for Testing Materials, 1934. 31 p., illus., 9x6 in., paper, $.50. This report by a committee of the A.S.T.M. discusses the usefulness of the several forms of impact test as applied to cast iron. An extensive program of tests formed the basis for the report, which contains the results and the conclusion of the committee.

INDUSTRIALIZED RUSSIA. By A. Hirsch. N. Y., Chem. Cat. Co., 1934. 309 p., illus., 8x6 in., cloth, $3.00. Presents pertinent facts about the present status of the chemical, metallurgical, agricultural, and other industries, and discusses business, government, law, living conditions, education, etc. A factual report by a sympathetic observer.

INTRODUCTION to MODERN PHYSICS. By F. K. Richtmyer. 2 ed. N. Y. & Lond., McGraw-Hill Book Co., 1934. 747 p., illus., 9x6 in., cloth, $5.00. Based upon lectures given at Cornell University to meet the needs of students who wish a survey of the origin, development, and present status of physics. Discusses the electromagnetic theory of light, the quantum theory, atomic structure, X rays, the wave theory of matter and other important developments.

MODERN POLYPHASE INDUCTION MOTORS, particularly those with Various Types of Single and Double Squirrel-Cage Rotors; tr. from the German by H. M. Hobart. By F. Punga and O. Raydt. Lond., Sir Isaac Pitman & Sons, 1933. 289 p., illus., 9x5 in., cloth, $5.00. Not a general textbook on the induction motor, but a discussion of the merits and advantages of the squirrel-cage type. The special windings and constructions that have been brought forward at various times to remedy the low starting torque of the type are reviewed.

Industrial Notes

Large Steel Mill Order to Westinghouse.—Amounting to nearly a million dollars, the largest single order for steel mill electrical equipment since 1929 was awarded to the Westinghouse Electric & Mfg. Company by the Mesta Machine Company. The electrical equipment, consisting of motors, control material, motor-generator sets, and auxiliary units, will be installed on a 76 inch strip mill being built by Mesta for the Youngstown Sheet & Tube Company. Wide strip steel, produced in the new mill, is used for automobiles but has a variety of other uses. Included in the order will be six 3,500 horsepower motors. Work on the order has begun in East Pittsburgh and it will be completed in less than six months.

New Consulting and Research Association.—According to a recent announcement 5 research engineers formerly employed in the Westinghouse research laboratories have formed a new company known as the Consulting and Research Association, at 823 Franklin Ave., Wilkensburg, Pa. The purpose of this organization is to provide a consulting, research, and development service to manufacturing companies. This organization includes research engineers who have specialized in the following subjects: air conditioning, heating, and ventilation, construction and application of electronic devices, oscillographs, television, electric circuits, radiography, mechanical design and application, and plant survey and layout. The need for such an organization, particularly for short time research problems confronting manufacturing companies without laboratory facilities, has long been recognized.

Delta Mfg. Co. Joins Raytheon.—Announcement has been made that the Delta Mfg. Co., formerly of Cambridge, Mass., makers of Acme-Delta transformers, chokes, and power equipment for radio amateurs, Delta high voltage rectifiers for broadcast stations, Delta voltage regulators, and other special power conversion equipment, has jointed the Raytheon Mfg. Co. The activities of the combined companies will be carried on under the name of Raytheon Mfg. Co., Electrical Equipment Division, in a newly acquired plant at 190 Willow St., Waltham, Mass. There has been no change in the Delta organization and all products formerly made by them will now continue to be manufactured by the same personnel and sold by Raytheon's electrical equipment division. In addition, new types of rectifying apparatus for converting alternating current into direct current are being designed to permit the use of rectifiers in industrial applications where previously only motor generators or storage batteries could be used. The Raytheon Production Corp., Raytheon Tube Division, continues as before with its manufacturing plant at Chapel St., Newton, Mass.

Single-Step Voltage Booster.—A low priced, pole mounted booster which automatically changes a feeder's voltage either 5% or 10% in a single step has been announced by the Westinghouse Electric & Mfg. Co. This new type B feeder voltage booster is particularly suitable for maintaining proper voltage for rural lines, isolated loads, or distribution circuits where the load changes once or twice daily from very light to practically full load.

New Across-the-Line Motor Starter.—The Electric Controller & Mfg. Co., Cleveland, O., announces type ZO, weather-proof and dust-tight, across-the-line, oil-immersed motor starter for motors up to 15 hp., 220 volt, and 30 hp., 440–550 volts. The starter is arranged for remote control, push button automatic operation. When desired, a self-contained ammeter in a dust-tight case is also furnished with the starter.

Combination Tester and Fuse Puller.—The Ideal Commutator Dresser Co., Sycamore, Ill., has developed a combination "Test-lite" and fuse puller. Made of reinforced Bakelite and resembling a pair of pliers, this new device combines a tool for testing, removing, or inserting fuses from 30 to 100 amperes, testing circuits of from 110 to 550 volts, and handling all types of current carrying electrical parts. The test pins are mounted on handle ends—opening or closing handle adjusts the pins to proper distance. The test light is enclosed in the handle. The tool is of pocket size, 7 inches long.

Trade Literature

Motors.—Bulletin 2173, 4 pp. Describes type AR squirrel cage induction motors, 1 to 75 hp. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Carbon Brushes.—Catalog 634. Describes brushes for single-phase and fractional horse-power motors. Helwig Co., 3466 S. 13th St., Milwaukee, Wis.

Aerial Cable.—Bulletin, 4 pp. Describes rubber insulated metallic and non-metallic sheathed aerial cable for overhead lines. General Cable Corp., 420 Lexington Ave., New York.

Street Lighting Cable.—Bulletin, 4 pp. Describes series street lighting cable, rubber insulated, "Thiokol" sheathed. General Cable Corp., 420 Lexington Ave., New York.

Laminated Bakelite.—Booklet describes laminated Bakelite in sheet, rod, tube, and other fabricated form. A distinctive feature of this booklet is that it contains actual samples of the material, enclosed in envelopes. The Synthane Corp., Oaks, Pa.

Battery Charging Rheostats.—Bulletin 2501, 4 pp. Describes battery charging rheostats and resistors, particularly suited for use where a number of different types of batteries are to be charged from the same direct current source. Prices are included. Ward Leonard Electric Co., Mt. Vernon, N. Y.

Transformer Manufacturer Moves.—The R. E. Uptegraff Mfg. Co., manufacturers of high-voltage power transformers, have moved to 300 N. Lexington Ave., Pittsburgh, Pa., where more than double the floor area of their former plant is provided. Recent production has necessitated double shifts.

Air Hoists.—Bulletin 12107, 32 pp. Describes "Utility" air hoists. The single-drum hoists are available in 10 sizes with capacities up to 2,000 lbs. straight line pull. The double-drum hoists are built in 4 sizes up to 2,000 lbs. capacity. A single lever controls all movements of the hoist. Ingersoll-Rand Co., 11 Broadway, New York.

Portable Instruments.—Bulletin 7, for catalog 123, 4 pp. Describes a new line of portable measuring instruments, types NPD and NPA, for general testing purposes. The NPD line includes direct current ammeters, voltmeters, milli-voltmeters and milli-ammeters of all ranges. The NPA types are a companion line of alternating current instruments. Roller-Smith Co., 233 Broadway, New York.

Insulated Cable.—Bulletin GEA-1837, 80 pp., "How to Select Insulated Cable." The more usual applications of cable are covered and there is presented in convenient form the information required for determining the cable best adapted for any particular installation. Two methods of selecting conductor size are given. The first, a comparatively simple one, covers cable for wiring buildings, small industrial plants, etc. The other method, more detailed, includes 27 tables of current-carrying capacities. General Electric Co., Schenectady, N. Y.

Lightning Arresters.—Bulletin 375, 100 pp. Describes Crystal Valve lightning arresters for both high and low voltage a-c service and for low voltage d-c service; tank type arresters, neutral arresters and coördinating gaps; Garton-Daniels lightning arresters for low voltage a-c and d-c service and for high voltage d-c railway service; ground testing equipment and ground fittings. Much technical information on the subject of lightning protection is included. Electric Service Supplies Co., 17th & Cambria Sts., Philadelphia, Pa.

Underground Conduit.—Bound data sheets, 12 pp., on the recently announced Transite electrical conduit, made of asbestos fiber and portland cement. The material is fireproof, highly corrosion-resistant and immune to electrolysis. Because of its unusually high mechanical strength it can be used as a cable subway without concrete covering. The sheets include full information on sizes, weights, and list prices, details and dimensions of fittings, illustrations of installation methods, etc. Johns-Manville, 22 E. 40th St., New York.

Published Monthly by

American Institute of Electrical Engineers

(Founded May 13, 1884)

Electrical Engineering

Registered U. S. Patent Office

August 1934
Volume 53
No. 8

The Official Monthly Journal and Transactions of the A.I.E.E.

J. Allen Johnson, President
H. H. Henline, National Secretary

Publication Committee

Publication Staff
G. Ross Henninger, Editor
C. A. Good, Advertising Manager

PUBLICATION OFFICE, 20th and Northampton Streets, Easton, Pa.

EDITORIAL AND ADVERTISING OFFICES, 33 West 39th Street, New York, N. Y.

ENTERED as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918.

SUBSCRIPTION RATES—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii and the Philippine Islands, Central America, South America, Haiti, Spain and Spanish Colonies; $13 to Canada; $14 to all other countries. Single copy $1.50.

CHANGE OF ADDRESS—requests must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered due to incorrect address cannot be replaced without charge. Be sure to specify both old and new addresses and any change in business affiliation.

ADVERTISING COPY—changes must be received by the fifteenth of the month to be effective for the issue of the month succeeding.

STATEMENTS and opinions given in articles appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters.

REPUBLICATION from "Electrical Engineering" of any institute article or paper (unless otherwise specifically stated) is hereby authorized provided full credit be given.

COPYRIGHT 1934 by the American Institute of Electrical Engineers.

ELECTRICAL ENGINEERING is indexed in Industrial Arts Index and Engineering Index.

Printed in the United States of America. Number of copies this issue—

16,500

This Month—

Front Cover

"Temple of Osiris" in Bryce Canyon, a scenic attraction in southwestern Utah, which will be conveniently available to those attending the Institute's 1934 Pacific Coast convention at Salt Lake City

Educational Series—No. 8

Fundamental Laws of Photoelectricity . . 1149
By A. L. HUGHES

Special Features

A Message From the President . . . 1142
By J. ALLEN JOHNSON

The Institute on its 50th Anniversary 1143
By J. B. WHITEHEAD

Toward the Making of a Profession . . 1146
By WILLIAM E. WICKENDEN

Analytical Representation of a Magnetizing Curve 1186
By A. VAN NIEKERK

A.I.E.E. Papers

Television by Electronic Methods . . 1153
By A. H. BROLLY

Simplified Measurements of Sound Absorption 1160
By ARTHUR L. ALBERT and TOM B. WAGNER

Theory and Tests of the Counterpoise 1163
By L. V. BEWLEY

Characteristics and Uses of the Carbon Arc 1173
By W. C. KALB

Lightning Investigation on Transmission Lines—IV 1180
By W. W. LEWIS and C. M. FOUST

Lightning Investigation on a 220-Kv System 1188
By EDGAR BELL

Lightning Performance of 132-Kv Lines 1195
By PHILIP SPORN and I. W. GROSS

Incandescence—Some Theoretical Aspects 1201
By SAMUEL G. HIBBEN

Low Pressure Gaseous Discharge Lamps—Part I 1204
By SAUL DUSHMAN

Insulator Surface and Radio Effects 1213
By W. A. HILLEBRAND and CHARLES J. MILLER, Jr.

The Insulator String 1221
By R. W. SORENSEN

News of Institute and Related Activities 1225

50th Annual Summer Convention Held at Hot Springs, Va. 1225

Last Call for the Pacific Coast Convention 1229

Officers, Delegates, and Members Hold Annual Conference at Hot Springs, Va. 1230

Letters to the Editor 1235

Membership 1242

Engineering Literature 1243

Industrial Notes 1244

Employment Notes (See Advertising Section)

Officers and Committees (For complete listing see p. 658–81, September 1933 issue of ELECTRICAL ENGINEERING)

A Message From the President

To the Institute Membership—

ALL OF US who grew up on farms will recall the occasions when trimming and pruning of the apple orchard became necessary. Dead wood and "suckers" had to be trimmed out, and the trees generally "tidied up." Some immediate crop was sacrificed, but if judiciously executed the process was salutary and in the end resulted in more shapely and accessible trees and more and better apples.

Some such process as this, I hope, is what is happening today to our American social and industrial system. If carried out with judgment and restraint the final results should be beneficial. Certainly a somewhat more orderly and controlled industrial organization, for better or worse, seems to be gradually emerging, and if lack of restraint does not result in destruction of the "orchard" we all at least may hope for "more and better apples."

Joseph Allen Johnson
A.I.E.E. President, 1934–35

In this "tidying up" of our social system the engineering profession as a whole, and the Institute in particular, must participate if they are to contribute to, and share in, its benefits. In fact several movements to this end are already under way or being considered. Among these are: (1) the Institute's new coördinated publication policy, (2) proposed "Junior" grade of Institute membership, (3) Engineers' Council for Professional Development, (4) reorganization of American Engineering Council, (5) Coördinating Committee of Engineering Societies, (6) proposed National Advisory Board of Engineers, (7) licensing of engineers by various States, (8) State societies of licensed professional engineers, and (9) proposed National Society of Licensed Professional Engineers.

In this seeming welter of developments and proposals, with various and apparently conflicting purposes and motives, it is difficult to see clearly what courses the individual engineer, on the one hand, and the existing professional engineering societies, on the other, should pursue. Which of these movements have objectives consistent with those of the Institute and other similar societies, and which have not? If some of these objectives are different from those of the Institute, are they therefore objectionable, or are they in themselves legitimate and desirable?

In several of these movements one or the other of 2 objectives seems to predominate. One of these is the *professional* advancement, the other the *economic* advancement of engineers. To what extent are these objectives mutually antagonistic and to what extent sympathetic? Can both be consistently promoted by a single organization or consistently supported by the same individual?

During the coming year your president will be obliged, perforce, to do considerable analytical thinking in these matters, and with ye editor's kind coöperation he shall hope to do some of it "aloud," so to speak, in ELECTRICAL ENGINEERING. If you should happen to agree with thoughts he may express, it would be helpful if you occasionally would drop him a line to that effect, and similarly contrariwise. Possibly by thus thinking together we both may be enabled to steer a truer course through the mist.

In anticipation therefore of occasionally writing you further on the above and perhaps other topics, and of occasionally hearing from you in reply, I am

Yours faithfully,

J. Allen Johnson

The Institute on Its 50th Anniversary

By J. B. WHITEHEAD, President A.I.E.E. 1933–34

TWO outstanding characteristics of the Institute's work have been especially striking during my term as president. The first is the high degree of efficiency and the smooth operation which characterizes the chief feature of the Institute's work, *viz.*, the reception, the consideration, the publication, the presentation, and the discussion of technical papers. The enthusiasm, energy, skill, and competence with which our technical committees function is evidently based upon a combination of profit from experience, and devotion to the Institute and its ideals. Changes of personnel, changes of administration, cannot disturb the smooth functioning of an organization perfected over the years and always animated by the highest professional spirit. Supported by an equally efficient and devoted headquarters staff, it is not to be wondered at that an incoming president, timorous with uncertainty, and dreading the necessity for the study of detail, should experience a feeling of immense relief at the realization of how large a proportion of the Institute's work can go on without his attention and probably be the better therefor.

My second vivid impression is related to that rather large group of questions which come before the board of directors of the Institute, which do not always fall naturally within the normal scope of either our technical or our general committees, and which, therefore, necessitate factual examination, discussion, and, of course, ultimate decision. Now questions of this character are characteristic of all large organizations, and I would not call especial attention to them in our own case were it not that many of these questions originate within our own membership, and apparently because of failure to recall first, the basic purposes for which the Institute exists, and second, the provision already made by the Institute for the answering of them. It is this latter aspect of these questions which has struck me so forcibly, and which leads to the principal theme of this brief address. In it I propose to state anew the purposes and ideals of the Institute as set forth by its founders and so carefully nurtured and revered through these 50 years, and to point out certain dangers of departures from them, as yet not serious, but whose manifestations, if allowed to pass unnoticed, may increase to threatening proportions.

The Institute's Tangible and Intangible Assets

First, however, and in order to indicate that my dominant feeling at this time is a hearty concurrence in the happy spirit of our anniversary celebration, and my confidence in a continuously expanding high future for the Institute, I ask you to review with me very briefly the grounds upon which, in our splendid anniversary issue of ELECTRICAL ENGINEERING, in the celebration meetings in the various Sections and Branches, and in this culmination meeting at the convention, we are basing our joy in the 50th birthday of the Institute. The answer is easy and is found at once in our record of accomplishment.

We may conveniently consider this record in terms of both tangible and intangible accumulated assets. Our material or tangible assets are obvious. Our contributions to the advance of the electrical art in ever-growing volume, as represented in the published file of our TRANSACTIONS; our continuous growth in membership only temporarily retarded at present; our unimpaired services to the membership in all phases of our work, even during the years of business depression; and finally, the distinguished list of names of those great engineers and scientists who have heartily participated in the Institute, and helped to build its high professional standards. These, I say, are some of our tangible assets. Together with others, they have been reviewed in detail in our recent publications and meetings, and I need not attempt to add anything to these reviews. Certainly they are sufficient grounds upon which to base a happy celebration.

However, I take it that it is eminently appropriate, in an anniversary year, to review also our intangible assets. These are the spirit which animates us, the traditions that guide us, and our faithfulness in carrying out the vision of the founders. Can any one doubt that the glorious record of achievement, strength, and unity, with which this record is continued from year to year is due to these intangible assets, to our unswerving adherence to the principle laid down by the founders that we exist primarily "for the advancement of the theory and practice of electrical engineering. . .and the maintenance of high professional standing. . . ." These latter phrases are in quotation marks. They are taken from our constitution. I cannot express too strongly my conviction that the remarkable growth and success of the Institute is primarily due to the single-mindedness with which successive administrations have adhered to the fundamental purposes of our existence, thus clearly stated.

Institute Interest in the Individual Engineer

The Institute has also indicated from time to time its concern for the "professional development" of the individual engineer. The question of the measures which should be taken in furtherance of this concern has occasionally caused differences of opinion among our membership. The meanings of words are always elastic and subject to special interpretation as related to the interests of those using them. To the more conservative of us, it has appeared that the Institute can best accomplish this purpose in the setting of high professional standards, in the maintenance of a high quality of technical papers

---

The president's message, presented at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. *Not published in pamphlet form.*

and discussions, in providing ample opportunity for younger members to hear and participate in meetings, to reward initial contributions, and to indicate desirable educational processes. To others, happily in my opinion relatively few in number, this avowed concern of the Institute for the professional development of a member has been interpreted as meaning an obligation to reach out if necessary into questions of semi-political and other controversial character often involving only the well-being of local engineering groups or even individuals.

As you know the Institute has adhered to the more conservative of these policies. That it has been actively interested in the professional welfare of its members is shown by its educational and other committees concerned with professional status, in its support of the splendid Engineering Societies Library, in the copious general matter in the monthly journal, and especially in the fine program of the Engineers' Council for Professional Development.

Does this mean that the Institute is not interested in the economic and social well-being of its members? By no means. It is very deeply interested in such questions and engages actively though indirectly in measures for their solution. It does mean, however, that the Institute has always felt that these activities lie outside the traditional constitutional purposes for which it exists, that questions of economic and social status usually pertain to the engineering profession as a whole, rather than to the electrical group only, and finally, that the Institute's concern and participation in such questions should be accomplished through joint agencies representative of all branches of the profession. As you know, the Institute participates actively in a number of such joint organizations, committees, and boards set up from time to time for discussion and action in matters of common interest to the entire engineering profession. What is not commonly understood, however, is that in practically every one of these cases, these agencies have been set up for the handling of just such types of questions as those we are considering, which seem to fall outside the traditional functional purposes of the separate founder societies, could not be effectively handled by any one of them, or all of them acting separately, and which, if so handled, would undoubtedly divert attention and financial support from their respective technical and strictly professional activities. Moreover, as evidence of the importance attributed by it to these matters of joint concern, the Institute has consistently assigned to these duties its most able and experienced professional talent. Our representatives on these joint agencies are commonly our presidents, past presidents, and past and present members of the board of directors. The Institute is, in fact, very deeply interested in both the professional and the economic status of the individual engineer and has always made ample provision for discussion and action on all public questions involving his well-being. This clear separation of questions of pure technical and professional character, as the Institute's first concern, from those involving the economic and social status of individuals or groups, and the provision which has been made for the separate adequate handling of each, are to my mind fine evidence of the high professional spirit which has guided the Institute through the years, and its consequent success.

Actions on National Questions

In order that you may understand the grounds which lead me to feel that this survey of old principles is desirable at this time, I will review briefly our action on several questions which have arisen during the past few months. These questions have emanated from our own membership, sometimes from individuals, and sometimes in the form of resolutions by individual Sections.

It will be recalled that in the inauguration by the Government of aggressive methods for fighting business depression, every organization of whatever character and so including the Institute, was asked through the mail to subscribe to the principles of the N.R.A. and to follow this up with the submitting of a code regulating the organization's activities. There was much immediate individual comment among our membership in opposition to any attempt to set up a code for engineers of the type proposed by the N.R.A., and no voice was heard in favor. American Engineering Council, one of our most effective joint organizations with other societies which exist exactly for the purpose of investigating and advising on such questions, proved itself here as usual wide awake, developed further information, and conferred with counsel of N.R.A. as to advisable action for the national engineering societies. It was learned promptly that the provisions of N.R.A. were not intended to apply to scientific and professional bodies. The Institute received similar opinion from its own counsel. The matter appeared to have been promptly settled by existing agencies, without the necessity for more than passing consideration and action by the board of directors. Up to this point, therefore, this is an admirable example of the effectiveness of our organization, and of our connections for the handling of questions extraneous to our normal functions.

However, as time proceeded, it was found that this clear separation could not be extended to certain branches of the construction industry in which many engineers were employed and that a code was being prepared which, in certain of its aspects, appeared likely to be regulatory in its effect upon certain classes of engineers. Several protests were received from both individuals and Sections with recommendations that the Institute should combat actively the setting-up of such a code. No specific recommendations of the action to be taken were made, nor was it immediately obvious as to how members of the electrical engineering profession were to suffer. In other words no conspicuously advisable action was indicated. However, it was soon realized that again in American Engineering Council and in other joint agencies with our sister societies, the matter was being discussed, apparent inequalities were being ironed out and, as time has progressed, it appears probable that if the engineers' construction code is adopted at all, it will be of very limited application, and may not affect the greater numbers of the mem-

berships of the founder societies, including, of course, our own. Again, in this case, it will be seen that the handling of the question and its solution have been practically automatic under existing agencies.

Another question which has occasioned wide concern, and properly so, is that of various disparities between the compensations of young, trained engineers and of ordinary labor, under the P.W.A. and the C.W.A. Here was an obvious injustice arising under Government regulations, and protests from somebody were obviously in order. American Engineering Council was again on the job, with a thorough examination of the facts, protests to proper governmental quarters, a final uncovering as to where the principal trouble lay, and suggestions as to how it might be corrected. The accumulation of facts and subsequent study of these questions require time and effort such as may not commonly be asked by the Institute of the members of either its technical or general committees. American Engineering Council, however, has been established primarily for just such purposes and in this, as in many other cases, has succeeded admirably.

Another highly important question involving the engineering profession, and which cannot yet be said to have been satisfactorily answered is that of the encouragement by the Government for the establishment of power plants under municipal and federal control which shall be in direct competition with others privately owned and in efficient operation. Suggestions that this is a matter for the Institute's concern have not been as frequent in this case, but they have not been entirely wanting.

Naturally the Institute is keenly interested in the many possible injustices of such a policy. However, it must be apparent that the Institute could not take an aggressive part in combating these measures without finding itself in a rapidly expanding program of public discussion outside its proper field with consequent demands upon the expert services of its members and committees, the expenditure of money, all to the serious detriment of normal programs of technical activities. In fact, the mere collection and analysis of information for the effective discussion of questions of this character would entail time and effort far beyond the normal voluntary services offered by its members to the Institute, and could not indeed be accomplished except through analytical, professional study involving the whole-time services of competent men. Yet the board of directors has been memorialized by more than one Institute Section with proposals that we should take active measures for the prevention or combating of the Government's action. What then was the proper course for the Institute to pursue? Its action was prompt. It referred the matter to American Engineering Council, and in the protracted discussions within Council of this matter, a very broad position in which we concur, in the form of dignified protests to proper Government agencies, has been taken.

In passing I may point out how very effective in this series of matters have been the services of American Engineering Council and how very important a part it has played in relieving the Institute of direct action in a variety of questions in which it is deeply interested. The Institute is also deeply indebted to United Engineering Trustees, to Engineering Foundation, and to several other bodies with which it is jointly associated, in the handling of many other matters of wide importance to the engineering profession, and which cannot be satisfactorily handled by the respective member societies. A joint Coördination Committee of Engineering Societies is at present reviewing the possibility of uniting into one general body these several important organizations. Its first report has just been submitted to the respective governing boards. No doubt a well considered conclusion will be reached from these discussions. If I may be permitted to inject a personal opinion, it has seemed to me that the respective spheres of American Engineering Council, United Engineering Trustees, Engineering Foundation, and other similar joint bodies are so diversified in scope, intensity, and location of their activities, that even if they were united, new subordinate bodies or committees equivalent to the present organizations would have to be set up. Certainly if an additional central body, with headquarters in New York, were set up, substantial further expense would be involved. Whatever may be the ultimate recommendation in this matter, it is my conviction that American Engineering Council must, for our best interest, be maintained in the high state of usefulness and efficiency, which has characterized it in recent years.

The Institute Has Due Cause to Celebrate

But I must not close on a serious note. The things which I have mentioned need cause no great concern and are far from being uppermost in my mind. Our thoughts and feelings are attuned to our anniversary celebration. And well they may be. A splendid past, no vain regrets, a healthy and efficient present in hard times, and a brightening prospect for the future, can cause only satisfaction and rejoicing.

As I approach the end of my term of office I find that I have 2 most vivid impressions. The first is of the fine morale, enthusiasm, and efficiency of our working committees, the vertebræ of our professional backbone. To chairmen and individual members I am happy to extend congratulations and thanks on behalf of the Institute.

Equally impressive is the recollection of my series of visits to 19 of our Sections. It was an inspiration to find everywhere the high spirit of our central purposes and methods reflected practically without question; enthusiasm and devotion to the Institute and its ideals; local provision for effectively bringing the work of the Institute to the membership; active recruiting committees. In fact, in addition to its other blessings the Institute seems to me to enjoy excellent health in spite of its 50 active years.

May I close with a brief but sincere personal word of thanks and deep appreciation to the board of directors, to the membership of all committees, to all Sections and Branches, particularly to those I have been able to visit, and to the headquarters staff, for their constant support and many courtesies.

Toward the Making of a Profession

An illuminating analysis of the reasons for and obligations of a profession, and in particular of the A.I.E.E.

By
WILLIAM E. WICKENDEN
MEMBER A.I.E.E.

President, Case School of Applied Science, Cleveland, Ohio

IN THIS paper an endeavor will be made to indicate not only the contributions of the Institute toward the making of a profession within its own sphere, but also to the growing and evolving part which professions in general are assuming in the manifold complex of functional units which make up the organism of a modern society.

Of professions there are many kinds—open professions like music to which any man may aspire within the limits of his God-given talent, and closed professions like medicine which may be entered only by a straight and narrow legal gate; individual professions like painting, whose devotees refuse to be herded into an organized body, and group professions like law, whose members constitute a special class in society; private professions like authorship, and public professions like journalism; artistic professions like sculpture which invite imagination, self-expression, and technical professions like surgery which impose the most rigorous of disciplines; localized professions like dentistry, and expansive professions like diplomacy; professions like social work which aim only at amelioration and professions like arms which achieve their ends through destruction. These diverse patterns may seem a mass of confusion and mutual contradictions; not so, for through all of them there runs a common warp on which each profession fashions its distinctive woof.

A profession in the corporate sense is a guild organized for self-government, and one limiting its admissions and recognition by high standards of technical competency, ethical purpose, and social accountability. A profession is the corporate trustee of a distinctive body of organized knowledge, a science, and of a distinctive body of techniques and skills, an art. A profession is a body of persons who deal with problems that have social significance and lie on a high intellectual plane, in a relationship of individual responsibility. A profession is a body of persons with an articulate conception of social function and duty, which includes but transcends the specific duties and tasks of individuals, invests them with a significance beyond the expediency of a moment, and lays upon its members the duty to consider their acts on a long-range time scale, and a wide scale of social consequences.

Evolution of Professions

The obligations of a profession grow out of its origin and evolution and cannot be considered as things apart. Professions have evolved from 2 types of parent stock, priestcraft with its magic and mysteries reserved to the initiate, and the corporate guilds of merchants and craftsmen which arose in the late middle ages. Engineering, without dispute has grown from the latter stem; the traditional learned professions from the former.

The guilds developed in the gap between feudalism and the centralized state. In a period of disintegration and remaking of the social order, before national governments had taken over judicial powers or cities their familiar police powers, commerce could exist only by mutual policing and protection, and trade only by self-imposed control. The far-flung argosies and caravans of merchants had no embassies, consulates, navies, and armies from which to demand protection. For the crafts, mutual regulation of hours of labor, terms of apprenticeship and quality of workmanship was the only alternative to competitive anarchy. The religious philosophy of the times favored the idea. The middle ages regarded society as a commonwealth divided into divinely ordained functions, where individualism was to be frowned upon and group activity favored.

When the cities began to consolidate their public powers, the guilds were already strongly entrenched. The cities recognized the priorities of the guilds, confirmed their privileges and monopolies and gave them a corporate part in the machinery of government. In London, the so-called "livery companies" preserve to this day these traditional prerogatives. The largest of the 3 federated educational units which make up the Imperial College of Science and Technology is the "City and Guilds Engineering College," whose endowments were set apart, by public direction, from the funds of ancient craft and merchant guilds, as the nearest modern equivalent to the old-time encouragement and regulation of apprenticeship.

In addition to regulating working conditions, quality of workmanship and apprenticeship, the guilds commonly required their members to contribute periodically to a fund for relief and burial of indigent craftsmen, to participate in certain religious observances, and to honor certain festivities and pageants. You may find all these features dramatically portrayed in Wagner's opera "Die Meistersinger." Most of them are perpetuated with a striking persistence in our own group of professional bodies. We engage in various forms of self-government; we associate ourselves in certain functions with cities, states, and nation; we maintain an employment service, and when occasion demands,

Essentially full text of an address presented at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. *Not published in pamphlet form.*

a relief service; The American Society of Mechanical Engineers included a formal religious service and a historical pageant in its late jubilee; and we are today celebrating our own golden anniversary.

Social Relationships

Under this time-honored tradition, the state accepts the actual or potential pre-existence of professional bodies, grants them public charters, grants or confirms more or less tangible monopolies and privileges, delegates certain police powers and recognizes their autonomy, in consideration of which each profession engages to admit only men of proved competency, to scrutinize the quality of their work and to protect the public against bungling and extortion. The admission of persons not strictly qualified to a professional body on a courtesy basis, or the winking at business piracy in any form or degree under the cloak of professional activity, is by its nature a breach of public trust.

The occasion which calls for professional service is often a human emergency, aggravated by emotional stress, under which the layman cannot be trusted to judge for himself of the quality of the service proffered. The same is true only in less degree in public emergencies. Under these circumstances the legal principle of *caveat emptor*—let the buyer beware—which holds in a purely commercial transaction breaks down. The public rightly places the burden of guaranteeing at least minimum standards of competency and ethics on the profession itself, and in return protects it from incompetent judgment by lay critics.

Before turning to a consideration of the distinctive professional qualities and services of our own body, it will be appropriate to recapitulate the standards by which the genuineness of professional status may be tested and its qualities appraised:

Attributes of Individual Professional Status

1. *A type of activity*, involving:
   a. A high degree of individual responsibility.
   b. The handling of problems of high social utility, on a high intellectual plane, under a code of ethical responsibility.
   c. The use of skills and techniques not commonly possessed.
2. *A motive of service*, distinct from that of profit, which differentiates professional activity from ordinary business.
3. *A motive of self-expression*, which implies a joy in one's work, imposes an austere standard of self-criticism, and leads to a single standard of workmanship—one's best.
4. *A conscious recognition of social duty*, to be fulfilled among other means by:
   a. Sharing advances in professional knowledge.
   b. Guarding the standards and ethical codes of one's profession and enhancing it in the understanding and esteem of the lay public.
   c. Rendering a fair share of gratuitous service, either to needy persons or for the public good in return for special advantages of education and status.

Attributes of Group Professional Status

1. *A corporate trusteeship* of a body of advanced knowledge (a science) and of a body of special skills (an art) held as a common possession and to be extended by united effort.
2. *An educational discipline* of professional aims and content, in which the professional body has a share of directive responsibility usually associated with gradations of title or rank to mark the progress of individual attainment.
3. *A standard of qualifications* for professional recognition, based upon:
   a. Character, worthy of public trust in emergencies.
   b. Training of adequate degree.
   c. Competency, both technical and social, to determine the "whether, when, and how," of professional problems.
4. *A standard of conduct* in relation to:
   a. Clients, based upon professional integrity.
   b. Colleagues, based upon regard for mutual rights.
   c. The public, based upon social and ethical intelligence.
5. *A formal recognition of status*, by one's colleagues or by organized society (not common in the artistic professions).
6. *An organization* based upon common interest in advancement of the profession and on social duty, rather than economic monopoly.

Since a profession must so largely govern itself, it is assumed to maintain certain codes:

1. A code of qualifications governing admissions.
2. A code of ethical practices in relations with clients.
3. A code of professional honor in internal relationships.
4. A code of public obligations.

Responsibility of Membership in a Profession

The obligations of a profession are so much a matter of attitude that codes alone are not sufficient to sustain them. Equal importance attaches to the state of mind known as professional spirit, which results from associating together men of superior type, and from their common adherence to an ideal which puts service above gain, excellence above quantity, self-expression above pecuniary incentives, and loyalty above individual advantage. The professional man cannot evade the responsibility to contribute to the advancement of his group. His skill he rightly holds as a personal possession, and when he imparts it to another he rightly expects a due reward in money or service. His knowledge, however, is to be regarded as part of a common fund; hence the obligation to publish researches and to share advances in professional practice. If his abilities do not permit him to do so personally, he can at least pay his debt by contributing financially to the dissemination of the works of others.

Many engineers need to be warned away from too short-sighted an attitude in this matter. There are doubtless thousands of us to whom the immediate tangible value of the publications of a professional society is much less than their cost, yet when one pauses to consider the magnificent body of knowledge which has been accumulated as a common heritage the tax levied in the form of professional dues assumes almost negligible proportions. Research is indeed one of the most potent means of enhancing a profession's prestige, as the advance in the standing of the medical profession in the last 3 decades so clearly testifies.

Professional status is therefore an implied contract to serve society in consideration of the honor, rights, and protection society extends to the profession. Through all professional relations runs a 3-fold thread of accountability to colleagues, to clients, and to the public. Business moves toward the professional area as its management passes from proprietors to a distinct administrative caste with little or no immediate stake in the profits of

trade. In so far as the rewards and status of this caste rest on long-range prosperity rather than quick returns, it is able to maintain the attitude of accountability to investors, workers, customers, and the public, which is the irreducible element in professional standing. Whatever of social loss has resulted from the blurring of the engineer's personal status, has been largely offset by what he has contributed as an administrator to the professionalizing of industry.

The Institute's emphasis on the several threads which make up the common warp of all professional activity has been unequal, to be sure, but its fidelity to the spirit and ideals has been notable. Considering the youth of the profession, some selection among the many aspects of a mature professional life was inevitable and this selection has been marked by a discriminating wisdom.

The Institute Is Broad in Scope

The inclusiveness of our membership has ranged us among the democratic rather than the aristocratic professional bodies. The scope of our interests has been wide enough to avoid an undue fragmentizing of personnel and activity. Among its sister organizations the Institute is notable for its success in assimilating the research scientist, on the one hand, and the industrial executive, on the other, into the common life of the profession. The one has been immensely fertilizing intellectually, and the other has advanced the frontier of professional service and standards in the business world. To it we may properly ascribe much of the high sense of social obligation which has characterized the electrical industries as a group and the leadership exercised by their officers in advancing movements for the public good. As our profession is more closely integrated than almost any other with corporate activity and is perhaps least involved in purely personal emergency services, there has been only moderate need to guarantee to the public the competency and character of our men. Our unique mission has not been to draw professional lines sharply, as in medicine, but to infuse industrial activity with professional tone, with a high sense of trusteeship for the advancement of science, and with the standards of accountability to investors, employees, customers, and the public which professional service entails.

Contributions of the Institute to Education

The ideal of educational service to young engineers was paramount in the organization of the Institution of Civil Engineers in Great Britain, which has been the prototype from which many of our traditions were drawn. To this ideal the A.I.E.E. has given both generous and constructive support. There has been far more concern that methods of recruitment and training should be such as to provide an adequate personnel for the fast-growing industry, than to protect any monopoly interest of men already established in the profession. The Institute has encouraged and not policed education. By giving the student a real part in the activities and associations of a professional body, it has done what the school alone could not do. The work of our beloved past president, Charles F. Scott, in articulating the interests of the schools, the industries, and the Institute, as instruments for the education of the electrical engineer, is itself an epic in the history of professional life in America.

The great work of stimulating engineers to a continuation of their serious education after the period of schooling has ended is the most important task immediately before the profession. Leadership in this field has been conspicuous in the electrical industries and it is but natural that members of the Institute have taken a conspicuous part in shaping the objectives of the Engineers' Council for Professional Development.

The Many Other Contributions of the Institute

The chief glory of the Institute has been its contributions to the making of the science and art of electricity and to establishing the new technique of progress to which the philosopher Alfred Whitehead alludes in his much quoted statement:

> "The greatest invention of the 19th century was the invention of the method of invention; . . . it is that which has broken up the foundations of the old civilization."

In the traditional crafts—the making of metal objects, of pottery, of textiles and the like—the art came first and the science long after. The tempo of progress by unaided evolution was exceedingly slow. The greatest invention of the ancients, the art of writing, is believed to have required a thousand years for its achievement.

In modern times, the old order of crude invention followed first by slow refinement and ultimately by research has been reversed and the tempo of progress vastly accelerated. Savery and Newcomer preceded Carnot by 125 years. Faraday's great researches on electromagnetic induction were but 35 years in advance of Gramme's generator and 54 years in advance of the Edison bi-polar machine. The mysteries of the "Edison effect" of 1883, revealed by Richardson's researches on emission 20 years later, became fruitful almost immediately in Fleming's 2-element valve and De Forest's 3-element audion.

Greater than any material resource or any endowment has been the Institute's intangible contribution to this science and art, through the stimulation of research, the recognition accorded to scientific disclosure, the dissemination of a literature of priceless value without reference to its commercial possibilities, the award of honors for notable achievement, the spur of the rostrum and the forum, and the emulation of great men engendered among young engineers. It is to be doubted if the roster of any engineering organization of equal youth has been as rich in the names of great investigators and creative inventors.

The formalizing of codes of professional courtesy, honor, and ethics has been to the Institute a sec-

(*Continued on page 1173*)

Fundamental Laws of Photoelectricity

By A. L. HUGHES
MEMBER AM. PHYS. SOC.
Washington Univ.
St. Louis, Mo.

Although the present amazing variety of applications of the photoelectric cell has been developed entirely during the past decade, the photoelectric effect was discovered during the nineteenth century. This article gives a brief account of the fundamental laws of photoelectric phenomena and their theoretical significance; it is the eighth of a series of special articles prepared under sponsorship of the A.I.E.E. committee on education, for full details of which see p. 238 of the February issue.

PHOTOELECTRICITY comprises that part of physics dealing with the electrical effects produced when light, or more generally, radiation, falls on matter. The photoelectric effect, which was discovered in the last century, received little or no attention except from physicists until the last decade, when an amazing variety of applications of photoelectricity made the photoelectric cell almost a household word. Essentially, the photoelectric cell is a device that delivers an electric current when light falls upon it, and, in general, the electric current is proportional, or nearly proportional, to the amount of light falling on the cell. Thus any change in the intensity of the light falling on the cell immediately produces a corresponding change in the resulting electric current. By means of properly designed amplifiers, it is possible to intensify this rather feeble electric current to any desired amount, and so the following applications among hundreds of others are practicable: automatic counting of objects when these objects are made to interrupt a beam of light, turning on of artificial light when daylight falls below a certain level, talking movies, television. However, it is not within the scope of this article to discuss the methods whereby these applications are realized; such a discussion now has become the province of the electrical engineer rather than that of the physicist. The purpose of this article is to give an account of the fundamental laws of photoelectric phenomena and their significance in the theory of the nature of radiation and of matter.

In studying the photoelectric effect, the principal characteristics of the radiation will be considered on the one hand, and those of electric current on the other. The chief variables involved in the radiation so far as the photoelectric effect is concerned are its intensity, its wave length, and its state of polarization. The photoelectric current has been shown to consist of a flow of electrons from the illuminated surface (restricting the discussion for the present to the photoelectric effect most investigated—that prevailing at metal surfaces). These photoelectrons vary in number, in velocity, and in direction of emission from the illuminated surface; it is the problem of the experimental physicist to find how these variables depend on the radiation variables, enumerated previously. Then again, different materials have different photoelectric effects, and therefore systematic studies of the photoelectric behavior of different materials have been carried out.

The photoelectric effect is of considerable significance in that it furnishes evidence as to the nature of radiation. The nineteenth century was a century of triumph for the wave theory of light. All the accumulated experimental evidence pointed in one and the same direction, namely, that light could be described completely as a wave motion in the hypothetical ether. These waves are essentially continuous in space and time. That is to say, the amplitude, if it changes, changes smoothly in any direction, and, if any one spot be considered, at that spot it changes continuously with time. At the end of the century, Planck found it necessary to introduce an element of discontinuity into radiation to account for the characteristic shape of the curve for the distribution of energy in the spectrum of an ideal black body. Following this notion of discontinuity in radiation and deciding to abandon altogether all elements of continuity in radiation in order to account for the photoelectric effect, Einstein in 1905 proposed to regard radiation as being made up of a torrent of tiny particles—corpuscles, photons, or quanta. Since then, a multitude of phenomena have been found which fit in most naturally with the new way of regarding radiation.

Optical phenomena fall into 2 classes: One great class includes all phenomena that can be interpreted only by the wave theory; the other contains a vast quantity of experimental results accumulated since 1900, which can be accounted for only by the corpuscular or quantum theory. To use the words of Sir W. H. Bragg, physicists at one time were content as a temporary expedient "to work with one theory on Mondays, Wednesdays, and Fridays, and with the other theory on Tuesdays, Thursdays, and Saturdays, but with the expectation that later on something could be done about reconciling the two totally different viewpoints." Recently it has been found that the ultimate particles of which matter is built, that is to say, molecules, atoms, electrons, protons, etc., have some properties that are describable only in terms of waves. Consequently, the present situation is such that *all* ultimate entities, radiation as well as atoms and electrons, have this twofold aspect: they seem to be particles and not waves for certain phenomena, and waves and not particles for other phenomena. Unable as physicists are to "picture" how this can be so from any large scale analogy that can be seen, touched, or handled

they accept this dualism as being a necessary, but unexplainable, part of a complete description of radiation and atomic phenomena. Photoelectric evidence in support of the corpuscular aspect of radiation now will be discussed.

Number of Photoelectrons in Relation to the Intensity of the Light

During the past 40 years many investigators have examined the relation between the number of photoelectrons released and the intensity of the light used. The method of experimentation easily can be visualized. A photoelectric cell is connected in series with a galvanometer and with a suitable battery the voltage of which is such as to pull the photoelectrons, which are released at the surface of the illuminated cathode, away from the cathode. The intensity of the light is changed by one of several standard methods (moving the source to different distances and using the inverse square law to compute the intensity being a common method) and the corresponding photoelectric current is indicated by the galvanometer.

In principle, any photoelectric cell could be used, but several factors often prevent commercial cells from giving the true relation. In the first place, one should use a vacuum cell because in gas filled cells, where the ionization by collision in the gas magnifies the original photoelectric current, the magnification factor may not be exactly constant.

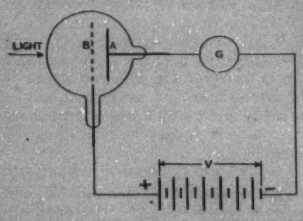


Fig. 1. Circuit illustrating fundamental properties of the photoelectric cell

Even in vacuum cells, complications often arise because the large areas of bare glass inside the cell frequently accumulate electrons which disturb the electric field inside. Also, these bare surfaces may have formed upon them monatomic transparent films of the active metal which, however, are more or less photoelectrically active and therefore contribute in an incalculable way to the measured photoelectric current from the illuminated surface.

These brief remarks may serve to explain why, in an apparatus designed to test the fundamental relations between the photoelectric current and the intensity of the light, extreme care has to be exercised to obviate any complication of the effect one is investigating. The conclusion of all investigators who have satisfied themselves that their cells are designed properly so as to measure the fundamental relationship unmodified by spurious effects, is that there is a strict proportionality between the number of photoelectrons and the intensity of the light producing them. (This relationship often is found for commercial cells, but cannot safely be assumed to be necessarily true for all such cells.) Such a result is a natural consequence of the corpuscular theory of light, for the number of photoelectrons released should be directly proportional to the number of quanta of light falling on the surface. What one should expect on the basis of the wave theory is not so clear.

Velocity of Photoelectrons and the Intensity of the Light

Velocity of photoelectrons is generally measured by, and expressed in terms of, the voltage necessary to stop them. Thus if A (Fig. 1) is the illuminated plate in front of which is a grid B, through which the light passes, the photoelectrons from A will get across to grid B, in spite of the retarding voltage V, if their kinetic energy $(^1/_2)mv^2$ exceeds Ve, the gain of potential energy, where e is the charge on the electron and m its mass. The procedure then is to increase V by small increments until the photoelectrons no longer get from A to B. When this condition prevails, the velocity of the fastest electrons is given by $Ve = (^1/_2)mv^2$.

Now it is found that the velocity of the electrons is totally independent of the intensity of the light falling on A. No matter whether the intensity of the light is so feeble that only a few photoelectrons are emitted in a minute or so strong that billions are emitted per second, the velocity with which they are emitted is precisely the same. Such an effect is quite unexpected on the basis of the wave theory of light, for, since intensity in the wave theory is measured by the amplitude of the wave, it is natural enough to suppose that the stronger the amplitude of the electric forces in the light beam, the more vigorously would the photoelectrons be ejected. Yet this is not so.

On the basis of quantum theory, the ejection of a photoelectron is, so to speak, a private affair between the electron and the quantum concerned in ejecting it. Whether few or many such quanta are raining on the surface does not matter; the velocity with which any individual electron is ejected by an individual quantum depends only on the nature of that particular quantum and is completely independent of the effects of other quanta at other parts of the surface.

Velocity of Photoelectrons and the Color of the Light

By substituting the quantum viewpoint of radiation for the wave aspect in an attempt to account for the photoelectric effect, Einstein, in 1905, made an exceedingly bold prediction as to the relationship to be expected between the velocity of electrons and the wave length of the light. According to the quantum theory, the energy in a quantum is $h\nu$, where h is Planck's constant and ν the frequency of the light. The latter depends on the wave length through the well-known relation $\nu\lambda = c$, where λ and c are the wave length and velocity of light,

respectively. Thus, the higher the frequency, or the shorter the wave length of the light, the more energy there is in the quantum. It is assumed now that when the quantum is completely and instantaneously absorbed in the surface, all its energy is taken up by an electron, which then starts off with its newly acquired energy $(^1/_2)mv^2$. If the quantum passes through the surface, it has to give up an amount of energy, p, to overcome surface electric forces that prevent, or tend to prevent, electrons from escaping. This leads to Einstein's famous photoelectric equation

$$(^1/_2)mv^2 = h\nu - p \qquad (1)$$

It is clear that this equation predicts that the energy of escape is a linear function of the frequency. That this was true experimentally was established simultaneously and independently in 1912 by Hughes and by Richardson and Compton. Four years later, Millikan verified the relation to a very high degree of accuracy, so that his measurements gave a precision determination of the highly important Planck's constant, h.

The Photoelectric Threshold

It is clear from eq 1 that if there were no forces at the surface tending to hold the electrons in, then all radiation, no matter how small its frequency or how long its wave length, would eject photoelectrons with the proper energy $(^1/_2)mv^2$. It is the finite size of p, the "work function" of the surface, that prevents this happening. The value of p depends greatly on the nature of the material and also on the state of the surface. For example, removing occluded gases from a surface by prolonged heating may change p by a large factor, possibly often by as much as 30 per cent. A surface from which impurities, such as occluded gases, have been removed is presumably the photoelectric threshold of a "clean" metal. The alkali metals, which are electropositive (i. e., lose electrons easily), have unusually low work functions and so their thresholds lie in the visible spectrum or in the infra-red region. On the contrary, metals like platinum and tungsten, which are electronegative (i. e., part reluctantly with electrons) and are chemically somewhat inert, have relatively large work functions; their thresholds are in the ultra-violet range.

The material with the lowest known work function, i. e., with a threshold in the infra-red region, is a composite surface consisting of a supporting surface of silver, then a very thin layer of an oxide of caesium, over which is laid a *monatomic* layer of caesium atoms. Such surfaces are employed in many modern photoelectric cells, since they are sensitive to a wide range of wave lengths, and therefore give a greater response to white light than cells having larger work functions.

Fowler's Theory of the Photoelectric Effect

Previous to 1927 it had been supposed that the electrons within a metal behaved very much like molecules of a gas in an enclosure the boundaries of which coincided with those of the metal. The higher the temperature, the greater is the kinetic energy of the molecules. However, even at 1,000 deg C the average kinetic energy of the molecules (or electrons) is about $^1/_{10}$ of an electron volt.

In 1927, Pauli proposed a very different picture of the state of the electrons in a metal. According to this picture the electrons are moving with far greater kinetic energies (of the order of 6 electron volts) than they were supposed to have by the old theory. What is more significant is that their energy is almost, but not quite, independent of the temperature, whereas by the previous theory, the energy was directly proportional to the temperature. Using this new viewpoint, Fowler found that the photoelectric threshold should appear to shift slightly with the temperature—a result not to be expected on the basis of the older theory—and moreover, predicted how the photoelectric current should depend on the temperature and on the frequency near the threshold. (To be strictly correct, a clear cut threshold exists only at absolute zero; at other temperatures electrons should be found for lower frequencies, though to be sure in rapidly diminishing number at frequencies decreasing from the threshold.) This prediction was verified quantitatively by DuBridge in a series of very skillfully designed experiments. There is convincing proof therefore that the new picture of the state of electrons in a metal fits the facts better than the theory previously held.

The Selective Photoelectric Effect

In 1894, 2 of the pioneers in the field of photoelectricity, Elster and Geitel, found a remarkable dependence in the photoelectric effect of sodium-potassium alloy on the state of polarization of the light used in their experiments. They directed a beam of light obliquely at the surface. The plane of polarization of this light could be rotated by means of a Nicol prism. When the light was polarized so that the electric force coincided with the plane of incidence, under which conditions there was a component perpendicular to the surface, the photoelectric effect was far greater than when the electric force was perpendicular to the plane of incidence and so was entirely parallel to the surface. This is precisely what would be expected on the basis of the wave theory of light, for it is reasonable to suppose that if the electric force has any component perpendicular to the surface it will be much more efficient in ejecting photoelectrons than when it is entirely parallel to the surface. An immense amount of work has been done on all kinds of surfaces in this field. For years quantitative correlation with theory was impossible to effect. It is true that when the light is polarized in the plane that gives the bigger effect, more of it is absorbed than when it is polarized in the other plane; but the trouble is that the difference is not nearly large enough to account for the large differences in the corresponding photoelectric effects.

Extensive work by Ives at the Bell Telephone Laboratories has shown that a radically different

point of view is necessary to bring theory and experiment into accord. It is well known that when waves of light are reflected in part from a surface the reflected waves combine with the incident rays to give a pattern of standing waves in the vicinity of the surface. The amplitude, and therefore the energy, of the electromagnetic disturbance may be computed just at the surface. The magnitude of this will depend greatly on the angle of incidence and on the state of polarization of the light. It is found that the magnitude of the photoelectric effect is related closely to the energy of the disturbance. Consequently, this new viewpoint of Ives may be considered to be a very important contribution to the theory of the selective effect.

Photoconductivity

So far, the effects arising when light falls on a metal surface have been considered; in addition, electrical effects are to be found when light is absorbed throughout a finite volume of some semitransparent substance. The change in resistance of a certain form of selenium when illuminated, was known long before the ordinary surface photoelectric effect was discovered. Yet, although hundreds of investigations have been made of it, but little is known as to the totality of effects in selenium. It was recognized that the photoconductivity of selenium probably was related to its crystalline structure. This led to a study of the effect of light on the conductivity of large single crystals. Practically all the present information in this field has been acquired since 1920 and has resulted almost entirely from the work of 2 Germans, Gudden and Pohl.

Comparatively few crystals change in conductivity when illuminated; in those that do, a secondary effect, not at all photoelectric in its nature, generally obscures the fundamental photoelectric effect. Thus any considerable photoelectric current passing through a crystal when illuminated alters it in such a way as to diminish its resistance. Hence, in order to study the underlying photoelectric effect successfully, it is necessary to work with the smallest possible currents so as to secure the least possible disturbance of the crystal. When this is done properly for crystals such as diamond and zinc blende, the photoelectric current is found to be directly proportional to the intensity of the light. It starts and stops instantly with the light. Perhaps the most convincing result found is that the number of photoelectrons released is very nearly identical with the number of quanta absorbed in the crystal. Under the influence of a sufficiently strong field the electrons released will move toward the anode, leaving the places from which they started positively charged. This results in the building up of a strong space charge within the crystal, an effect readily demonstrated.

In certain crystals, such as rock salt, no photoelectric current can be found if the crystals are perfectly clear and transparent. Such crystals sometimes can be colored by long exposure to X rays and by other agents. When in this state, they show strong photoconductivity on illumination by visible light. It is believed that the colored rock salt owes its color to the presence of neutral atoms of sodium dispersed through the regular rock salt lattice. When light is absorbed by any one of these neutral atoms, it emits a photoelectron and so the existence of a photoelectric current is accounted for.

Cuprous Oxide Cells

It has been known for a long time that, if cuprous oxide (Cu_2O) is formed on copper by heating in oxygen, the interface between the oxide and the metallic copper acts as a rectifier. If a current be considered as a flow of electrons, such an interface offers a high resistance to the movement of the electrons when the voltage drop is such as to drive them from the oxide to the copper; but it offers a low resistance to the movement of the electrons when the voltage drives them from the copper to the oxide. In 1926, Grondahl noticed that the behavior of such a rectifier was influenced by illumination, and realized that it could be used as a photoelectric cell. Nothing further was done until 1930 when Lange devised an arrangement of the materials to allow as much light as possible to reach the sensitive interface and so give a large photoelectric current; his arrangement is shown in Fig. 2. A thin layer of cuprous oxide is formed on a base plate of copper, which forms one electrode. The other electrode may be a grid pressed on the top surface, or a semitransparent film of metal deposited by evaporation or sputtering. When light falls on such a cell, it is found that the photoelectric current is directed so that electrons flow from the oxide to the copper—an unexpected result, for this is the direction in which the device, regarded as a rectifier, has a high resistance.

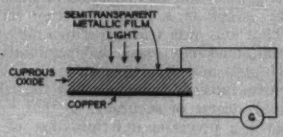


Fig. 2. Cuprous oxide photoelectric cell devised by Lange in 1930

The yield of such cells is astonishingly high, a result that, because of its practical implications, led to an intensive study of such cells immediately after Lange published his discovery. It should be noted that this cell gives a photoelectric current without any need of an auxiliary battery to supply voltage. This must mean that the kinetic energy of the electrons is sufficient to carry them across the interface from the oxide to the copper. The fundamental primary effect at the interface may be either the development of an electromotive force or the development of a current. Experiments carried out by Auwers and Kirschbaum show that the latter is correct. Such a result is in accord with the view that each quantum of light sets free a photoelectron and the current is directly proportional to the num-

ber of photoelectrons made available. It is found that the passing of the photoelectrons across the interface tends to set up a voltage difference across it which, because it is in the direction of easy flow for the electrons across the boundary (regarding the cell in its rectifier aspect), causes many of the electrons to leak back across the interface. Thus the cuprous oxide cell itself tends to act as an undesirable shunt, which allows some of the photoelectrons to leak back instead of going through the indicating instrument in the outer circuit. Because of this effect it is desirable to keep the resistance of the outer circuit, including the meter, as small as possible. When this is done, the current indicated by the instrument is found to be very closely proportional to the amount of light falling on the cell.

The cuprous oxide cell has a threshold in the far infra-red region, and a maximum sensitivity in the near infra-red region, i. e., not far from the red boundary of the visible spectrum. The position of the maximum is determined, in part, by the strong absorptive properties of the oxide which, even in a thin layer, absorbs the visible spectrum strongly and so allows very little light to pass through to the interface where the photoelectric activity originates. Such a view is confirmed by the results obtained with a "front wall" cell, i. e., a cell so made that the active interface is the one between the semitransparent metal film and the copper oxide. In such a cell there is less absorbing material for the light to go through and, as would be expected, a much greater sensitivity in the visible spectrum. Further information about the photoelectric effect may be found in:

1. Photoelectric Phenomena, A. L. Hughes and L. A. DuBridge. McGraw-Hill Book Co., New York, 1932.

2. Photoelectricity, H. S. Allen. Longmans, Green and Co., New York and London, 1925.

3. Photocells, V. K. Zworykin and E. D. Wilson. John Wiley and Son, New York, 1930.

4. Cuprous Oxide Rectifier and Photoelectric Cell, L. D. Grondahl. *Review of Modern Physics*, v. 5, 1933, p. 141.

5. Photoconductivity, C. M. Nix. *Review of Modern Physics*, v. 4, 1932 p. 723.

Television by Electronic Methods

By
A. H. BROLLY
ASSOCIATE A.I.E.E.

Television Laboratories, Ltd., San Francisco, Calif.

A number of recent advances in television methods, such as electronic scanning, receiver synchronizing via the signal channel, and light sensitive devices of great sensitivity have made possible the construction of television equipment which is thoroughly useful. Scenes with motion thus may be transmitted instantaneously, and the resulting image is stated to be almost equal in detail to good home motion pictures. The various units of a complete modern television system are discussed in this paper, with particular emphasis on the scanning, amplifying, and light translation devices. Transmission is stated to be feasible by either wire or radio.

TELEVISION, for many years a dream of inventors, has become a reality through the ingenious application of fundamental principles in electrical engineering. It differs from other methods of electric communication, including particularly telephotography, by providing practically instantaneous transmission and reproduction of scenes with the illusion of motion. Its development has reached a stage where broadcasting and reproduction of entertaining programs are technically feasible. Pending commercialization, development proceeds toward improving details.

Several outstanding advances in television methods have made possible its present practicality. Among these are electronic scanning, receiver synchronizing via the signal channel, light sensitive devices of greater sensitivity than the simple photoelectric cell, and improved technique and apparatus for amplification. The relation between essential units of a complete modern television system incorporating these late improvements is shown diagrammatically in Fig. 1. The various units of the system will be discussed in detail following an outline of the system with reference to this diagram.

The transmitter centers about the "pick-up" or analyzer which, in the Farnsworth television system, is known as the "image dissector," *A* in Fig. 1. This vacuum tube converts the various light intensities of a scene focused upon its photo-sensitive surface into fluctuations of an electric current. It is also part of the scanning system which includes its enveloping coil assembly *B* and the scanning oscillators *C* and *D*. Their combined function is to analyze

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. Pacific Coast convention, Sept. 3–7, 1934. Manuscript submitted Apr. 24, 1934; released for publication June 6, 1934. *Not published in pamphlet form.*

the area of the scene into a regular succession of space elements and convert them into corresponding signal currents suitable for transmission over a single communication channel. The current impulses are amplified by the electron multiplier E, which is an integral part of the tube, and by the vacuum tube amplifiers F and G, to produce signal voltages great enough to modulate a radio carrier. The connections H and K between the scanning circuits and the amplifier provide signal impulses for automatically synchronizing the reproducers which are tuned to the transmitter.

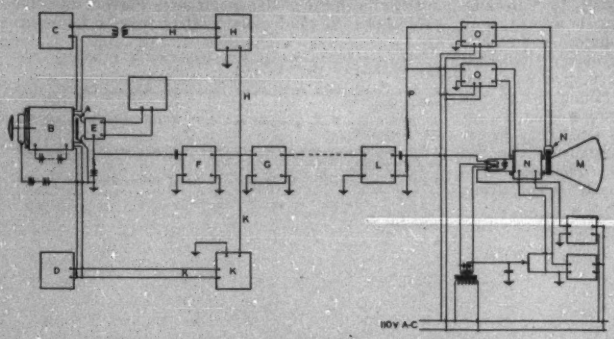


Fig. 1. A modern television system, showing elements of transmitter and receiver

The heart of the reproducer is the cathode ray tube M which converts the received electric impulses into corresponding variations of light intensity, and arranges them in regular space sequence so as to reproduce the image of the scene at the transmitter. This is accomplished with the aid of the scanning system consisting of the coils N-N, the associated oscillators O-O and the tube M itself. Again the scanning oscillators are linked to the signal channel, as indicated by P, to effect automatic control from the transmitter.

Action at both the transmitter and the reproducer involves the same general processes, namely: scanning, light translation, amplification, and the intermediate propagation of the signal. The scanning process at the transmitter analyzes the space dimensions of the field of view into a time function of electric current; that at the reproducer synthesizes the electric currents into an orderly space sequence. The light translation process at the transmitter converts light intensities into electric intensities, and at the reproducer performs the converse operation. Amplification compensates for the inefficiencies of translation and transmission while propagation of the signal completes the train of processes.

Scanning

The effect of scanning is similar to that obtained by moving a small aperture, h units in width and height, horizontally across the picture field, as indicated in Fig. 2. If the aperture is moved across n closely adjacent parallel strips, it covers an area

$$H = n \times h \text{ units high} \qquad (1)$$

The 2-dimensional area of the picture is thereby reduced to 1-dimensional line. The picture is thus dissected into elementary squares each of whose different average intensities in light is converted into different intensity or magnitude of electric current. Consequently, the 2 characteristics of an electric current, its duration in time and its magnitude or amplitude, convey the space dimensions and light intensities, respectively, of a scene over a single channel as a magnitude-time function.

Conversely, at the receiver, the magnitude-time function is converted into 2-dimensional space areas of different light intensities, regularly assembled to constitute a visible duplicate of the image at the transmitter.

The signal-producing and picture reproducing mechanism cannot distinguish detail smaller than

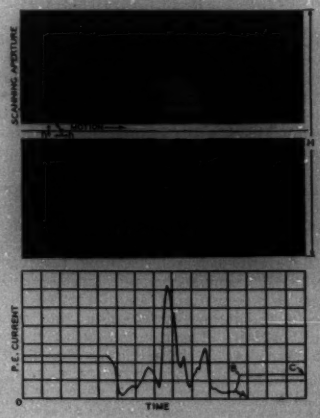


Fig. 2. The scanning operation

The aperture and scanning line are of proportions for 240-line picture
The wave below the picture results from scanning the line set apart

scanning aperture. Therefore, the amount of detail in a reproduced picture depends upon the size of the scanning aperture and upon the ability of the electric circuits to respond to the rapid changes of signal intensity during scansion. As the circuits are generally designed to respond to as many changes of intensity per unit length of scanning line as there are lines per unit height of picture field, it is customary to define the detail in terms of the number of lines in the field. Experiments indicate that at least 200 lines per picture field are essential in producing pictures that are satisfactory for sustained entertainment. (See "Television," a book, by Edgar H. Felix, McGraw-Hill Book Co.; and "Notes on Television Definition," by W. H. Wenstrom, I.R.E. *Proc.*, v. 21, no. 9, 1933, p. 1317–27.)

The time allowable for scanning the entire picture, as determined from the eye's persistence of vision, may be from $^1/_{12}$ to $^1/_{30}$ sec, depending upon the rapidity of motion of objects in the scene, the tolerable amount of flicker, and the brilliance of reproduction. (See "The Principles of Optics," a book, by A. C. Hardy and F. H. Perrin, McGraw-Hill Book Co.) Periods of $^1/_{20}$, $^1/_{24}$, and $^1/_{30}$ sec are common in current experimental work.

Electronic Scanning

Electronic scanning with the image dissector analyzer and its auxiliaries, *A-B* Fig. 1, closely approaches the elementary operation of Fig. 2. It is accomplished by periodic magnetic deflection of cathode rays set up by an optical image of the scene to be transmitted. Scanning in this device is closely associated with light translation as they both take place in the same tube.

In operation of the image dissector, Fig. 5, a lens *a* produces an optical image of the scene to be transmitted on the translucent photo-electric film *b*. This emits electrons in numbers proportional to the intensity of illumination of the optical image. Electrons from any point of the image on *b* are brought to a focus at a corresponding point on the anode *x* to which they are drawn by its positive potential. The focusing is accomplished electromagnetically as described in Appendix I, where it is shown that the d-c field of coil *c* overcomes the divergence of the electron paths indicated by the dotted lines *d*. The result is as if the electrons all traversed parallel paths *e*. Thus, the distribution of cathode rays impinging upon the surface of *x* represents truly the optical image on *b*, and an electrical image is said to exist in the plane of *x*.

In the center of *x* is a square aperture *i* whose area is $h^2 = (H/n)^2$ from eq 1, where H is determined by the dimensions of the tube and n by its intended application. Aperture *i* selects the cathode rays from an elementary area of the electrical image as the aperture in Fig. 2 selects the light. Thence the rays pass into compartment *v* containing the elements of an electron multiplier which is part of the amplifier. These rays constitute an electron current flowing into *v*, whose magnitude is always proportional to the brightness of the part of the optical image whence the electrons are emitted. This current constitutes the initial picture signal which is amplified in *v*, and succeeding stages *F* and *G* of Fig. 1.

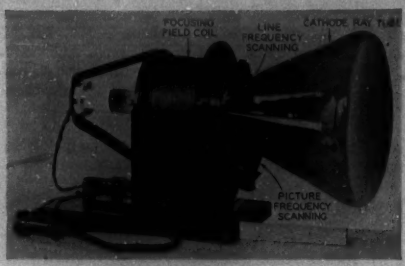


Fig. 4. Television reproducer; synthesizer for electronic scanning

To scan the scene, alternating currents are supplied to coils *o* and *q*, Fig. 5. Their transverse magnetic fields, superimposed on the longitudinal d-c field of coil *c*, cause the cathode rays *e* to bend as explained in Appendix I. This displaces the electrical image on *x* by an amount proportional to the instantaneous value of the scanning current. The fields of *o* and *q* act at right angles to each other. The amplitude of current in *o* and in *q* is each adjusted to cause a total displacement equal to the corresponding dimension of the image on *x*. The a-c supplied to coil *o* has a frequency equal to the picture frequency, N. The frequency supplied to coil *q* is N times the number of scanning lines desired. For a 240 line picture repeated 24 times per second, *o* would carry a 24 cycle current and *q* a 5,760 cycle current. The resultant horizontal and vertical motion of the electrical image across the aperture *i* is equivalent to a traversal of the image by the aperture as described in connection with Fig. 2. A complete analyzer unit including lens and scanning coils is shown in Fig. 3. Current for the tube and

Fig. 3. Television pick-up; analyzer for electronic scanning

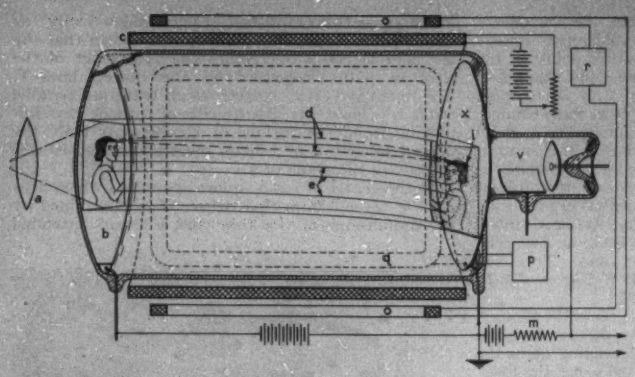


Fig. 5. The Farnsworth image dissector

scanning coils is supplied over a cable which also has a conductor for the signal output.

Sawtooth Wave Required for Scanning

The scanning currents are supplied to coils *o* and *q* by vacuum tube oscillators *r* and *p*, respectively, Fig. 5. The wave form of these currents is important because the signal intensity depends upon the rate of scanning. Therefore, if the rate of scanning is ununiform across the width of a picture field, the signal will not bear the same relation to light intensity in all parts of the field. This effect is exaggerated by the reproducer so that the picture appears to be unequally illuminated. To insure a uniform scanning rate a "sawtooth" wave form scanning current is employed. (See Fig. 7.) Such a wave form provides straight-line variations with time for scanning (*C-A* Fig. 7), and quick back-traces *A-B*. The latter provide convenient intervals in the picture signal for transmission of synchronizing impulses to control reproducer scanning. In Fig. 7 is shown the relation between the synchronizing impulses and the scanning wave.

The circuit of the oscillators used in the Farnsworth system to supply the sawtooth scanning currents is shown in Fig. 6. It employs a special tetrode similar to the ordinary power tubes employed in radio receivers except for the grid used for synchronizing. The circuit is similar to that of the conventional vacuum tube oscillators, but the peculiar wave form results from 2 unusual circuit parameters. First, the iron core transformer works in the region of saturation during part of the cycle; second, the grid of the tube is over-excited by an excessively large voltage developed in the grid winding of the transformer. The frequency is adjusted by varying the time constant of the *R-C* circuit in series with the grid winding. In the reproducer, the frequency, when set to the approximately correct value by variation of the grid leak, is controlled by signal impulses applied to the synchronizing grid of the tube. The same circuit, except for the manner of connecting to the deflecting coils, is used for both low and high frequency scanning. The generators consume from 10 to 30 watts each and are entirely dependable. The same type of generator is used in transmitter and receiver.

Electronic Scanning in the Reproducer

Electronic scanning in the reproducer operates on essentially the same principles as it does in the analyzer. The chief difference is that the electron stream in the cathode ray reproducer tube is of small cross section in contrast to the complex bundle of rays in the image dissector. The small ray in the reproducer tube is magnetically focused to a small spot on the fluorescent screen in the tube and is deflected back and forth across the screen by fields

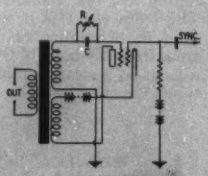


Fig. 6. A sawtooth wave generator

of sawtooth alternating currents in such a way that the desired area of the reproduction is traced with 240 or more parallel lines each $^1/_{24}$ sec. The picture signal acting on a grid in the cathode ray tube modulates the ray as it moves about and thereby reproduces the scene upon the fluorescent screen.

Light Translation in the Analyzer

Light translation in the photo-electric film of the analyzer is essentially a conversion of light energy into that of electron motion whereby electrons are released from the photo-surface. The chief requirements of the photo-electric film for television are sensitivity, rapidity of response, electron emission,

linearity between emission current and light intensity, and response to a convenient color range.

Maximum sensitivity and rapidity of response are made particularly necessary by the scanning operation as shown by the following example. It was determined by experiment with the dissector that a picture field illuminated at an intensity of 188 ft-c produced an image of 1.37 ft-c intensity on the surface of *b*, Fig. 5, when a fast lens was used. The area of the image on *b* was 0.0875 sq ft and the photoelectric sensitivity 35 μa per lumen. The total emission was 4.2×10^{-6} amp. The emission from an element of area, the size of the scanning aperture, for 240-line scanning would be $4.2 \times 10^{-6}/n^2 = 0.695 \times 10^{-10}$ amp. In Appendix II it is shown that an aperture of this size crosses a boundary in 0.725 μsec. Thus the quantity of electricity would be $0.725 \times 10^{-6} \times 0.695 \times 10^{-10} = 0.504 \times 10^{-16}$ coulomb or only 317 electrons.

In television transmission from motion picture film a much more intense illumination is possible than that assumed in the foregoing example. This makes limited sensitivity a less serious difficulty in motion picture transmission. By use of the electron multiplier, small electron currents such as those of the above example are readily amplified so that scenes from life with very moderate light intensity may be transmitted.

The alkali metal film photo-electric surfaces are electron emissive and their light response is very nearly linear. For this reason they qualify for television use. Sunlight and the light from incandescent lamps is rich in red radiation and for this reason a red sensitive photo-electric material is to be preferred. A film formed of caesium on oxidized silver is by far the most sensitive of all materials to red light and at the same time it meets the other requirements named above. It is therefore used in the image dissector. Caesium-oxide-silver films have a sensitivity to light from the mazda lamp, ranging from 20 to 40 μa per lumen. This sensitivity is 10 times as great as that of a plain metallic caesium surface and about 10,000 times as great as that of a metallic potassium surface.

Light Translation in the Reproducer

In reproduction of light from the television signal the character of light source is much influenced by the method of scanning. The sources of artificial light are relatively few, namely: incandescence, ionization of gas, and fluorescence (or phosphorescence). Incandescence of the familiar types and gas ionization are too sluggish to operate well with the high scanning speeds now in use and they are not well adapted to electronic scanning. Fluorescence has the advantage of responding to an excitation of very short duration as well as making the direct application of cathode ray scanning relatively simple. There are a large number of fluorescent materials, but the one favored at present for use in tubes for television purposes is synthetic zinc silicate closely resembling in composition the mineral, Willemite. Two outstanding qualities effect its choice: It is highly resistant to chemical decomposition under electron bombardment, and the pale green light which it produces is near the color range to which the human eye responds most strongly. The intensity of illumination is approximately proportional to the current in the cathode ray, which makes possible an illumination response nearly linear with respect to signal voltage in a properly designed tube. A strong cathode ray will produce a fluorescent light intensity of several candle power, which is adequate for a small field.

Excellent pictures can now be reproduced for viewing directly on the cathode ray tube; these may be as large as 5 by 7 in. A tube for this service is shown in Fig. 4. They are bright enough to be viewed in a moderately illuminated room, and are almost equal in detail to good home motion pictures. Much attention is now being given to development of tubes which will produce pictures of sufficient brilliance to permit projection, while retaining the outstanding good television characteristics of the present tubes.

Amplification

The unusual wave forms typical of television, and the exceeding smallness of the current output from a picture element, combine to make severe demands

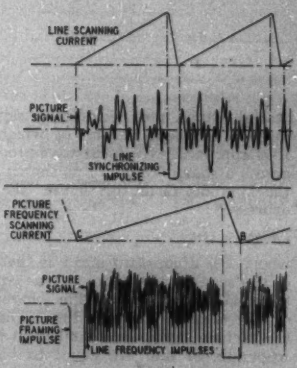


Fig. 7. Sawtooth scanning waves, television signal, and synchronizing impulses showing relative positions on time axis

upon an amplifier if it is to give true reproduction. The resistance-capacitance coupled amplifier is employed at the transmitter (*F* and *G* Fig. 1) and the receiver. Being designed for a wide band of frequencies and good transient response, it meets the requirements in all respects except amplification of the minute initial signals produced by low levels of light intensity. The capabilities of the amplifier are shown by analysis of a typical signal, Fig. 2, which it transmits. This wave was obtained by plotting photo-cell currents due to light passing through an aperture moved across the picture as indicated.

The outstanding characteristics of the wave in Fig. 2 which determine the requirements of the am-

plifier are: Amplitude range, transient nature of parts of the wave, range of frequency components, and dissymmetry.

The amplitude, corresponding to ranges of light intensity, expressed by the ratio of maximum to minimum photo-electric current, is found to be 30:1. The wave is made up of parts approaching

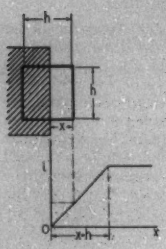
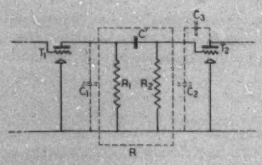
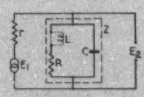


Fig. 8. Scanning across a sharp boundary

Fig. 9 (left, below). Schematic of resistance-capacitance coupled amplifier stage

Fig. 10 (right, below). Equivalent circuit of an amplifier stage





straight lines, not periodically repeated and therefore of transient nature, of which A-B is typical. A-B approaches the ideal wave produced by scanning across a sharp boundary as shown in Fig. 8. Using the symbols from this figure, the current may be expressed:

$$i = khx = khvt \qquad (2)$$

where k is a constant and v is the constant velocity of the scanning aperture. This equation, from Fig. 8, explains the straight line character of the parts of the wave of Fig. 2. The highest frequencies in the picture signal are found from eq 2 as shown by Appendix II and are equal to $^1/_2Nn^2$ where N is the number of picture repetitions per second and n is the number of scanning lines per picture. This frequency is 691 kc when $N = 24$ and $n = 240$. By contrast, the lowest frequencies of the signal are generally equal to the picture frequency N.

Dissymmetry of the picture signal wave exhibited by Fig. 2 is common. The high peaks corresponding to the brilliant areas of the picture are termed the positive signal. The synchronizing impulses which are introduced at the end of each scanning line and at the end of each picture are also unsymmetrical and are given a negative polarity and large amplitude. (See Fig. 7.) These qualities permit their selection from the picture signal for control purposes by a part of the receiver amplifier L in Fig. 1. Due to the unsymmetrical character of the signal and impulses together with a 180-deg phase-shift per stage in the amplifier, a positive signal and image can be created only from alternate stages. An even number of stages is employed with the analyzer and reproducer here described.

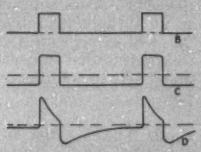
Circuit Characteristics of the Amplifier

The circuit characteristics of a resistance-capacitance coupled amplifier which are employed to provide the foregoing qualities are shown by a brief analysis of a typical stage. A complete interpretation of the transient behavior in terms of circuit constants involves somewhat difficult mathematics, but a good approximation may be had from an analysis of steady state behavior at the upper and lower limits of the frequency range.

To amplify the lowest frequencies in a typical stage such as that of Fig. 9 the resistance of R_2 is made large compared to the reactance of C'. For $f = 24$ cycles per second and $C' = 0.1$ μf, $X_c = 66{,}000$ ohms. By employing 500,000 ohms for R_2, a small number of stages gives good results. Failure to provide a large enough value for the time constant $C'R_2$ produces the distorted form shown as D in Fig. 11 from a very low frequency square-topped wave like B of Fig. 11.

At the high frequency end of the band the reactance of C' becomes neglible and the combination $R_1C'R_2$ acts as a single resistor R. But the reactance of inter-electrode capacitance in the tubes and the stray capacitance of the circuit elements to ground becomes comparable to R, thus introducing phase shift and attenuation of high frequencies. Since the highest frequencies are components of transient waves, their attenuation causes blurred and indistinct outlines or boundaries of objects in a scene, as indicated by the rounded corners of C in Fig. 11.

Fig. 11. Traces from oscillograms showing distortion of typical square television wave by a deficient amplifier



The manner in which these distortions are avoided may be shown by a brief analysis of the equivalent circuit of a single tube and its coupling unit in Fig. 10. This is a circuit of a generator with a high resistance, but is complicated by the fact that the frequency is variable between wide limits. The internal plate resistance of the tube is represented by r. Z is the load or coupling unit in which is included the sum of the inter-electrode and stray capacitances, C. Its simplest form is R and C in parallel, but it is sometimes desirable to add inductance L in the R branch so as to maintain the value of Z and limit the phase angle to a higher frequency range. E_1 is the voltage developed in the plate circuit of the tube and is equal to the product of the grid voltage and the amplification factor of the tube. E_2 is the voltage applied to the grid of the next tube.

From Kirchhoff's laws, $E_2/E_1 = Z/(r + Z)$, an expression whose values may readily be calculated by aid of the chart shown in Fig. 12. Here the horizontal lines represent resistances and the oblique lines represent reactances, those sloping to the right being capacitive and those sloping to the left being inductive. For example, line 2 is $R = 10{,}000$ ohms; line 8 gives the reactance of a 40-$\mu\mu$f condenser at various frequencies, and line 7 the reactance of a 4-mh inductance. By calculating a few values of Z for various reactances, the balance of the curve may be sketched in, and thence the values E_2/E_1 may be calculated at salient points.

Curve 3 gives Z for a typical amplifier stage with a total shunt capacitance of 40 $\mu\mu$f and indicates the effect of the falling reactance of the capacitive component. Curve 5 gives the phase angle, which reaches 45 deg at 400 kc and would cause much trouble in a picture having frequency components of this value. Curve 4 shows Z with 4 mh inductance in the R branch of the same amplifier and illustrates the improvement in the upper frequency range, the impedance holding up to 600 or 700 kc; below 400 kc the phase angle is less than in the case without inductance.

Circuit characteristics of this nature, employed with present types of radio receiver tubes, permit voltage gains of from 6 to 18 db per stage. The frequency response may be judged from the characteristics in Fig. 12. The total gain required is, of course, dependent upon the power of the radio carrier to be modulated.

The smallest value of initial signal which can be amplified by even the best amplifier is limited by spurious noise (see "A Study of Noise in Vacuum Tubes and Attached Circuits," by F. B. Llewellyn,

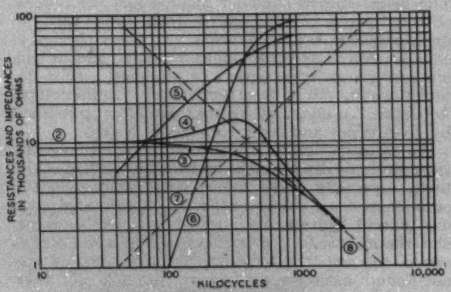


Fig. 12. Amplifier response curves

I.R.E. *Proc.*, v. 18, no. 2, 1930, p. 243–65), associated with the input and first stage. The initial signal may easily be below this limit with the best present-day photo-electric surfaces when the light intensity is much below the value given as an example in the foregoing discussion of light translation. To overcome this limitation, an electron multiplier is employed in the Farnsworth system for pre-amplification, and a resistance-capacitance coupled amplifier used only for final stages in the transmitter.

The electron multiplier E, Fig. 1, and V, Fig. 5, is an ingenious device for increasing electron currents by secondary emission. It is able to produce large amplification without distortion and makes possible the "pick-up" of television images from life with fine scanning and moderate illumination. A description of this instrument is beyond the scope of this paper.

Propagation

Transmission of the television signal may be accomplished by wire or radio. Wire transmission is expensive because of the very wide frequency channels required for transmission of scenes which will sustain human interest. For this reason broadcasting by radio is generally accepted as the most

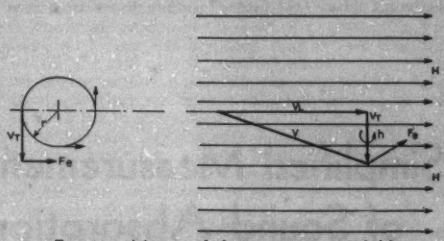


Fig. 13. Motion of electron in magnetic field

useful application of television. Television seems destined to make use of the ultra-high radio frequencies in the region between 30 and 300 megacycles (10 to 1-m wave length). (See "Seventh Annual Report of the Federal Radio Commission," for the fiscal year 1933.) The propagation of these frequencies is limited to relatively short range by rapid attenuation of waves beyond the horizon, but in spite of this they offer an effective means of local broadcasting well adapted to the wide frequency channels of television.

The engineering features of radio transmitting and receiving equipment for television present little that is novel, wherefore it is unnecessary to dwell on this phase of the television system.

Appendix I

Magnetic focusing of an electron stream in vacuum is based upon the fact that an electron in motion constitutes a current which is surrounded by a magnetic field (h in Fig. 13) in the same manner as a current in a conductor. (See "A Text Book of Physics," a book, by A. Wilmer Duff. P. Blakistons' Sons and Co.) Likewise it is subject to the same type of forces due to an external field. The velocity V of an electron in a magnetic field of intensity, H may be resolved into components V_L parallel to the field and V_T at right angles. (See Fig. 13.) V_T may be considered independently of V_L (see "Principles of Electricity," a book, by L. Page and N. I. Adams. D. Van Nostrand Co.). F_e represents the force on the electron due to interaction between h and H. It is always per-

pendicular to both V_T and H and its magnitude is $F_s = HeV_T$, where e is the charge on the electron. V_L has no effect upon F_s.

F_s acts as a centripetal force and the path of the electron is a circle. By Newton's law, a centripetal force, $F_s = mV^2/r$ where m = electron mass, $V = V_T$ of the preceding equation, and r = radius of circular path. Combining these equations, $H(e/m) = V_T/r$. V_T/r is the angular velocity w and e/m is constant. Therefore, if H is constant, w is constant; whence it follows that if V_T increases r decreases and *vice versa*.

A group of electrons with different values of V_T, issuing from the same point, will go around circles of different radii, r, all completing the cycles in the same time $t = 1/w = (2\pi r)/V_T$. If all have the same value of V_L, which condition can be closely approached in practice, they will travel the same distance l, in the direction of V_L, in the time t, thus:

$$l = tV_L = (2\pi r V_L)/V_T = (2\pi m V_L)/He$$

Thus at a distance l from their source, all electrons of such a group occupy the same positions with respect to one another as they did at their source. If the virtual source is an aperture, as is the case of the anode of a cathode ray tube, at distance l from this aperture the electron paths converge to a bundle slightly smaller than the aperture from which they issued. Similarly if the source be a plane area such as the photo surface of the image dissector, in a plane section at a distance l the electrons come into the same relation to one another as they had at the source, and an electrical image is formed.

When a transverse deflecting field is superimposed upon a focusing field, V_L of the foregoing equations becomes the transverse velocity with respect to the new field. Then the axes of the electron rays are bent on arcs of circles by this new field until the electrons pass beyond the influence of this field. This accomplishes the deflection of the electron paths.

Appendix II

In Fig. 8, when the scanning aperture completes the crossing of the boundary, $x = h$. If the corresponding value of t is called t', eq 2 of text becomes $t' = h/v$. For a picture period of P sec and n scanning lines, $v = n^2h/P$ whence $t' = P/n^2$. When $P = 1/16$ sec and $n = 240$ lines, $t' = 0.725$ μsec. An amplification system is ordinarily assumed to be satisfactory if it will transmit frequencies of which the period is twice that of t', that is, $1/2$ cycle occurs in time t'. On this basis it is usually stated for a square picture that the highest frequency in the television signal is $f = 1/2n^2/P$. Where $1/P = N$ = picture repetitions per second, $f = 1/2Nn^2$. A more rigorous equation may be provided by introducing the ratio, r, of width to height of picture, and the factor C, where the edge shadow is Ch instead of h units wide. Then $f = 1/2CrNn^2$.

Simplified Measurements of Sound Absorption

By
ARTHUR L. ALBERT
ASSOCIATE A.I.E.E.

TOM B. WAGNER
ENROLLED STUDENT A.I.E.E.

Oregon State College, Corvallis

A modification of the tube or reflected wave method for measuring the sound absorption coefficients of acoustic and building materials over a wide frequency range is described in this paper. Modern communication equipment is used, and a high degree of reliability is obtained. The method is especially well adapted to rapid routine tests of acoustic materials in commercial production, and in other instances where measurements by the more elaborate and expensive reverberation-chamber method are not justified.

THE AMOUNT of sound absorbing material in a studio or auditorium is a very important factor in determining the acoustical characteristics, and hence the suitability of such rooms for speech and music. The sound-absorption coefficients of the materials used in the construction and acoustical treatment of such rooms, therefore, must be known. The reverberation-chamber method and the tube or reflected-wave method have both been used to measure absorption coefficients. Of these, the first is usually considered the more reliable, and is the method generally accepted as standard. (For descriptions of both of these methods see "Architectural Acoustics," a book, by Vern O. Knudsen, published by John Wiley and Sons, New York, N. Y.)

An examination of the literature describing the tube methods discloses the fact that in certain of the tests, especially those made some years ago, the equipment used was unsatisfactory compared with our present high-quality microphones, loudspeakers, and thermionic-tube amplifiers. This is, no doubt, one of the important reasons the tube method was not found entirely satisfactory and has not been widely accepted.

This paper describes the results of an investigation in which modern equipment was used to determine the sound-absorbing properties of materials by a tube method. The results are very satisfactory, indicating that with inexpensive and easily obtainable apparatus it is possible to build equipment for quickly and reliably determining the sound-absorption coefficients of unknown specimens by comparing them with known materials previously standardized by the reverberation-chamber method.

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. Pacific Coast convention, Sept. 5–7, 1934. Manuscript submitted May 14, 1934; released for publication June 12, 1934. *Not published in pamphlet form.*

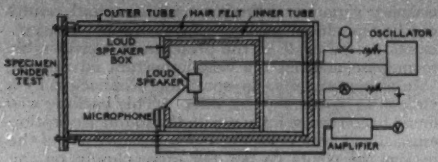


Fig. 1. Simplified diagram of apparatus used

Theoretical Considerations

When a sound wave strikes a smooth surface such as varnished wood, 3 phenomena occur. First, a very small part of the sound energy is transmitted through the wood. Second, a small amount is absorbed in air-friction losses in the surface irregularities and interstices. Third, about 97 per cent of the sound energy is reflected back into the room, causing a prolonging of the sound and, under certain conditions, excessive reverberation.

If one end of a tube is closed with some material such as varnished wood, and if a pure tone is introduced at the other end, reflection from the closed end of the tube will be almost perfect. Under the proper conditions of frequency and length of tube, standing waves with pronounced nodes and antinodes will result along the tube. These are caused by the combinations of the initial and reflected waves at various points along the tube.

If now the end is closed with a sound-absorbing material such as hair felt, only about 40 per cent (depending largely upon the type and the frequency) of the sound is reflected, and the remainder is absorbed in the interstices of the hair felt. With such a material closing the end of the tube, the reflected wave will be relatively weak and the standing waves along the tube will not be so pronounced. The sound-absorption coefficient of any specimen therefore can be determined by comparing the standing waves this unknown material causes with those produced by a previously standardized material having known coefficients.

In this investigation, simplicity, commercial practicability, and engineering reliability were considered of primary importance. Thus, although it is possible to calculate the sound-absorption coefficients from measurements made by the tube method (see previously mentioned book by Vern O. Knudsen), it was decided best to obtain these coefficients by comparison with materials previously tested by the reverberation-chamber method.

Apparatus Used

A schematic diagram of the equipment used in this investigation is shown in Fig. 1, and a front view with the test specimen removed is shown in Fig. 2. The inner and outer tubes are made of fir lumber about $^3/_4$ in. thick. The 2 tubes are separated by hair felt one inch thick. This construction keeps room noises from affecting the microphone and also largely prevents sound radiation into the room. The inner tube is provided with a wooden flange and bolts upon which the test specimen is clamped.

The loud-speaker box is made of fir plywood and is lined with hair felt one inch thick. Two hair felt baffles are also placed lengthwise in the box. This absorbing material prevents the box and the tube from exerting an appreciable influence upon the back of the loud-speaker cone.

Preliminary experiments indicated that a loud speaker having a uniform frequency response was necessary, and a moving-coil or dynamic loud speaker of the type widely used in radio receiving sets was adopted. Provisions were made, as shown in Fig. 1, for holding the input current and the field excitation at constant values.

A piezo-electric crystal microphone was used to measure the sound-wave pressure in the tube. This device is rugged, not subject to mechanical shock, has good frequency response and constant output, and is inexpensive. The microphone was connected to a 3-stage resistance-coupled amplifier using type 30 tubes. The amplifier output was measured with a copper-oxide voltmeter.

As Fig. 2 shows, the microphone was fastened directly to the loud-speaker baffle, and the entire assemblage was moved along the tube by the screw-drive arrangement shown in this figure. A coiled flexible steel tape was arranged to indicate the dis-

Fig. 2. Front view of equipment with test specimen removed

Fig. 3. Rear view of tube and of electrical equipment

tance between the loud-speaker baffle and the specimen under test. This tape, the handwheel for turning the screw, and the measuring equipment are shown in Fig. 3.

Test Procedure

After the apparatus was assembled, extensive tests were made to find the optimum loud-speaker current at the various test frequencies. Also, many positions along the tube for the loud speaker and microphone were studied to determine the best location at each test frequency.

The results of moving the apparatus along the tube and taking measurements at various points are illustrated in Fig. 4. This curve can be explained in the following simple manner. Suppose that the loud speaker and microphone are located a distance of $^1/_4$ wave length from the specimen under test, and that at a given instant the loud-speaker cone is moving forward sending out a maximum pressure wave. By the time this impulse moves forward to the specimen, is reflected, and arrives back at the baffle, the cone is moving in the opposite direction, and wave cancellation and a minimum voltage output results. Now assume that the apparatus is located $^1/_2$ wave length from the specimen under test. The path is now one wave length long, and a reflected wave arrives back at the baffle in phase with the motion of the cone, and a pressure peak results producing a maximum voltage indication.

The equipment was calibrated to measure the sound-absorption coefficients by placing materials having known coefficients on the end of the tube and observing the voltage output under the best operating conditions as previously determined. As mentioned, materials which had been tested by the reverberation-chamber method were used. From data thus obtained, calibration curves such as Fig. 5 were made for each test frequency. With these curves available, it is merely necessary to place an unknown specimen on the end of the tube, adjust the apparatus for operating conditions, measure the output voltage, and obtain the sound-absorption coefficient at the test frequency from the proper calibration curve.

Discussion of Results

As is evident, this method is simple in operation, and requires only inexpensive apparatus. The assembled equipment must, however, be carefully studied to ascertain optimum test conditions. Once the calibrations are made, they are not affected by ordinary variations in room conditions, and results can be reproduced readily. Furthermore, measurements can be made in the presence of considerable room noise, and this is a very important advantage.

In making all tests, the specimen was backed by a piece of fir plywood $^3/_4$ in. thick. This backing was found to exert some influence on the sound absorption especially at low frequency, and is possibly one of the reasons the points do not fall more closely on the calibration curve of Fig. 5. Another reason these calibration points do not fall on the curve is that wide discrepancies apparently exist in the results various observers obtain with the reverberation-chamber method. Furthermore, individual samples deviate widely from published coefficients and from the mean value of a large number of measurements (see "Less Noise—Better Hearing," v. 6, No. 1, 1934, of Celotex Acoustical Department, 919 North Michigan Avenue, Chicago, Ill.).

It may be assumed that the tube method here described is not as good as reverberation-chamber tests because in the latter, actual conditions of installation are more nearly reproduced. There is, undoubtedly, some truth in this, especially where the material is mounted on large panels which themselves absorb sound. The standardized materials used to calibrate the tube were tested, however, by different authorities under different conditions of mounting, and the agreement as Fig. 5 indicates is fairly good.

One of the important advantages of this tube method is that with a single group of equipment, tests can be made over a wide frequency range. In this investigation the coefficients at frequencies of 512, 1,024, 2,048, and 4,096 cycles were obtained readily. For frequencies below 512 cycles, the tube vibrated so badly that tests were impossible. This could be remedied by constructing a tube of thicker lumber.

Conclusions

It is apparent that the tube method of measuring the sound-absorption coefficients of various acoustic and building materials is satisfactory when modern apparatus is used. With properly calibrated equipment, the method is entirely satisfactory for original measurements over a wide frequency range. It is especially well adapted, however, for making routine tests such as required in the commercial production of absorbing materials, and for approximate determinations, where the more elaborate and expensive reverberation-chamber tests are not justified.

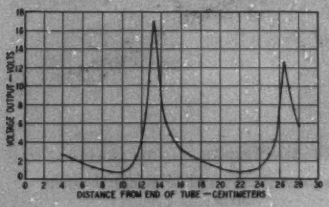
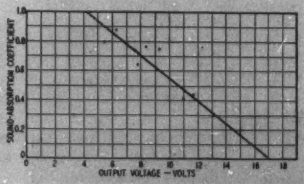


Fig. 4 (left). Voltage output of amplifier as the loud speaker and microphone are moved along the tube when it is closed with varnished wood

Fig. 5 (right). Calibration curve for tube at 2,048 cycles per second



Theory and Tests of the Counterpoise

Different theories have been advanced as to the behavior of the counterpoise in the protection of power transmission lines against lightning. In an attempt to learn more about the counterpoise and to check the theories of its behavior, a series of basic field tests was conducted. The results of these tests, made on both the parallel insulated counterpoise and the buried counterpoise, are reported in this paper. The data obtained are analyzed, and conclusions are drawn.

By
L. V. BEWLEY
ASSOCIATE A.I.E.E.

General Electric Co.
Pittsfield, Mass.

THE counterpoise, consisting of conductors connected to transmission line towers so as to reduce the tower footing impedance, has recently been subjected to considerable study as a means of securing protection against lightning. The purpose of the field tests described herein was to study the action of a counterpoise in detail; particularly in the light of an analytic theory (see "The Counterpoise," by L. V. Bewley, *G.E. Rev.*, 1934, v. 37, p. 73–81) and with the object of testing the validity of that theory. Theoretical considerations had pointed to 3 major effects present in the behavior of a counterpoise:

1. The transient impedance, beginning with the initial or surge impedance effect and ending with the final or leakage resistance effect, the time of transition depending upon the ground resistivity and, due to the formation of corona, on the surge voltage.

2. The coupling effect with overhead conductors, depending primarily upon the location of the current images and the direction of the counterpoise.

3. The multi-velocity wave components, particularly the low velocity component predominating on the counterpoise and governing the time of arrival of reflections.

Various investigators have proposed different theories to account for counterpoise behavior, but there has been lack of agreement both with respect to the mechanism of the phenomena and with respect to the magnitude of the several factors involved. And this has led, quite naturally, to very pronounced differences in the calculated effects. Previous field tests on counterpoises have not been sufficiently complete in one respect or another to permit a rational verification of any theory; although these previous tests have provided several salient datum points for checking purposes. It was therefore deemed desirable to make a set of basic field tests on counterpoises which would place the analytic theory on trial and determine its exactness and rigor. The most favorable location for such tests would be in a region of very high soil resistivity and where the water level is at great depth; for under such conditions the counterpoise action is very definite. The only objection is the difficulty of securing a low resistance ground for the cathode ray oscillograph. Obviously, if the ground resistivity is nil, no effect can be expected of a counterpoise buried in earth which is already an excellent conductor. Unfortunately the circumstances under which the present tests were made were far from ideal for the purpose of studying counterpoise action, because the water level was not far down and the soil resistivity not high. Therefore the recorded effects were not as pronounced or consistent as could be desired, but nevertheless serve to verify the validity of the theory.

A lightning stroke of surge impedance Z and voltage wave E striking a transmission line tower having a ground wire, line wire, counterpoise, and footing resistance, is shown in Fig. 1. In order to simulate this condition, the test set-up was arranged as shown in Fig. 2. The portable impulse generator, representing the cloud, was 3,077 ft away from the counterpoise pole. It was rated 0.0125 μf and 1,000 kv on open circuit. The surge was initiated from the cathode-ray oscillograph over a spare line conductor.

The 3,077 ft of line between the impulse generator and the counterpoise pole, representing the surge impedance of the lightning stroke, was No. 6 copper wire supported on 30-ft wood poles with 6-unit insulators.

The portable cathode-ray oscillograph was situated at the counterpoise pole, Fig. 3, and in telephone communication with the impulse generator. Incidentally, both these pieces of equipment were veterans of several years previous field tests carried on by the lightning arrester engineering department of the General Electric Co. An independent driven ground of 60 ohms was obtained for the oscillograph about 20 ft from the pole.

At the counterpoise pole there were 2 overhead No. 6 copper wires at 8.5-ft horizontal spacing and sup-

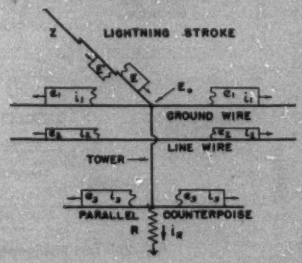


Fig. 1. Conditions at the stricken tower

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. Pacific Coast convention, Salt Lake City, Utah, Sept. 3–7, 1934. Manuscript submitted May 31, 1934; released for publication June 25, 1934. *Not published in pamphlet form.*

ported with pedestal insulators on 30-ft wood poles. One of these conductors could be used to represent a ground wire and the other the line wire. This was preferable to a permanent ground wire, because it allowed the ground wire effect to be segregated.

The counterpoise was a 0.25-in. steel wire with a total length of 927 ft. It was initially supported on short treated wood insulating stakes so as to avoid the leakage effect, but was finally buried in the earth to a depth of 12 in. It was first tested perpendicular and then parallel to the overhead conductors. When laid perpendicular to the line it was verified that there was no coupling with the line conductors.

Tests on Parallel Insulated Counterpoise

A 925-ft counterpoise was laid parallel and directly underneath the 2 line conductors, and grounded at its far end through pipes driven into the ground. It was boped by this procedure to obtain very definite values for the velocity of propagation and surge impedance and hence definitely locate the voltage and current images. However, the tests under this condition were somewhat disappointing in these respects; because the earth resistivity was so low that normal test errors in the determination of the velocity and surge impedance were sufficient to cause a wide variation in the values obtained.

The tests made on the parallel insulated counterpoise are shown in Fig. 4. Three conditions were investigated:

I. Counterpoise present but disconnected, and the surge applied to one of the overhead wires. This condition is similar to that of lightning striking a ground wire at midspan. For the purpose of these tests this connection allowed the effect of the ground wire to be segregated.

II. Surge applied to the counterpoise alone, with the 2 overhead wires isolated. This test segregates the effect of the counterpoise alone.

III. Surge applied jointly to an overhead wire and the counterpoise. This condition yields the combined effect of a ground wire and counterpoise, and corresponds to the practical case of lightning striking a tower having both ground wire and counterpoise.

Table I—Tests on Parallel Insulated Counterpoise

Condition	I—Fig. 4	II—Fig. 4	III—Fig. 4
e_1	47,600	3,015 (2,850)	32,400
e_2	11,520 (11,320)	3,015 (2,850)	8,725 (9,200)
e_3	2,950 (2,350)	44,400	32,400
i_1	86 (85)		60.5 (54.2)
i_2		100 (106.5)	80 (74.3)
$F_{1,2}$	0.242 (0.238)		
$F_{1,3}$	0.062 (0.049)		
$F_{2,3}$		0.068 (0.064)	
$F_{12,3}$			0.269 (0.254)

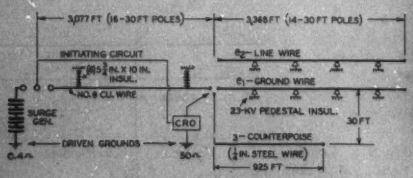


Fig. 2. Test arrangement

The average results of these tests are summarized in Table I, the figures in parentheses being calculated values, and the F's coupling factors.

The surge impedance of the counterpoise was measured in 3 different ways:

1. By the ratio of voltages at the junction between line and counterpoise.

2. By reflection from the end of the counterpoise grounded through various values of resistance.

3. By the ratio of the voltage to the current taken at the entrance to the counterpoise.

In general the 3 methods gave results of the same order, but the first method is too sensitive to small variations in the applied surges; while the second method does not take into consideration that the impulse resistance of a driven ground is somewhat lower (about 20 per cent) than its d-c resistance. Furthermore, only the last method provides a way of showing the variation of the surge impedance as function of time. From the oscillograms of condition II of Fig. 4 it is seen that after 0.5 μsec the counterpoise voltage is increasing, while its current is decreasing, so that the surge impedance is increasing with the passage of time. There was an 8.8-ohm resistance connected in series for making current measurements and therefore the surge impedance was

$$Z_3 = \frac{e_3}{i_3} - 8.8 = \begin{cases} 398 \text{ ohms at } t = 0.5\ \mu\text{sec} \\ 445 \text{ ohms at } t = 2.0\ \mu\text{sec} \end{cases}$$

The velocity determination, as ascertained by the time required for reflections to return from the end of the counterpoise, gave values from 81 per cent to 92 per cent of the velocity of light. This, of course, was the average velocity, and should be associated with the average surge impedance. The velocity on the overhead lines was between 96 per cent and 99 per cent of the velocity of light.

Fig. 3. Cathode ray oscillograph at location

Theoretically, the inductance and capacitance can be computed from the surge impedance and the velocity, and therefrom the location of the voltage and current images.

$$L = \frac{2}{10^9} \log\left(\frac{2h}{r}\right) = \frac{Z}{v} = \frac{\text{surge impedance}}{\text{velocity}}$$

$$\frac{1}{C} = 18 \times 10^{11} \log\left(\frac{2H}{r}\right) = Zv$$

in which

$2h$ = distance to current image
$2H$ = distance to voltage image
r = radius of conductor
Z = surge impedance
v = velocity of propagation

Small variations in the measured values of either Z or v will cause radical changes in the calculated value of h. Thus if $Z/v \simeq 18 \times 10^{-9}$, then an error of only ± 5 per cent in the determination of this ratio will make a 300 per cent variation in the location of the current image. On the other hand, inductance coefficients are not sensitive to variations in h and therefore its precise determination is not mandatory. Using an average value of 420 for the surge impedance and 85 per cent for the mean velocity gives

$$L = \frac{420}{0.85 \times 3 \times 10^{10}} = \frac{16.4}{10^9} = \frac{2}{10^9} \log\left(\frac{2h}{0.125}\right)$$

$$\therefore 2h = 38 \text{ ft}$$

$$\frac{1}{C} = 420 \times 0.85 \times 3 \times 10^{10} = 107 \times 10^{11} = 18 \times 10^{11} \log\left(\frac{2H}{0.125}\right)$$

$$\therefore 2H = 4 \text{ ft}$$

Incidentally, these figures agree with other data, as well as theory, showing that the zero potential plane for voltage images is very close to the surface of the earth. The capacitance of the counterpoise as measured by a bridge was 3.13×10^{-9} for 925 ft as compared with 2.64×10^{-9} by the above calculation.

Using $h_3 = 19$ and $H_3 = 2$ ft, and designating the ground wire, line wire, and counterpoise by subscrips 1, 2, and 3, respectively, there are:

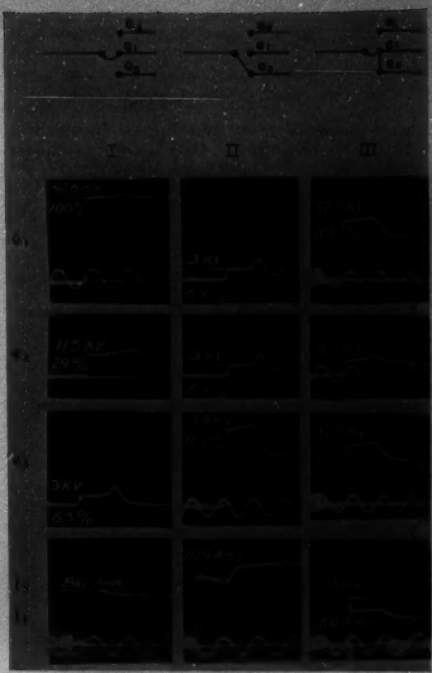


Fig. 4. Oscillograms taken on insulated counterpoise

$r_1 = 0.081$ in.	$h_1 = 48$ ft	$L_{11} = 9.55 \times (2 \times 10^{-9})$	$K_{11} = 0.1154 \div (18 \times 10^{11})$
$r_2 = 0.081$ in.	$h_2 = 48$ ft	$L_{22} = 9.55 \times (2 \times 10^{-9})$	$K_{22} = 0.1154 \div (18 \times 10^{11})$
$r_3 = 0.125$ in.	$h_3 = 19$ ft	$L_{33} = 8.20 \times (2 \times 10^{-9})$	$K_{33} = 0.1700 \div (18 \times 10^{11})$
$R_1 = 0.081$ in.	$H_1 = 31$ ft	$L_{12} = 2.43 \times (2 \times 10^{-9})$	$K_{12} = -0.0252 \div (18 \times 10^{11})$
$R_2 = 0.081$ in.	$H_2 = 31$ ft	$L_{13} = 0.84 \times (2 \times 10^{-9})$	$K_{13} = -0.0020 \div (18 \times 10^{11})$
$R_3 = 0.125$ in.	$H_3 = 2$ ft	$L_{23} = 0.84 \times (2 \times 10^{-9})$	$K_{23} = -0.0020 \div (18 \times 10^{11})$

Referring to Appendix A, the auxiliary constants are:

$I_{11} = I_{22} = 1.040$	$a_{11} = 1$	$Y_{11} = 0.1407/60$
$I_{13} = I_{21} = 0.038$	$a_{12} = 1$	$Y_{12} = 0.0892/60$
$I_{12} = I_{23} = 0.118$	$a_{13} = 1$	$Y_{13} = 0.0706/60$
$I_{31} = I_{32} = 0.059$	$a_{21} = -1$	$Y_{21} = -0.1407/60$
$I_{33} = 1.391$	$a_{22} = 1$	$Y_{22} = 0.0892/60$
$v_1 = 1.000$	$a_{23} = 1$	$Y_{23} = 0.0706/60$
$v_2 = 0.981$	$a_{31} = 0$	$Y_{31} = 0$
$v_3 = 0.836$	$a_{32} = -0.343$	$Y_{32} = -0.0612/60$
	$a_{33} = 2.965$	$Y_{33} = 0.418/60$

In terms of the multi-velocity wave components $f_1(x - v_1t)$, $f_2(x - v_2t)$, and $f_3(x - v_3t)$ the voltage surges on the 3 conductors are

$$\left.\begin{aligned} e_1 &= f_1 + f_2 + f_3 \\ e_2 &= -f_1 + f_2 + f_3 \\ e_3 &= -0.343 f_2 + 2.97 f_3 \end{aligned}\right\} \quad \text{(A)}$$

The current surges are

$$\left.\begin{aligned} i_1 &= (0.1403 f_1 + 0.0892 f_2 + 0.0706 f_3)/60 \\ i_2 &= (-0.1403 f_1 + 0.0892 f_2 + 0.0706 f_3)/60 \\ i_3 &= (-0.0612 f_2 + 0.4180 f_3)/60 \end{aligned}\right\} \quad \text{(B)}$$

The magnitudes and signs of f_1, f_2, and f_3 depend upon the terminal conditions. Corresponding to the 3 conditions of test, there are:

Condition I

$e_1 = E_0$ = voltage applied to ground wire
$i_2 = 0$ = current in line wire
$i_3 = 0$ = current in counterpoise

Hence by eqs A and B

$f_1 = 0.381\ E_0$; $f_2 = 0.540\ E_0$; $f_3 = 0.079\ E_0$

and therefore, writing $E_0(v_1)$ for a component of magnitude E_0 traveling at a velocity v_1, there is by eq A:

$$\begin{aligned} e_1 &= 0.381\,E_0(v_1) + 0.540\,E_0(v_2) + 0.079\,E_0(v_3) = (1.000\,E_0) \\ e_2 &= -0.381\,E_0(v_1) + 0.540\,E_0(v_2) + 0.079\,E_0(v_3) = (0.238\,E_0) \\ e_3 &= - 0.185\,E_0(v_2) + 0.234\,E_0(v_3) = (0.049\,E_0) \end{aligned}$$

Due to symmetry of the overhead conductors with respect to the counterpoise, there is no v_1 component in the counterpoise surge, and the terms of this velocity balance between e_1 and e_2. The coupling factors are

$$F_{1\text{-}2} = \frac{e_2}{e_1} = 0.238 \text{ and } F_{1\text{-}3} = \frac{e_3}{e_1} = 0.049$$

The currents are, by eq B:

$$\begin{aligned} i_1 &= [0.0536\,E_0(v_1) + 0.0482\,E_0(v_2) + 0.0056\,E_0(v_3)]/60 = (0.1074E_0/60) \\ i_2 &= [-0.0536\,E_0(v_1) + 0.0482\,E_0(v_2) + 0.0056\,E_0(v_3)]/60 = 0 \\ i_3 &= [- 0.0330\,E_0(v_2) + 0.0330\,E_0(v_3)]/60 = 0 \end{aligned}$$

The surge impedance of the ground wire, therefore, is

$$Z_{11} = e_1/i_1 = 558 \text{ ohms}$$

Condition II

$i_1 = 0$ = current in ground wire
$i_2 = 0$ = current in line wire
$e_3 = E_0$ = voltage applied to counterpoise

Hence by eqs A and B

$$f_1 = 0;\ f_2 = -0.244\,E_0;\ f_3 = 0.308\,E_0$$

and therefore,

$$\begin{aligned} e_1 &= -0.244\,E_0(v_2) + 0.308\,E_0(v_3) = (0.064\,E_0) \\ e_2 &= -0.244\,E_0(v_2) + 0.308\,E_0(v_3) = (0.064\,E_0) \\ e_3 &= +0.084\,E_0(v_2) + 0.916\,E_0(v_3) = (1.000\,E_0) \end{aligned}$$

$$\begin{aligned} i_1 &= [-0.0218\,E_0(v_2) + 0.0218\,E_0(v_3)]/60 = 0 \\ i_2 &= [-0.0218\,E_0(v_2) + 0.0218\,E_0(v_3)]/60 = 0 \\ i_3 &= [0.0149\,E_0(v_2) + 0.1289\,E_0(v_3)]/60 = 0.1438\,E_0/60 \end{aligned}$$

Thus the initial coupling factor is about 6.4 per cent, and the surge impedance of the counterpoise is

$$\frac{e_3}{i_3} = \frac{60}{0.1438} = 417 \text{ ohms}$$

By the approximate method of Appendix B, there is for comparison with the values (in parentheses) given by the complete multi-velocity theory:

$$\begin{aligned} v_1 = v_2 &= \sqrt{p_{11}/L_{11}} = \sqrt{9.11/9.55} = 0.978\ (0.981) \\ v_3 &= \sqrt{p_{33}/L_{33}} = \sqrt{5.95/8.20} = 0.852\ (0.836) \end{aligned}$$

$$\begin{aligned} Z_1 = Z_2 &= \sqrt{p_{11}L_{11}} = 560\ (558) \\ Z_3 &= \sqrt{p_{33}L_{33}} = 419\ (417) \end{aligned}$$

$$\frac{e_2}{e_3} = \frac{L_{33}}{L_{33}\,(1 + v_3/v_1)} = \frac{0.84}{8.20\,(1 + 0.852/0.978)} = 0.055\ (0.064)$$

The agreement is seen to be quite good, and thus justifies the use of the more simple approximate method.

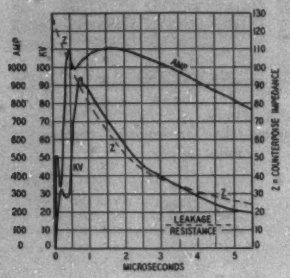
Condition III

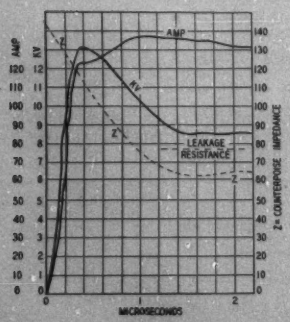
Referring to eqs 1 to 10 of Appendix A there results

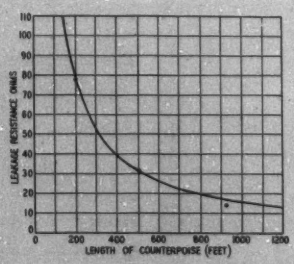
$$f_1 = 0.358\,E_0,\ f_2 = 0.273\,E_0,\ f_3 = 0.369\,E_0$$

and the voltage and current equations are

$$\begin{aligned} e_1 &= 0.358\,E_0(v_1) + 0.273\,E_0(v_2) + 0.369\,E_0(v_3) = (1.000\,E_0) \\ e_2 &= -0.358\,E_0(v_1) + 0.273\,E_0(v_2) + 0.369\,E_0(v_3) = (0.284\,E_0) \\ e_3 &= - 0.093\,E_0(v_2) + 1.093\,E_0(v_3) = (1.000\,E_0) \end{aligned}$$







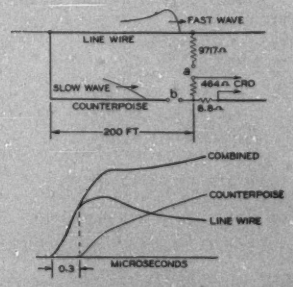


Fig. 5 (left). Transient impedance of 925-ft buried counterpoise, from oscillograms of voltage and current

Fig. 6 (below, left). Transient impedance of 200-ft buried counterpoise, from voltage and current oscillograms

Fig. 7 (below, middle). Test points and curve of uniform leakage resistance

Fig. 8 (below, right). Method of determining velocity of propagation on the counterpoise

$$i_1 = [\ 0.0503\ E_s(v_1) + 0.0244\ E_s(v_2) + 0.0261\ E_s(v_3)]/60 = (0.1008\ E_s/60)$$

$$i_2 = [-0.0503\ E_s(v_1) + 0.0244\ E_s(v_2) + 0.0261\ E_s(v_3)]/60 = (0.0000\ E_s/60)$$

$$i_3 = [-\ 0.0167\ E_s(v_2) + 0.1543\ E_s(v_3)]/60 = (0.1376\ E_s/60)$$

In this case the coupling is 4 per cent higher than with the counterpoise disconnected; and due to the mutual coupling between the ground wire and counterpoise the currents are less than under conditions I and II. It will be observed that when the counterpoise is connected, the surge which it carries is essentially a low velocity wave.

Tests With Buried Counterpoise

The counterpoise was buried to a depth of about 12 in., parallel and directly underneath the line conductors. Tests were made on lengths of 200, 500, and 925 ft with surges of 15 kv and 90 kv. The latter was the highest voltage at which current measurements could be made without making special arrangements to insulate the portable cathode ray oscillograph truck. For slightly higher voltages the truck tires would arcover.

In Figs. 5 and 6 are replots of voltage and current oscillograms taken on the 925- and 200-ft counterpoises, respectively, with the overhead conductors isolated. The ratio of voltage to current here is plotted as the transient impedance. Initially the counterpoise behaves as a surge impedance and finally as a distributed leakage resistance to ground. The equation for the transient impedance is given in Appendix C. The points on the plotted impedance curve lie on a smooth curve beyond 0.5 μsec, but the accuracy is very poor between 0 and 0.5 μsec. However, the extrapolation of the impedance curves on these and other plots indicates that the initial, or *surge impedance*, value lies between 120 and 160 ohms. From this value the transient impedance falls in a somewhat exponential fashion until the final, or *leakage resistance*, value is reached. In the case of the 925-ft counterpoise this final value has not yet been reached at the end of 6 μsec (at which time reflections from the generator interfered). But on the 200-ft counterpoise the transient impedance has very definitely reached its steady state value at the end of 1.5 μsec. At the instant of maximum voltage the transient impedance is 88 and 112 ohms, respectively, in Fig. 5 and Fig. 6. Very likely this impedance is considerably less at the much higher voltages corresponding to natural lightning. Incidentally, in each of 5 plots which have been made, the impedance curve closely parallels the tail of the voltage wave. The leakage resistance, Fig. 7, measured 77.5, 31.5, and 14 ohms on the 200, 500, and 925 ft lengths of counterpoise, respectively.

The propagation of a surge in a counterpoise buried in low resistive earth appears to be as much diffusion as traveling wave phenomenon. For this reason attempts to discover a velocity of propagation from reflections on the oscillograms proved futile. The abrupt change at 1.5 μsec on the tail of the voltage wave for the 200-ft counterpoise, Fig. 6, as contrasted with that of the 925-ft counterpoise, Fig. 5, was at first taken for the return of a reflection. In order to determine more carefully the velocity, E. J. Wade devised a most ingenious method, the essential elements of which are shown in Fig. 8, the waves being replots of actual oscillograms. The surge was applied to both the line wire and the counterpoise. The cathode ray oscillograph was placed 200 ft farther along where the counterpoise was opened as shown in Fig. 8, and a series resistance of 8.8 ohms inserted. By closing *a* the fast wave on the line was recorded. By closing *b* (with *a* open) the flattened front slow wave on the counterpoise was recorded. Finally by closing both *a* and *b* the 2 waves superimposed after a time Δt which could be determined by placing the oscillogram of the fast wave over that of the combined wave so that their fronts coincide, and observing the point at which they diverge. It will be appreciated that the success of this method depends upon the 3 resistance elements being of widely different values, and the one to the line wire should be high. In Fig. 8 the slow wave arrived 0.3 μsec after the fast wave, and the velocity therefore is (since the fast wave travels at the velocity of light):

$$v_2 = \frac{l}{t_2} = \frac{l}{t_1 + \Delta t} = \frac{l}{\Delta t + l/v_1} = \frac{200}{0.3 + 200/985} = 400 \text{ ft}/\mu\text{sec}$$

But when this test was repeated at 500 ft the velocity was apparently only 330 ft/μsec. The reason for the decrease in velocity as the distance traveled increases is given later under "Discussion." The method of testing determines only the average velocity. Now the longer the length of counterpoise under test the less the influence of the initial higher velocity and the more nearly will the average velocity be equal to the final velocity. On the basis of this argument the velocity will be assumed as 30 per cent that of light. Taking the surge impedance as $Z_3 = 142$ and the velocity at $v_3 = 30$ per cent, the inductance and capacitance coefficients, as well as the position of the equivalent current images, are as follows:

$$L = \frac{2}{10^9} \log_e \left(\frac{2h}{r}\right) = \frac{Z_3}{v_3} = \frac{142}{0.3 \times 3 \times 10^{10}} = \frac{15.8}{10^9} \text{ h/cm}$$

$$\therefore 2h = \frac{2700}{8 \times 12} = 28 \text{ ft}$$

$$C = \frac{1}{18 \times 10^{11} \log_e (2H/r)} = \frac{1}{Z_{\varphi 3}}$$

$$= \frac{1}{142 \times 0.3 \times 3 \times 10^{10}} = \frac{0.80}{10^{13}} \text{ farad/cm}$$

$$\therefore 2H = 0.25 \text{ in.}$$

In earth of such low resistivity, burying the counterpoise may raise the effective position of the ground current considerably, because current is then flowing above and on both sides of the counterpoise as well as below it. In such cases the depths of current as determined for the insulated and buried counterpoise are not comparable. But in high resistivity soil, where counterpoises are most likely to be used, there will probably be little difference found in the location of the current image for either an insulated or buried counterpoise.

Current distribution along the counterpoise was obtained with the cathode ray oscillograph at the 0, 200, and 500-ft points. Representative oscillograms

Table II—Tests on Buried Counterpoise

Condition	Fig. 11 II	Fig. 11 III	Fig. 12 II	Fig. 12 III
s_1	1,600	14,480	5,990	90,150
s_2	1,600	4,050	5,990	23,820
s_3	16,400	16,480	94,500	90,150
i_1		40.5		187
i_2	178	161.1	1,107	1,107
F_{2-1}	0.098		0.063	
F_{13-1}		0.280		0.264

are replotted in Fig. 9. The initial current wave is quite steep, having a front of less than 0.5 μsec. There is considerable flattening of the front and drop in magnitude as the current wave travels along the counterpoise. The average values obtained from these tests at 2.5 μsec were:

Distance	0 ft	200 ft	500 ft
Current	134 amp	107.6 amp	14.4 amp

Since the counterpoise current is so rapidly drained off, the coupling effect with the overhead conductors practically vanishes within a short distance—say beyond 300 ft. Attempts also were made to measure the currents by surge crest ammeters, but the reversals due to reflections were too large to permit accurate results.

The superposition of voltage waves taken on counterpoises of 200, 500, and 925-ft length is shown in Fig. 10. There is obviously nothing to gain under these conditions by using a counterpoise longer than 200 ft for applied wave fronts less than 1.5 μsec. In soil of higher resistivity a longer length

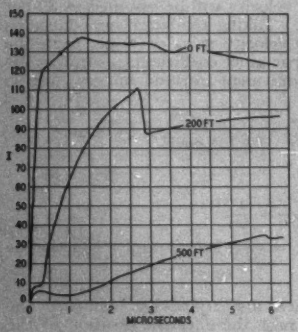
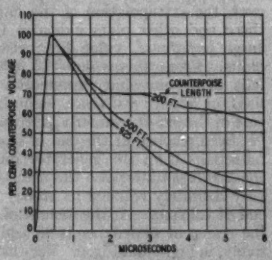


Fig. 9 (left). Current waves in 925-ft counterpoise at 0, 200, and 500-ft points

Fig. 10 (right). Superposition of voltage waves for counterpoises of different lengths



is justifiable, but it is doubtful if lengths greater than 300 ft are worth the extra cost. On the other hand, very short counterpoises of the order of 50 ft may give rise to substantial reflections which would raise the tower voltage.

In Figs. 11 and 12 are shown the effects of the buried counterpoise on coupling for the 2 conditions: (II) Surge on the counterpoise alone with the overhead conductors isolated; and (III) surge on both the counterpoise and ground wire. Figure 11 is for a low voltage surge of 15 kv and Fig. 12 is for a 90-kv surge. The data (averaged) is summarized in Table II.

By eq 27 of Appendix B the mutual impedance between the counterpoise and the overhead conductor, based upon the current image at 28-ft depth, is

$$Z_{3-2} = L_{32}\left(\frac{v_3 v_2}{v_3 + v_2}\right) = \frac{1.20}{10^9}\left(\frac{1 \times 0.3}{1.3}\right) 3 \times 10^{10} = 9.0$$

From Fig. 11 the current is 178 amp. Therefore, the induced voltage is

$$e_2 = Z_{3-2} i_2 = 9.0 \times 178 = 1.6 \text{ kv (1.6 test)}$$

Likewise from Fig. 12 the induced voltage is

$$e_2 = 9.0 \times 1100 = 9.9 \text{ kv (6 test)}$$

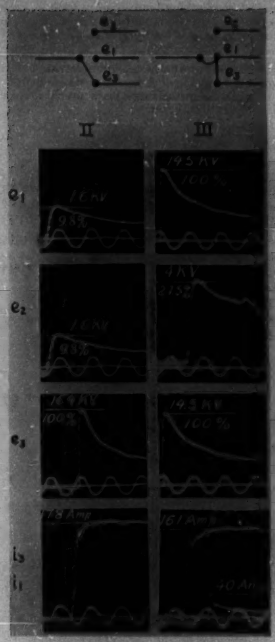
This latter is a very poor check. Presumably the only difference in the 2 tests was the higher voltage in the case of Fig. 12. But if this made any difference at all one would expect it to *increase* rather than decrease the coupling. The author has no explanation to offer.

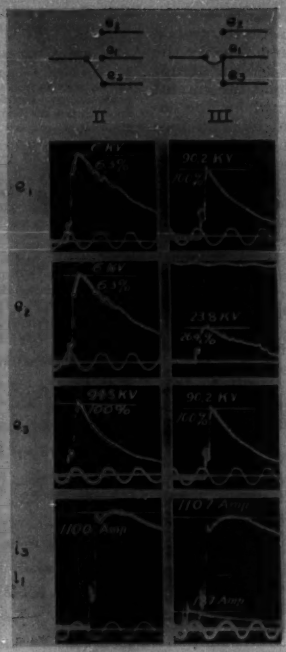
Discussion

In seeking evidence from these tests in support of the multi-velocity theory, perhaps the most conclusive is that shown in Fig. 4. According to the conventional theory of traveling waves there is no current on an isolated conductor—it merely floats in the electrostatic field of adjacent conductors and takes on the corresponding potential, and therefore, the shape of an induced surge is an exact replica of the inducing surge. But according to the multi-velocity theory there are current-carrying wave components on an isolated conductor, and in general these components travel at different speeds. Now it was shown that under condition I on the insulated counterpoise the voltage surge is

$$e_2 = -0.185\, E_0(v_2) + 0.234\, E_0(v_3) = (0.049\, E_0)$$

When this surge reaches the end of the counterpoise, which was grounded through driven pipe grounds, it reflects negatively and returns to the starting end of the counterpoise. The fast wave by that time has separated from its slower companion and so appears on Fig. (4I) as a positive bump.





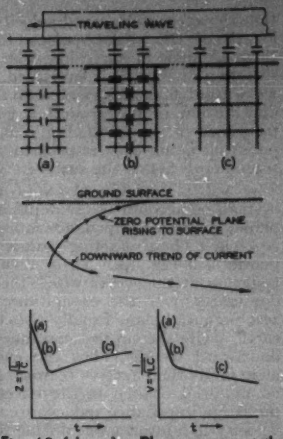


Fig. 13 (above). Phenomenon at the wave front

Top. Equivalent network at successive instants

Middle. Current and zero potential plane in the earth

Bottom. Variation of surge impedance and velocity

Fig. 11 (left). Oscillograms taken on buried counterpoise, for a low voltage surge of 15 kv

Fig. 12 (center). Oscillograms taken on buried counterpoise, for a 90-kv surge

But the slower wave is the larger of the 2, and therefore, dominates upon its arrival, reducing e_3 almost to zero.

Again in Fig. (4II) the positive bump is evident on e_1 and e_2, whose initial components were found to be:

$$e_1 = -0.244\ E_0(v_2) + 0.308\ E_0(v_1) = (0.064\ E_0)$$
$$e_2 = -0.244\ E_0(v_2) + 0.308\ E_0(v_1) = (0.064\ E_0)$$

Under condition II it is evident that the induced waves e_1 and e_2 register a positive bump at the same time when the main surge e_3 experiences a voltage drop and i_3, a current increase. This is rather conclusive evidence that the isolated conductors are not merely "floating in the electrostatic field of the main surge," but are conforming to the main surge *current*. This is all in complete agreement with multi-velocity theory, which predicted that the induced voltage from a counterpoise is due to the counterpoise current. Indeed, according to Appendix B

$$\frac{e_2}{e_3} = \frac{L_{23}}{L_{22}\,(1 + v_2/v_1)}$$

Thus the coupling factor is constrained by the limits

$$\frac{1}{2}\left(\frac{L_{23}}{L_{22}}\right) \leq \left(\frac{e_2}{e_3}\right) \leq \left(\frac{L_{23}}{L_{22}}\right)$$

or has no more than a 2:1 range as far as capacitance coefficients (which are included in the velocities) are concerned.

Under condition III the bump in e_3 is less than under condition II. This is because there are 2 inducing currents involved, i_1 and i_3, and due to reflection i_1 decreased when i_3 increased, but not so much, so that the net effect on e_3 is still a positive bump.

The multi-velocity components, therefore, are seen to be present and behaving in conformity with theory. The numerical checks are probably as good as can be hoped for in this kind of calculation; especially in a situation where the order of magnitude of some of the quantities involved is not very much greater than the order of magnitude of the test errors.

In many problems dealing with traveling waves it is permissible to ignore the phenomenon at and immediately following the wave front, but in studying the action of a counterpoise some cognizance should be taken of this behavior, since the major effect is confined to the first few microseconds. When the surge impedance for the insulated counterpoise was plotted as function of time by taking the instantaneous ratios of voltage to current from oscillograms with fast sweep it was observed that the impedance dropped sharply from a high to a minimum value within the first half microsecond, then increased slowly as shown in the bottom sketch of Fig. 13. It has already been remarked in this paper

that the average observed velocity decreases with the length of the counterpoise. In order to explain these changes in surge impedance and velocity the situation of Fig. 13 is envisaged. When the abrupt wave front first arrives at a given point the current distribution in the ground is governed by the capacitance of the earth, Fig. 13*a*, and thus the zero potential plane with respect to voltage images is at some depth below the surface. Consequently, since $Z = \sqrt{L/C}$ and $V = 1/\sqrt{LC}$ and the effective C is small on account of the depth of the zero potential plane, the surge impedance is high and the velocity is high. These starting values are designated as points *a* in Fig. 13. There then ensues a very fast transient at the end of which the resistance network dominates over the capacitance network, and the zero potential plane rapidly rises to the surface of the earth, while the current continues its relatively slow downward trend. Thus the end of this readjustment finds the effective C much increased, but with no material change in the effective L. Therefore, the surge impedance reduces to a minimum and the velocity to a lower value during this transition stage, designated by points *b* in Fig. 13. Thereafter the effective capacitance does not change, since the zero potential plane is already at the surface, but the current continues its downward displacement, thereby increasing the effective L, and thus causing the surge impedance to increase slowly and the velocity to decrease slowly. These effects, which are clear and definite for an insulated counterpoise, are masked by the leakage effect in the case of the buried counterpoise.

Conclusions

The conditions under which these tests were made were not conducive to the most accurate type of determination of the factors involved. The effects were not pronounced enough, and the test errors too erratic, to permit of any "rock-bound" conclusions; but the following facts seem to have been established.

1. The impedance of a buried counterpoise is a variable starting at a value equal to its surge impedance and ending at a value equal to its leakage resistance. The transition may require from 1 to 10 μsec, depending upon the length of the counterpoise and the earth resistivity. Propagation of surges on counterpoises is thus as much diffusion as traveling wave phenomena.

2. The coupling effect of a counterpoise depends primarily upon the position of the current images, and is not greatly dependent upon the capacitance relationships. The higher the earth resistivity and the greater the depth to the water level, the lower the current images and the higher the coupling.

3. The earth's surface may be considered the zero potential plane for voltage images of traveling waves.

4. Multi-velocity waves exist on a counterpoise, but the only one of importance is very slow, traveling at about $^1/_3$ the velocity of light. The arrival of reflections may be estimated on that basis.

5. A new and accurate method for determining velocities on counterpoises has been devised (E. J. Wade). This method indicated that the initial velocity of the wave when it first enters the counterpoise is higher than its ultimate velocity. This is reasonable theoretically.

6. Due to the leakage the current in a counterpoise drops off rapidly and the front of the advancing wave is greatly flattened. For this reason the coupling effect vanishes at points a few hundred feet from the tower.

7. Counterpoises more than 200 to 300 ft long do not appear justifiable. If greater effect is desired it should be secured by a multiplicity of counterpoises of this length arranged radially. Very short counterpoises give rise to reflections and are therefore not so efficient as one long enough to be practically free of this source of additional voltage.

8. The multi-velocity theory appears to be adequate for numerical calculations as well as for a description of the mechanism of counterpoise action. But for routine design calculations a much simpler approximate method of analysis is sufficient.

Appendix A

The multi-velocity wave components on a 3-conductor system comprising a ground wire, line wire, and counterpoise are (see "The Counterpoise," by L. V. Bewley, *G. E. Rev.*, 1934, v. 37, p. 73–81):

$$\left.\begin{aligned} e_1 &= a_{11}f_1(x - v_1t) + a_{12}f_2(x - v_2t) + a_{13}f_3(x - v_3t) \\ e_2 &= a_{21}f_1(x - v_1t) + a_{22}f_2(x - v_2t) + a_{23}f_3(x - v_3t) \\ e_3 &= a_{31}f_1(x - v_1t) + a_{32}f_2(x - v_2t) + a_{33}f_3(x - v_3t) \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} i_1 &= Y_{11}f_1(x - v_1t) + Y_{12}f_2(x - v_2t) + Y_{13}f_3(x - v_3t) \\ i_2 &= Y_{21}f_1(x - v_1t) + Y_{22}f_2(x - v_2t) + Y_{23}f_3(x - v_3t) \\ i_3 &= Y_{31}f_1(x - v_1t) + Y_{32}f_2(x - v_2t) + Y_{33}f_3(x - v_3t) \end{aligned}\right\} \quad (2)$$

in which the velocities v_1, v_2, v_3 are given by the roots of

$$(I_{11} - v^{-2})(I_{22} - v^{-2})(I_{33} - v^{-2}) + I_{12}I_{23}I_{31} + I_{13}I_{21}I_{32} - (I_{11} - v^{-2})I_{23}I_{32} - (I_{22} - v^{-2})I_{13}I_{31} - (I_{33} - v^{-2})I_{12}I_{21} = 0 \quad (3)$$

and the a coefficients are (for $r = 1, 2$, or 3)

$$a_{11} = a_{12} = a_{13} = 1 \text{ (arbitrarily)}$$

$$\left.\begin{aligned} a_{2r} &= \frac{I_{31}I_{12} - I_{32}(I_{11} - v_r^{-2})}{I_{13}I_{32} - I_{12}(I_{33} - v_r^{-2})} = \frac{I_{23}I_{32} - I_{21}(I_{33} - v_r^{-2})}{(I_{22} - v_r^{-2})(I_{33} - v_r^{-2}) - I_{23}I_{32}} \\ a_{3r} &= \frac{-I_{13}I_{21} + (I_{11} - v_r^{-2})(I_{22} - v_r^{-2})}{I_{12}I_{23} - I_{13}(I_{22} - v_r^{-2})} = \frac{I_{21}I_{32} - I_{31}(I_{22} - v_r^{-2})}{(I_{22} - v_r^{-2})(I_{33} - v_r^{-2}) - I_{23}I_{32}} \end{aligned}\right\} \quad (4)$$

where, in general,

$$I_{rs} = (L_{1r}K_{1s} + L_{2r}K_{2s} + L_{3r}K_{3s}) \quad (5)$$

$$Y_{sr} = (K_{s1}a_{1r} + K_{s2}a_{2r} + K_{s3}a_{3r})v_r \quad (6)$$

The L's and K's being the inductance and capacitance coefficients.

If there are 2 ground wires in a horizontal plane, or 2 parallel counterpoises, then the inductances and electrostatic coefficients are to be calculated as for an equivalent single conductor. Thus for 2 ground wires 1 and 1′

$$L_{11} = \frac{2}{10^9}\log_e\frac{2\,h_1}{\sqrt{rm}} = \text{self inductance of the pair}$$

$$L_{12} = \frac{2}{10^9}\log_e\sqrt{\frac{aa'}{bb'}} = \text{mutual inductance of the pair to the line conductor}$$

where

$2\,h_1$ = height of ground wire from its image
r = radius of ground wire conductor
m = separation between ground wires
b = separation between ground wire 1 and line wire
a = separation between image of 1 and line wire
b' = separation between ground wire 1′ and line wire
a' = separation between image of 1′ and line wire

Similarly for a pair of counterpoises the electrostatic coefficients are likewise

$$p_{11} = 18 \times 10^{11}\log_e\frac{2\,H_1}{\sqrt{rm}}$$

$$p_{12} = 18 \times 10^{11}\log_e\sqrt{\frac{aa'}{bb'}}$$

where $2\,H_1$ is distance to the electrostatic image and R is the radius of the effective corona envelope.

If a lightning stroke of surge impedance Z and incident wave E strikes a tower having ground wire and counterpoise, and tower footing resistance R, then

$$f_1 = \frac{E_0}{\Delta}\left[(a_{33} - 1)\,Y_{22} - (a_{32} - 1)\,Y_{23}\right] = b_1E_0 \quad (7)$$

$$f_1 = \frac{E_0}{\Delta}\left[(a_{22} - 1)\, Y_{21} - (a_{21} - 1)\, Y_{22}\right] = b_1 E_0 \tag{8}$$

$$f_2 = \frac{E_0}{\Delta}\left[(a_{21} - 1)\, Y_{12} - (a_{11} - 1)\, Y_{21}\right] = b_2 E_0 \tag{9}$$

$$\Delta = \left[a_{22}\,(Y_{12} - Y_{21}) + a_{21}\,(Y_{22} - Y_{11}) + a_{12}\,(Y_{11} - Y_{22})\right] \tag{10}$$

$$E_0 = \frac{(2E)}{Z\left[\frac{1}{R} + \frac{1}{Z} + 2(Y_{11}+Y_{21})b_1 + 2(Y_{12}+Y_{22})b_2 + 2(Y_{13}+Y_{23})b_3\right]} \tag{11}$$

The equations of this appendix permit the calculation of the behavior of a counterpoise. Reflections up and down the tower have been ignored in accordance with the justifications given in original paper on this analysis. ("The Counterpoise," *G. E. Rev.*, 1934, v. 37, p. 73–81).

Perpendicular Counterpoise

If the counterpoise is perpendicular, the voltage equations are

$$e_1 = \frac{Y_{22}E_0(x - v_2 t) - Y_{21}E_0(x - v_2 t)}{(Y_{22} - Y_{21})} \tag{12}$$

$$e_2 = \frac{a_{21}Y_{12}E_0(x - v_1 t) - a_{12}Y_{11}E_0(x - v_2 t)}{(Y_{12} - Y_{11})} \tag{13}$$

$$E_0 = \frac{2\,E}{Z\left[\frac{1}{R} + \frac{1}{Z} + 2\,Y_{22} + 2\left(\frac{Y_{11}Y_{22} - Y_{12}Y_{21}}{Y_{12} - Y_{21}}\right)\right]} \tag{14}$$

$$\frac{1}{\psi^2} = \frac{(I_{11} + I_{22}) \pm \sqrt{(I_{11} - I_{22})^2 + 4\,I_{12}I_{21}}}{2} \tag{15}$$

$$\left.\begin{aligned} a_{21} &= (\psi_1^{-2} - I_{11})/I_{12} \\ a_{12} &= (\psi_2^{-2} - I_{11})/I_{12} \end{aligned}\right\} \tag{16}$$

$$\left.\begin{aligned} Y_{11} &= (K_{11} + a_{21}K_{12})\psi_1 \\ Y_{12} &= (K_{11} + a_{22}K_{12})\psi_2 \\ Y_{21} &= (K_{12} + a_{21}K_{22})\psi_1 \\ Y_{22} &= (K_{12} + a_{22}K_{22})\psi_2 \end{aligned}\right\} \tag{17}$$

$$\left.\begin{aligned} I_{11} &= L_{11}K_{11} + L_{12}K_{12} \\ I_{12} &= L_{11}K_{12} + L_{12}K_{22} \\ I_{21} &= L_{22}K_{12} + L_{12}K_{11} \\ I_{22} &= L_{22}K_{22} + L_{12}K_{12} \end{aligned}\right\} \tag{18}$$

Appendix B

The general analysis given in Appendix A is not only complicated and laborious (a complete set of computations requiring at least 2 days' work), but small errors made in the auxiliary constants may throw the final results quite far off the correct values. In this appendix a much shorter approximate method is developed which should suffice for ordinary calculations.

Referring to eqs 12 and 13 of Appendix A, the initial coupling factor between 2 conductors No. 1 and No. 2, the main surge being applied to No. 1 and the induced surge measured on No. 2, is

$$F_{12} = \frac{a_{21}Y_{22} - a_{22}Y_{21}}{Y_{22} - Y_{21}} \tag{19}$$

Now if one of these conductors lies on the ground surface, the mutual capacitance coefficients are zero ($K_{12} = K_{21} = 0$). On this basis, substituting eqs 15, 16, 17, and 18 into 19 and simplifying (it is quite a long job) there finally results

$$F_{12} = \frac{L_{12}}{L_{11} + \sqrt{(L_{11}L_{22} - L_{12}^2)}\,\frac{\rho_{11}}{\rho_{22}}} \tag{20}$$

or neglecting L_{12}^2 in comparison with L_{11} L_{22} and substituting

$$\psi_1 = \sqrt{\frac{\rho_{11}}{L_{11}}}\,,\quad \psi_2 = \sqrt{\frac{\rho_{22}}{L_{22}}} \tag{21}$$

the initial coupling factor may be written

$$F_{12} \cong \frac{L_{12}}{L_{11} + \sqrt{L_{11}L_{22}}\,\frac{\rho_{11}}{\rho_{22}}} = \left(\frac{L_{12}}{L_{11}}\right)\frac{1}{1 + (\psi_1/\psi_2)} \tag{22}$$

Now disregarding the multi-velocity wave components of Appendix A, a linear set of equations may be tentatively written between the voltages and currents on the system:

$$\left.\begin{aligned} e_1 &= Z_{11}i_1 + Z_{12}i_2 + Z_{13}i_3 = \text{ground wire} \\ e_2 &= Z_{21}i_1 + Z_{22}i_2 = \text{line wire} \\ e_3 &= Z_{31}i_1 + Z_{32}i_2 + Z_{33}i_3 = \text{counterpoise} \end{aligned}\right\} \tag{23}$$

When multi-velocity components do not exist these are the exact canonical equations for traveling waves, but if multi-velocities do exist they are only approximate, however give close results for the first few microseconds. It remains to identify the coefficients. Obviously

$$\left.\begin{aligned} Z_{11} &= \sqrt{L_{11}\rho_{11}} = \text{surge impedance of ground wire} \\ Z_{22} &= \sqrt{L_{22}\rho_{22}} = \text{surge impedance of line wire} \\ Z_{33} &= \sqrt{L_{33}\rho_{33}} = \text{surge impedance of counterpoise} \end{aligned}\right\} \tag{24}$$

Suppose that only current i_1 is flowing. Then

$$\frac{e_2}{e_1} = \frac{Z_{21}}{Z_{11}} = F_{12}$$

and since both conductors are overhead, F_{12} must be computed by eq 19. Therefore

$$Z_{21} = Z_{11}F_{12} = Z_{11}\left[\frac{a_{21}Y_{22} - a_{22}Y_{21}}{Y_{22} - Y_{21}}\right] \tag{25}$$

Likewise, interchanging subscripts

$$Z_{12} = Z_{22}F_{21} = Z_{22}\left[\frac{a_{12}Y_{11} - a_{11}Y_{12}}{Y_{11} - Y_{12}}\right] \tag{26}$$

For the coefficients involving the counterpoise, the simplification of the type of eq 22 can be used, thus:

$$\left.\begin{aligned} Z_{13} &= Z_{23}F_{21} = Z_{23}\,\frac{L_{13}}{L_{23}}\,\frac{1}{1 + (\psi_3/\psi_1)} = L_{13}\left(\frac{\psi_1\psi_3}{\psi_1 + \psi_3}\right) \\ Z_{23} &= Z_{23}F_{23} = Z_{23}\,\frac{L_{23}}{L_{23}}\,\frac{1}{1 + (\psi_3/\psi_2)} = L_{23}\left(\frac{\psi_2\psi_3}{\psi_2 + \psi_3}\right) \\ Z_{31} &= Z_{11}F_{13} = Z_{11}\,\frac{L_{13}}{L_{11}}\,\frac{1}{1 + (\psi_1/\psi_3)} = L_{13}\left(\frac{\psi_1\psi_3}{\psi_1 + \psi_3}\right) \\ Z_{32} &= Z_{22}F_{23} = Z_{22}\,\frac{L_{23}}{L_{22}}\,\frac{1}{1 + (\psi_2/\psi_3)} = L_{23}\left(\frac{\psi_2\psi_3}{\psi_2 + \psi_3}\right) \end{aligned}\right\} \tag{27}$$

It is seen that $Z_{13} = Z_{13}$ and $Z_{23} = Z_{32}$.

Having established all the coefficients of eqs 23, these equations may be used directly. Assuming as in Appendix A that a lightning stroke of surge impedance Z and incident wave E strikes a tower having ground wire, line wire and counterpoise, and tower footing resistance R, then remembering that $i_3 = 0$ on the line wire:

$$\left.\begin{aligned} e_1 &= E_0 = Z_{11}i_1 + Z_{12}i_2 \\ e_2 &= E_0 = Z_{21}i_1 + Z_{22}i_2 \\ e_3 &= Z_{31}i_1 + Z_{32}i_2 \end{aligned}\right\} \tag{28}$$

But the total current from the stroke in terms of the incident wave E and the reflected wave E' is

$$\frac{E - E'}{Z} = \frac{2E}{Z} - \frac{E + E'}{Z} = \frac{2E}{Z} - \frac{E_0}{Z} = 2(i_1 + i_2) + \frac{E_0}{Q} \tag{29}$$

Solving for i_1 and i_2 from eq 28 and substituting in eq 29 there results

$$\left.\begin{aligned} i_1 &= E_0\left(\frac{Z_{22} - Z_{12}}{Z_{11}Z_{22} - Z_{12}^2}\right) = b_1 E_0 \\ i_2 &= E_0\left(\frac{Z_{11} - Z_{12}}{Z_{11}Z_{22} - Z_{12}^2}\right) = b_2 E_0 \\ E_0 &= \left(\frac{2E}{1 + 2Z\,(b_1 + b_2) + Z/R}\right) \end{aligned}\right\} \tag{30}$$

Hence substituting in eq 28

$$\left.\begin{aligned} e_1 = e_2 = E_0 &= \frac{2E}{1 + 2Z\,(b_1 + b_2) + Z/R} \\ e_3 = (Z_{31}b_1 + Z_{32}b_2)E_0 &= \frac{2E\,(Z_{31}b_1 + Z_{32}b_2)}{1 + 2Z\,(b_1 + b_2) + Z/R} \end{aligned}\right\} \tag{31}$$

Appendix C

In order to approximate the effects of the transition of the impedance of a counterpoise from its initial condition of surge impedance to its final condition of leakage resistance, the following method of analysis appears to have some merit. Assume the leakage resistance $R_s = 1/gl$ to be concentrated at the end of a counterpoise of surge impedance, Z_s, and length T (to be defined later). Then successive reflections will eventually supplant Z_s with R_s, and the problem reduces to that of computing these reflections. The time T is to be chosen so that the transition occurs in the required length of time, either as estimated from tests or as calculated from the following formula:

$$Z_s(t) = \frac{1}{gl\left\{1 - \sum_{s=1}^{\infty} \frac{8e^{-\alpha t}}{(2s-1)^2\pi^2}\left[\cos \omega_s t + \left(\frac{g}{4\omega_s C} - \frac{\omega_s C}{g}\right)\sin \omega_s t\right]\right\}} \tag{32}$$

where

$$\omega_s = \frac{1}{2}\sqrt{\frac{(2s-1)^2\pi^2}{LCl^2} - \frac{g^2}{C^2}} \cong \frac{(2s-1)\pi}{2l\sqrt{LC}}$$

$$\alpha = g/2C$$

assuming $(g/\omega_s C)$ to be a small quantity, this reduces to

$$Z_s(t) = \frac{1}{gl\left\{1 - e^{-\alpha t}\sum_{s=1}^{\infty}\left[\frac{8\cos \omega_s t}{(2s-1)^2\pi^2} - \frac{4}{gl}\sqrt{\frac{C}{L}}\,\frac{\sin \omega_s t}{(2s-1)\pi}\right]\right\}} \tag{33}$$

The first term under the summation sign is a triangular wave, and the second term a rectangular wave. Therefore it is easily seen that

$$\left.\begin{aligned} Z_s(t) &= \frac{1}{gl} \text{ at } t = \infty \\ Z_s(t) &= \sqrt{\frac{L}{C}} \text{ at } t = 0 \end{aligned}\right\} \tag{34}$$

Thus if g, L, C of the counterpoise are known, $Z_s(t)$ may be computed and the time of transition from $\sqrt{L/C}$ to $1/gl$ readily found. The transition is brought about by the presence of the term $e^{-\alpha t}$. Therefore considering the transition as essentially complete when $e^{-\alpha t} = 0.05$, it follows that

$$t = \frac{3}{\alpha} = \frac{6C}{g} = \text{time of transition}$$

Now consider any set of wave components (f_1, f_2, f_3) on the ground wire, line wire, and counterpoise, in accordance with eqs 1 and 2 of Appendix A. When these waves reach the end of the counterpoise they will give rise to reflections (f_1', f_2', f_3') and transmitted waves (f_1'', f_2'', f_3'') and the transition point equations become

$$\left.\begin{aligned} e_1 + e_1' &= e_1'' \\ e_2 + e_2' &= e_2'' \\ e_3 + e_3' &= e_3'' \\ i_1 + i_1' &= i_1'' \\ i_2 + i_2' &= i_2'' \\ i_3 + i_3' &= i_3'' = e_3''/R_s \end{aligned}\right\} \tag{35}$$

From these the new components $(f_1', f_2', f_3', f_1'', f_2'', f_3'')$ may be determined. Now regarding the reflected waves (f_1', f_2', f_3') as new incident waves (dropping the primes) approaching the tower, an exactly similar set of equations to those above obtain, except that R_s is now to be replaced by the resistance of the tower footing and the lightning stroke surge impedance in parallel, that is the last equation becomes

$$i_3 + i_3' = i_3'' = e_3''(R + Z)/RZ \tag{36}$$

Thus it is possible to calculate the effect of the transient impedance of the counterpoise as a problem in successive reflections. But the work involved is so excessive that the approximation given in the text appears to be sufficiently accurate under the circumstances.

Toward the Making of a Profession

(*Continued from page 1148*)

ondary, perhaps a minor, function. It has wisely chosen to be the inspirer rather than the policeman of the profession. The intangibles of the spirit, the creating of an atmosphere, a tone, a fellowship, have far outweighed the letter of the law. In its contributions to public welfare, the Institute has wisely contented itself to work through the most inclusive agencies of the profession, the American Engineering Council, the national and international standardizing agencies, and most recently the E.C.P.D.

Relation of the Institute to the Modern State

In conclusion, only a hint can be given of the significant contribution of the Institute to the growing and evolving idea of a profession as a functional element in the complex of social organisms we call the modern state. The traditional fabric of society with its political and geographical strands is breaking apart under the stress of a complex life. In its place we see emerging the modern conception of the corporative state, a society in which the constituent units are not parties or political subdivisions, but functional groups, such as trade associations, labor unions, consumers' coöperatives, professional guilds, agricultural groups, and the like. The idea which underlies much of our democracy and in which Jefferson and his disciples so firmly believed, that the citizenry acting collectively would transcend their wisdom and intelligence as individuals, is sadly discredited. Too often the reverse is all too evident in political life. In professional bodies such as our own the idea of collective superiority has been vindicated; as a group we tend to act on a higher plane of idealism and of devotion to the common good than as individuals.

The future of society appears to depend more and more upon the vitality of such functional groups. Our greatest concern may well be to extend professional ethics and ideals to the wider areas of industrial and public life. The Institute has seen no necessary antithesis between economic profit and social gain. In emphasizing the long-range or professional view, as against the short-range or business view, it has sought to reconcile social profit with the profit of the balance sheet, to reconcile service and gain, to reconcile scientific progress with humanitarianism and to reconcile the highest stimulation of individual achievement with the widest distribution of social benefits. Before its members it has upheld the ideal of progress through sharing, rather than beating the game. In the larger concerns of society, as well as in the activities and relations of its thousands of individual members, the Institute has kept the faith, not alone in the letter that killeth, but even more in the spirit that maketh alive.

Characteristics and Uses of the Carbon Arc

The high efficiency of the carbon arc, the flexible and uniform quality of radiation it provides, and its extremely high intrinsic brilliancy give it a prominent place in the broad field of illumination. For applications in which a powerful light must be obtained from a source of small dimensions, it is unsurpassed. Characteristics of the various types of carbon arcs and their applications are outlined in this paper.

By
W. C. KALB
MEMBER A.I.E.E.

National Carbon Co.,
Cleveland, Ohio

THE CARBON ARC has passed through many interesting phases of development influenced by many factors of varied character. In early types, the street lamps of the "gay nineties," solid electrodes of coke composition, usually copper coated, were burned without protection from the air. Subsequent enclosure to prolong the burning period called for a reduction of the ash content of the electrodes and led to the development of the lampblack carbon. Steadiness of the light was improved greatly by the introduction of a center core of softer neutral composition which stabilizes the arc stream and prevents it from shifting about the rim of the crater. Further improvement was effected for certain types of lamps by the introduction of a metal coated negative carbon considerably smaller in diameter than the positive carbon.

Neutral Core Carbon Arc

Light from the solid or neutral core carbon arc operated on direct current comes almost entirely from the crater of the positive carbon. Little light is emitted from either the arc stream or the tip of the negative carbon. The light has a bluish tint with a strong band of ultra-violet radiation just outside the visible range. The energy distribution through the visible and ultra-violet range is shown in Fig. 1. In Fig. 2 is reproduced a photograph of the direct current arc with neutral cored positive electrode operated in the position shown in Fig. 4. This illustration clearly shows the positive crater as the principal source of light, and its brilliancy indicates the reason for the early popularity of this light source in motion picture projection.

The relatively high output of blue, violet, and ultra-violet radiation gave the carbon arc early popularity as an artificial source of illumination for photography, the emulsions then in use having little or no sensitivity to yellow, orange, and red. The carbon arc also attained extensive use in blue printing and photo-engraving, and the high-current direct-current arc was used by Finsen in his pioneer work in artificial light therapy.

The alternating current arc with neutral cored carbons is not as efficient as the direct current arc for, while the craters of the carbon electrodes are still the principal sources of light, their brilliancy, as may be seen from Fig. 3, is far less than that of the positive crater of the direct current arc.

In earlier applications of the carbon arc to motion picture projection, an inclined vertical "trim" was used as indicated in Fig. 4. The condenser lens in these lamps picks up a solid cone of light of approximately 45 deg. The crater is formed partially on the side of the carbon so as to present as large an effective area as possible to the condenser lens. Considerable attention on the part of the projectionist is required to maintain the proper crater formation and position

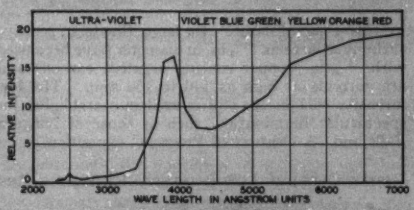


Fig. 1. Spectral energy distribution from neutral core carbon arc

Fig. 2. Direct-current neutral-core carbon arc

Fig. 3. Alternating-current neutral-core carbon arc

Full text of a paper recommended for publication by the A.I.E.E. committee on production and application of light, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted June 20, 1934; released for publication July 5, 1934. *Not published in pamphlet form.*

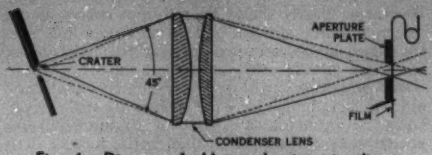
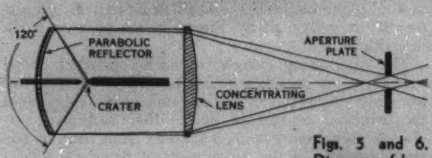
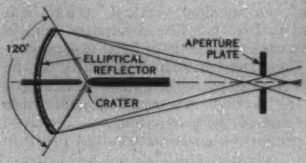


Fig. 4. Diagram of old type low-intensity direct-current projector lamp





Figs. 5 and 6. Diagrams of low-intensity direct-current reflecting arc lamps with parabolic mirror (above) and elliptical mirror (left)

in this type of lamp. In large theaters, positive carbons as large as $1^1/_8$ in. in diameter have been used with $^{17}/_{32}$-in. copper coating negative carbons and arc currents as high as 140 to 150 amp. The low intensity carbon arc still is used in searchlights for spectacular illumination, such as those at Niagara Falls and "A Century of Progress" exposition.

Direct-Current Low-Intensity Reflector Arc

Development of the reflector arc lamp added greatly to the efficiency of the low-intensity neutral-cored carbon arc in motion picture projection, increasing the light pick-up from a solid angle of 45 deg to one of approximately 100 deg. In this type of lamp, diagrammatically illustrated in Figs. 5 and 6, the carbon trim is horizontal with the crater of the positive carbon directly facing the mirror, thus exposing its full area to the optical system and at the same time simplifying the problem of the automatic control. At arc currents of 28 to 42 amp with positive carbons 12 or 13 mm in diameter, the direct-current low-intensity reflector arc provides a sufficient intensity of screen illumination for theaters of considerable size. More lamps of this type than of any other are used in motion picture theaters today. These lamps usually are operated from the standard voltage line through a transformer and rectifier or a motor generator set. The arc voltage is usually about 55 volts in this type of lamp.

The intrinsic brilliancy of the crater in the low-intensity neutral-cored carbon arc is limited by the vaporization temperature of carbon which is 4,126 deg K. When this temperature has been reached, further increase in arc current will increase the crater area and the rate of carbon consumption, but cannot increase the intrinsic brilliancy of the crater any more than the boiling point of water in open air can be raised by applying more heat. Light from this arc approaches pure white in color, but retains a definite tinge of yellow.

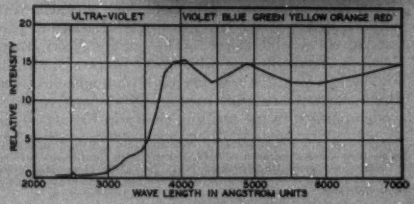
The Flame Arc

Introduction of flame supporting minerals in the cores of carbon electrodes transfers the principal source of light from the tips of the carbons, as in the neutral cored carbon arc, to the flame like arc stream, and provides a much longer arc than that between neutral cored carbons. There is little difference in the appearance, behavior, or output of the flame arc on direct current or alternating current. Figure 7 shows a photograph of an alternating current flame arc. The intrinsic brilliancy of the flame is relatively low, but, because of its size, it gives off a large volume of light and is a very efficient source of radiation. For like reason certain types of flame arcs are highly efficient sources of ultra-violet radiation.

An important characteristic of the flame arc is its flexibility, that is, the possibility of modifying the quality of the light by the choice of flame supporting materials in the core. In Fig. 8 is shown the energy distribution for the white flame carbon arc, the core of which contains minerals of the rare earth group, particularly cerium. By comparison of this curve with Fig. 1 it may be noted that the emission of

Fig. 7. Alternating current flame arc

Fig. 8 (below). Spectral energy distribution from white flame carbon arc



radiant energy in the visible range is increased greatly by this modification of the core composition and that the intensity of radiation is approximately the same in all primary color bands. The resultant light is bluish white, closely resembling daylight. This resemblance is also apparent in the spectrum of this arc which, like that of the sun, is practically a continuous band.

Carbons having polymetallic cores containing several metals including iron, nickel, and aluminum (know commercially as the "C" type) give less visible light than the white flame carbon, but much greater ultra-violet output as may be seen from Fig. 9. Strontium, Fig. 10, increases the red and infra-red emission from the arc with slightly lower ultra-violet output than that from the cerium cored carbon.

The white flame carbon arc finds extensive application in photography, where its light is considered photographically equivalent to daylight. It is used more largely in photo-engraving than any other light source. In light therapy a similar carbon known as the "Sunshine" carbon is used extensively where it is desired to duplicate artifically the physiological effects of natural sunlight. The "C" type and the strontium cored "E" type carbons likewise find extensive therapeutic use where emphasis on the ultra-violet or the infra-red bands of radiation is desired.

There is increasing use of the flame arc in industrial and photochemical processes such as accelerated testing of paints and dyes, the processing of certain materials, such as linoleum, patent leather, and tobacco, and the rapidly extending irradiation of milk for the purpose of increasing the vitamin *D* content.

The low-intensity alternating-current white-flame arc has found limited application in small motion picture theaters where direct current is not available; but the superiority of the direct-current low-intensity reflector arc, operated from a suitable rectifier or motor generator set, has given it preference over the former type for projection purposes. Reference will be made later to a recent development that promises to modify greatly projection practice in theaters of small and intermediate sizes.

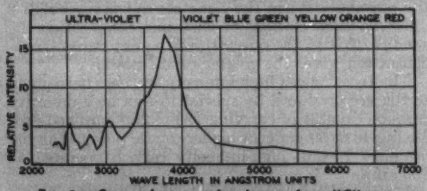


Fig. 9. Spectral energy distribution from "C" type carbon arc; these carbons have polymetallic cores containing iron, nickel, and aluminum

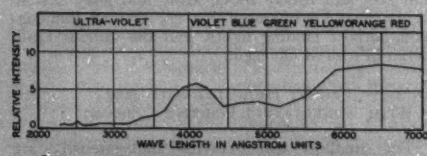
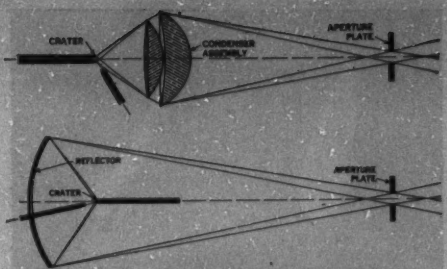


Fig. 10. Spectral energy distribution from "E" type carbon arc; these carbons have strontium cores



Figs. 11 and 12. Diagrams of high intensity arc lamp: (above) condenser type; (below) reflector type

The various types of lamps using flame type carbons embrace a wide range of arc conditions. Arc currents from 6 to 100 amp or more are used, and arc voltages from 25 to 60 volts. The large lamps most popular in industrial applications and light therapy at the present time are operated at 60 amp and 50 volts on alternating current, and at 50 amp and 60 volts on direct current.

Direct-Current High-Intensity Arc With Rotating Positive Carbon

Development of the high-intensity direct-current arc overcame the limitation of intrinsic brilliancy referred to in the discussion of the direct-current low-intensity arc. The positive electrodes of the direct-current high-intensity arc are operated at current densities much higher than those of the low intensity arc—450 to 860 amp per square inch (70 to 133 amp per square centimeter) for the former in comparison with 120 to 200 amp per square inch (18.5 to 31 amp per square centimeter) for the latter. Cored positive carbons 9 to 16 mm in diameter without metallic coatings are operated with copper coated negative carbons of smaller diameter at arc currents ranging from 60 to 190 amp, the arc voltage ranging from 45 to 90 volts.

In the condenser type high-intensity arc lamp, as indicated in Fig. 11, the positive carbon is held in a horizontal position with its crater directly facing the condenser assembly. Since the current density in the carbon is very high and the high efficiency of this type of arc is dependent on the maintenance of a well-formed cup-like crater, the positive carbon is allowed to project but a short distance from the holder and is rotated continuously while the arc is burning. The negative carbon is set at an angle to the positive, usually 40 to 60 deg below the horizontal. The feeding mechanism is designed to advance both carbons as they are consumed and should be adjusted to feed the positive carbon forward at

Fig. 13. High-intensity direct-current arc, front and side views

the same rate it is being burned, thus maintaining the crater at a fixed position in relation to the condenser and to the point of intersection with the axis of the negative carbon. The rate of feed of the negative carbon is also adjustable relative to that of the positive, and when properly adjusted maintains an arc of uniform length.

The reflecting principle of light concentration has been applied also to the high intensity arc. In all high intensity reflecting arc lamps the positive carbon is held in a horizontal position. The negative carbon also may be held horizontally or inclined to the positive, as shown in Fig. 12.

Light from the high intensity arc emanates from 2 distinct sources, the crater and the tail flame. The tail flame produces about 30 per cent of the total light from this type of arc, but is of little value for most applications since its size, shape, and position prevent its being focused accurately. Therefore, a consideration of the characteristics of the high intensity arc is concerned chiefly with the crater light from the positive carbon. The whiteness and intrinsic brilliancy of this crater light exceeds that of incandescent carbon volatilized at atmospheric pressure. Evidently its source is something more than the solid tip of incandescent carbon since its color and brilliancy indicate a temperature of about 5,500 deg C. This intensified light can be considered as coming from a portion of the luminous gases of the flame material retained in the crater of the positive carbon by the force of the negative arc stream. This explanation may not accord with physical facts but it aids the imagination in visualizing the reason for the remarkably high intrinsic brilliancy of the high intensity carbon arc as compared with other artificial sources of illumination.

Maximum intrinsic brilliancy from the high intensity arc is attained by adjusting the position of the negative carbon so that the negative arc stream compresses within the crater of the positive carbon a substantial portion of the brilliantly luminescent vapors emanating from that point. This produces a bluish white light of very high candle power and much brighter than can possibly be obtained from incandescent carbon alone. A photograph of the

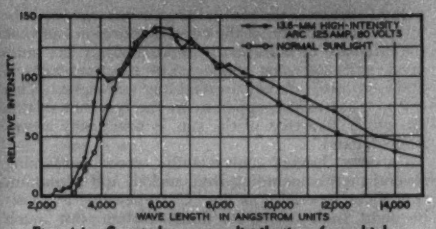
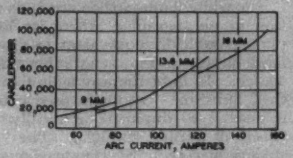


Fig. 14. Spectral energy distribution from high-intensity direct-current arc compared with that from normal sunlight

Fig. 15. Candle power of crater light from high intensity arc for carbons of 3 different sizes



direct-current high-intensity arc is reproduced in Fig. 13.

The energy distribution curve for a typical high intensity carbon arc is shown in Fig. 14. On this is superposed the energy distribution curve for normal sunlight. Radiation from the arc as here measured is the radiation from the positive crater only since in most applications of this type of arc the crater light is all that can be utilized. These curves show the striking similarity between this light source and natural sunlight through the entire range of the spectrum. The candle power of the crater light directly in front of the arc is shown in Fig. 15. As would be expected, the candle power increases with the current. When the same current is used with 2 different sized carbons of the same composition the smaller, that is, the one with the higher current concentration, gives the greater candle power.

The term "super high intensity arc" has been given to the arc produced by special 16-mm high-intensity carbons capable of carrying 195 to 200 amp and producing 40 to 60 per cent higher candle power than the ordinary 16-mm high-intensity carbon operated at 150 amp.

Motion picture projection in the larger theaters is the principal field of application for the high intensity arc. There are many other applications, however, including theater spotlights, motion picture studio sun arcs and rotary spots, army and navy searchlights, searchlights used for spectacular illumination, airport landing lights, and the famous Lindbergh beacon at Chicago.

Direct-Current High-Intensity Arc With Nonrotating Positive Carbon

The smallest direct-current high-intensity arc with rotating positive carbon in general use is the so-called "Hi-Lo" projection lamp which uses a 9-mm

Table I—Arc Conditions for Direct-Current High-Intensity Arc with Nonrotating Positive Carbon

Carbon Diameter, mm		Arc Current, Amperes	Arc Voltage	Current Density in Positive Carbon	
Postive	Negative			Amp per Sq In.	Amp per Sq Cm
6	5	35–40	28–35	800–910	124–141
7	6	45–50	29–36	755–840	117–130
8	7	60–65	30–37	770–835	119–129

Table II—Arc Conditions for Alternating-Current High-Intensity Arc

Carbon Diameter, mm	Arc Current, Amperes	Arc Voltage	Current Density	
			Amp per Sq In.	Amp per Sq Cm
6	40–45	18–24	910–1,025	141–159
7	60–65	23–26	1,005–1,090	156–169
8	75–80	24–29	960–1,025	149–159

positive carbon operating at 60 to 65 amp and 45 to 50 volts. A rather large interval exists between the screen illumination available from this lamp and that practicable with the low intensity reflector arc used in the majority of small theaters. There is also a marked difference in the color of light from these 2 types of arcs. The low intensity arc gives a yellowish white light whereas the high intensity arc gives a snow white light generally considered more desirable for the projection of motion pictures. To bridge this gap and provide for the small theater screen illumination of high intensity, quality, and brilliancy, a metal coated carbon of small diameter has been developed to operate at an intermediate current. The carbons for this small high intensity arc have been so designed that the positive carbon does not need to be rotated and the negative can be coaxial with the positive. The carbons are protected from oxidation and their electrical resistance reduced by the metal coating making it practicable to hold the carbon at any convenient distance from the arc. Arc current and voltage ranges for the standard size trims are indicated in Table I.

Most efficient operation of this nonrotating direct-current high-intensity arc with its short arc length and low voltage calls for a motor generator set of not more than 50 to 55 volts rating. It should be possible for designing engineers to provide a generator for this purpose of such characteristics that no ballast resistance will be required in series with the arc.

Alternating-Current High-Intensity Arc

Operation of a direct current arc of any type from an alternating current power circuit requires the use of a motor generator set or a transformer and rectifier. The development of an alternating-current high-intensity carbon arc permits operation through a suitable transformer directly from the alternating current power line thus eliminating all rotating intermediate apparatus as well as the heavy power loss in ballast resistance. This provides a very efficient source of projection light. The alternating-

Fig. 16. Alternating-current high-intensity arc

current high-intensity arc, together with the direct-current high-intensity arc with nonrotating positive carbon, promise to supersede to a very large extent the direct-current low-intensity reflector arc which at present is used in approximately 60 per cent of the motion picture theaters in the United States. The alternating-current high-intensity arc is essentially a development from the ordinary flame arc obtained by increasing the current and reducing the voltage usually used with the ordinary flame arc, the intrinsic brilliancy of which is too low to be suitable for projection. Light emitted by the white flame arc at currents up to 30 or 35 amp increases directly as the voltage, but as the square of the current. The rate of increase of light with increased current decreases for currents of more than 30 to 35 amp until at very large currents the rate of light increase becomes equal to the rate of current increase. By increasing the current but decreasing the arc length and voltage, the arc becomes steadier and the sources of light are concentrated into smaller volume near the electrode tips.

The alternating-current high-intensity arc does not have the same crater formation as the direct-current high-intensity arc with rotated positive carbon, but the light has the brilliant snow white quality characteristic of all high intensity arcs. The appearance of this arc is shown by the photograph reproduced in Fig. 16.

Lamps designed for operation with alternating-current high-intensity carbons are of the reflector type. Both carbons are of the same diameter and are burned in a horizontal position without rotation. Metal coating provides high electrical conductivity and permits support of the carbons at a distance from the arc. Arc currents and voltages for most satisfactory operation are given in Table II.

Although practically all of the light projected onto the screen is picked up from the carbon facing the reflector and this carbon is of negative polarity during alternate half cycles, there is no noticeable flicker in the screen illumination. This is because the light is of almost equal intensity during both positive and negative half cycles. In this respect the alternating-current high-intensity arc differs materially from the alternating-current low-intensity arc, and resembles the arc from rectified alternating current as may be seen from the oscillograms reproduced in Figs. 17 and 18. It is apparent from Fig. 17 that the screen illumination from the low intensity arc during the negative half cycle is less than half the peak reached during the positive half cycle, while the high intensity arc shows very little

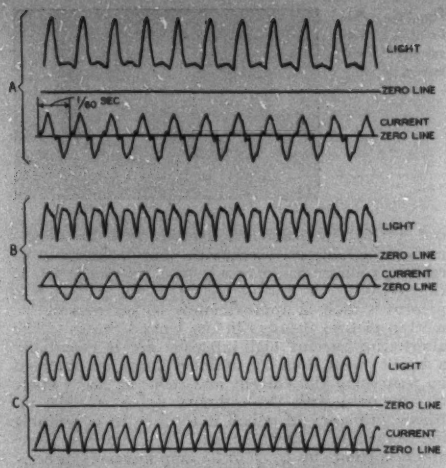


Fig. 17. Oscillograms of arc current and instantaneous light on projection screen without projector shutter running

A. Low-intensity 60-cycle alternating-current arc
B. High-intensity 60-cycle alternating-current arc
C. Low-intensity rectified-current arc

difference between positive and negative half cycles. Figure 18 indicates the flicker that results from the harmonic between the shutter speed and the circuit frequency with the low-intensity arc and the absence of a pronounced harmonic with the high-intensity arc.

A valuable feature of this arc and likewise of the direct-current high-intensity arc with nonrotating positive carbon is that the brilliant screen illumination made available to small theaters permits a level of general illumination that provides immediate comfortable vision to those entering the theater. This is of decided advantage from the standpoint of safety as well as that of attracting patronage, and has heretofore been available only to the large theaters using powerful direct-current high-intensity projection lamps or to those "neighborhood" theaters small enough for the direct-current low-intensity arcs to provide a corresponding level of illumination.

At present, application of the alternating-current high-intensity arc is confined to motion picture projection, but its possibilities are not limited to this use and it undoubtedly will find other fields of application.

Improved Motion Picture Studio Carbon Arc

The effectiveness of a light source in photography is dependent upon the distribution of its radiant energy throughout the spectrum and upon the spectral sensitivity of the photographic emulsion. The plain carbon arc with only 17 per cent of its radiant energy in the visible and photographically effective

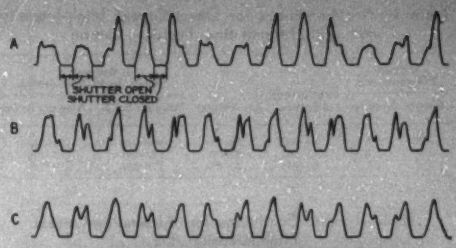


Fig. 18. Oscillograms of instantaneous light on projection screen with 2-blade projector shutter running at 1,440 rpm (film speed 90 ft per minute)

A. Low-intensity 60-cycle alternating-current arc
B. High-intensity 60-cycle alternating-current arc
C. Low-intensity rectified-current arc

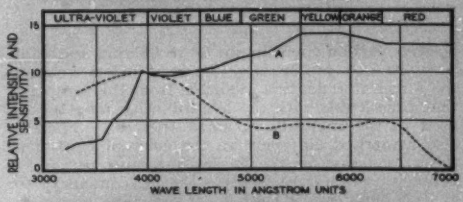


Fig. 19. Spectral energy distribution of 40-amp studio-carbon arc (A) and color sensitivity of supersensitive panchromatic motion picture film (B)

ultra-violet range of the spectrum was satisfactory for the emulsions of an earlier day which were most sensitive to the blue, violet, and ultra-violet rays. Early panchromatic emulsions, while extending the range of sensitivity to all visible colors, were still low in sensitivity to yellow, orange, and red. A special type of flame carbon strong in orange and red emission was developed to meet the demands of that period for an efficient light source giving equal photographic effect for all colors. The development of present day supersensitive panchromatic emulsions, having much greater sensitivity to orange and red than the early types, calls for a light source of almost equal strength in all color bands; in fact, the color sensitivity of these emulsions is almost perfectly balanced to the radiant energy distribution of normal daylight.

An improved white flame photographic carbon recently has been developed to match the sensitivity of these latest photographic emulsions, thus giving the motion picture studios the advantages of speed and coolness which characterizes the use of the carbon arc in photography. More than 40 per cent of the radiation from this arc is photographically effective. This new electrode is a metal coated carbon 8 mm in diameter with a core composed of rare earth chemicals of the cerium group. Special lamps developed for use with this carbon in the studio operate silently with continuous and uniform feeding of the carbons. These lamps overcome the ob-

jections to noisy and jumpy operation which were raised against the old types of arc lamps when sound was introduced into motion picture productions.

The new studio carbon arc is operated on direct current at 35 to 40 amp with about $37^1/_2$ volts across the arc. At this current density, 450 to 510 amp per square inch (70 to 79 amp per square centimeter) and with the relatively short arc length employed, the arc departs from normal characteristics of the regular white flame arc and takes on many of the characteristics of the high-intensity arc; however, the crater formation in the positive carbon, while distinct, is not deep. The brilliant gas ball at the tip of the positive carbon consequently has a highly effective lateral emission.

This arc at 40 amp and $37^1/_2$ volts gives about 9,330 candle power in the horizontal direction. A twin arc (2 arcs in series) without reflector gives approximately 200,000 lumens at this current and arc voltage compared with 158,000 lumens for the regular white flame arc using 13-mm carbons under the same conditions. On a 115-volt circuit this represents an efficiency of 43.5 lumens per watt as compared with 34.4 lumens per watt from the ordinary white flame twin arc. The energy distribution curve at 40 amp and $37^1/_2$ volts is shown in Fig. 19 together with the color sensitivity curve of a modern panchromatic photographic emulsion. Radiant energy of this new carbon in the visual part of the spectrum is considerably greater than that of earlier types of flame carbons and shows a peak in that region where supersensitive films are least sensitive.

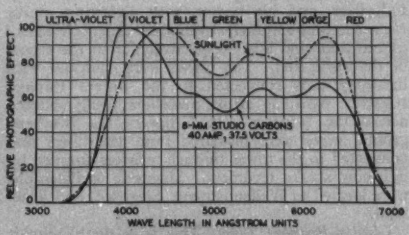


Fig. 20. Photographic effect from studio carbon arc compared with that from sunlight

Ordinates represent the product of transmission of glass lens, relative sensitivity of film, and spectral energy distribution of light source; values adjusted to give maximum equal to 100

Figure 20 shows the photographic effectiveness of the light from these carbons compared with that of natural sunlight. These curves take into account the spectral sensitivity of the photographic emulsion, the energy distribution of the light source, and the transmission factor of the camera lens. The close similarity to daylight in photographic effect is readily apparent from the figure.

This new carbon with the improved silent lamps designed for its use is restoring the popularity of the carbon arc in motion picture studios for black and white photography and has proved indispensable in the latest color process. Its high electrical and photographic efficiency makes it an equally desirable source of illumination for all kinds of photography.

Intrinsic Brilliancy

In many applications such as searchlights, spotlights, and motion picture projectors, it is essential that a powerful light be obtained from a source of small dimensions. In this respect the carbon arc is unsurpassed. The intrinsic brilliancy, that is, the candle power per square millimeter, for several types of arcs is given in Table III. For comparison, the intrinsic brilliancy of other light sources is included in the data presented.

Manufacture of lighting carbons requires a large investment in specialized equipment. The raw materials used are the purest commercial form of carbon available and the bonding agents are refined and distilled to required characteristics under conditions permitting very close control. Careful laboratory supervision at every stage of production is necessary to maintain the required standards in the finished product.

The carbon arc provides the basis for a ceaseless program of research. Steady improvements are being made in electrode manufacture as well as in lamp design. Longer electrode life, steadier operation, and higher electrical efficiency are being attained. New fields of application are being disclosed. Better adaptation to the many uses in which the arc now is applied is being achieved.

The high efficiency of the carbon arc as a source of visible and ultra-violet radiation, the flexible and uniform quality of radiation it provides, and its extremely high intrinsic brilliancy in relation to other artificial sources of radiant energy give the carbon arc a prominent and increasingly important place in the broad field of illumination.

Table III—Intrinsic Brilliancies of Light Sources

Light Source	Candle Power per Square Millimeter	Source of Data
Magnetite arc stream	6.2	W. R. Mott, National Carbon Co. Lab.
Flame arc stream	8.0	W. R. Mott, National Carbon Co. Lab.
900-watt special-tungsten-filament clear gas-filled bulb	26.6	International Critical Tables
Positive crater of cored, d-c low-intensity carbon arc	155– 175	*Journal*, Soc. of Motion Picture Engrs.
Crater of a-c high-intensity carbon arc	280	*Journal*, Soc. of Motion Picture Engrs.
Positive crater of nonrotating d-c high-intensity carbon arc	380	*Journal*, Soc. of Motion Picture Engrs.
Positive crater of rotating d-c high-intensity carbon arc	400– 800	*Journal*, Soc. of Motion Picture Engrs.
Positive crater of d-c "super high intensity" carbon arc	1,000–1,200	National Carbon Co. Lab.
Sun at zenith	920– 950	

Lightning Investigation on Transmission Lines—IV

Lightning currents ranging from about 4,000 to 63,000 amp in the towers of electric power transmission lines have been measured by the surge crest ammeter, of 64 readings obtained, all but 2 showed currents of negative polarity. This paper is the fifth in a series by the same authors reporting the results of a continued investigation of lightning effects on several typical transmission lines in different parts of the United States.

By
W. W. LEWIS
MEMBER A.I.E.E.

C. M. FOUST
MEMBER A.I.E.E.

Both of the General Elec. Company, Schenectady, N. Y.

THE YEAR 1933 was the eighth year of a continuous investigation of lightning effects on electric power transmission lines, carried on co-operatively by the General Electric Company and several operating power companies. This paper is the fifth of a series of A.I.E.E. papers by the same authors, reporting the results of this investigation.[1]

During 1933 the investigation was conducted mainly on the Wallenpaupack-Siegfried 220-kv line of the Pennsylvania Power and Light Company and the 132-kv Glenlyn-Roanoke (Va.) line of the Appalachian Electric Power Company (American Gas and Electric Company system). The field work dealt largely with the measurement of tower currents resulting from lightning discharges, for which purpose the surge crest ammeter was used almost exclusively. The conclusions of the preceding paper in this series are confirmed and restated in the first 3 paragraphs of the following summary of results:

1. The overhead ground wire definitely has been shown to be effective in reducing line tripouts.

2. Beneficial effects of low tower footing resistance have been shown by the data and analysis. A 220-kv line with normal insulation and conventional ground wire arrangement has operated for 5 years without flashover on towers with footing resistance 12 ohms or less.

3. The counterpoise is an effective means for securing low tower footing resistance.

4. In 64 readings obtained with the surge crest ammeter the tower current ranged from 4,000 to 63,200 amperes.

5. Practically all currents measured in transmission towers have been of negative polarity, indicating discharge from negative clouds and upward travel of the current in the stroke.

These data and accompanying theory indicate that lines may be designed for lightning conditions on the basis of correlating tower current, tower footing resistance, and line insulation strength.

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. Pacific Coast convention, Salt Lake City, Utah, Sept. 4–7, 1934. Manuscript submitted May 23, 1934; released for publication May 31, 1934. *Not published in pamphlet form.*

Lines and Measuring Equipment

Wallenpaupack-Siegfried Line. This single circuit horizontally arranged line in eastern Pennsylvania extends from Wallenpaupack generating station to Siegfried, a distance of approximately 65 miles.[3] At Siegfried the line joins the Siegfried-Plymouth Meeting line and at Bushkill the line is tapped by the Bushkill-Roseland (N. J.) line.

For a distance of 27.2 miles the line is equipped with 2 overhead ground wires and for the remaining 37.5 miles it has no overhead ground wires. Of the ground wire section 2.6 miles are equipped with a continuous tower-to-tower counterpoise (buried copper cable) and 23.6 miles are equipped with radial counterpoises (4 buried copper cables each 50 ft long). One mile of the ground wire section has no special provision for reducing the tower footing resistance. Tower footing resistances in the tower-to-tower counterpoise section were reduced from 50–150 ohms to 1–1.5 ohms, and in the radial counterpoise section from 10–150 ohms to 5–75 ohms by the addition of the counterpoises.

All insulator strings were equipped with surge indicators and all towers with lightning stroke recorders and surge crest ammeter magnetic links,[2] placed 2 in. and 8 in., respectively, from the corner of the angle iron. Ten towers were equipped with lightning rods connected to the towers through resistors, lightning stroke recorders being shunted across the resistors. At 5 towers the overhead ground wires were insulated from the tower and connected to the tower through resistors shunted by lightning stroke recorders. Magnetic oscillographs were located at Wallenpaupack, Siegfried, and Roseland.

Glenlyn-Roanoke Line. This is a double-circuit vertical line in Virginia approximately 65 miles long with one overhead ground wire at the peak of the towers.[4] Tower footing resistance measurements were made between October and December 1931 with the ground wire detached; these ranged from 5 to 400 ohms. In May and June 1932 counterpoises were installed at 20 towers on the Roanoke end and 20 towers on the Glenlyn end. The footing resistances were checked at the Roanoke end and a 50-per cent reduction in resistance was found as compared with the measurements made in 1931.

The counterpoise at each tower consisted of 380 ft of $^1/_{16}$ x 2-in. galvanized iron strap. Two lengths of 150 ft each extended out from diagonally opposite tower legs, parallel with the line; 2 lengths each 40 ft long extended out at right angles to the line from the other 2 tower legs. The counterpoise conductors were buried approximately 18 in. under the

surface of the ground where conditions permitted, and were bolted to the tower legs.

All 3 conductors of one circuit of the line were completely equipped with expulsion protective gaps.[8] All towers were equipped with lightning stroke recorders and surge crest ammeter magnetic links on one leg; 60 towers had magnets on all 4 legs. Each leg installation consisted of 2 magnetic links placed 1 in. and 7 in., respectively, from the corner of the angle iron. Twenty towers had tower top lightning rods connected to them through resistors shunted by lightning stroke recorders. In addition, the rods were equipped with surge crest ammeter magnetic links. Crossarms of 90 towers had surge crest ammeter magnetic links on the side not equipped with expulsion protective gaps, one link per crossarm. An automatic magnetic oscillograph was installed at Glenlyn to assist in determining the characteristics of the fault current.

Lightning Currents in Towers

In previous years tower currents have been determined by means of the lightning stroke recorder. This instrument measured the potential drop across a portion of the tower leg and this drop was translated into current by means of a laboratory calibration. Because of the uncertain cause of this potential drop, i. e., whether attributable to resistance, reactance, wave front, or a combination of these, it was not possible to make a reliable translation of the readings into current, and there is ample reason to believe that most of the readings of appreciable magnitude were too high. This instrument still is used; it is of value in checking polarity and in determining the location of the stroke.

The surge crest ammeter magnetic link responds only to the magnetic flux set up by the current passing down the tower leg and gives an accurate measurement of that current. Its only drawback is that oscillating or alternating current tends to demagnetize the links. However, theory and evidence seem to indicate that the lightning current itself is unidirectional. Correction readily may be made for the slight demagnetizing effect of the power frequency current that follows the lightning stroke current down the tower.

Table I gives the results of all the readings obtained on the Wallenpaupack-Siegfried line with the surge crest ammeter. These readings are divided into 3 groups. Items 1 to 10, inclusive, were for the section of line with overhead ground wires. No flashed insulators and no tripouts resulted (there was one surge indicator operation). The product of current and tower footing resistance for all readings was less than 400 kv.

The second group of readings, items 11 to 22, inclusive, was for sections of line having no overhead

Table I—Surge Crest Ammeter Readings, Flashovers, and Tripouts on Wallenpaupack-Siegfried 220-Kv Line During 1933

Item No.	Line Name	Tower No.	Footing Resistance, Ohms	Surge Crest Ammeter Reading, Amperes	Products IR × 10⁻³	Overhead Ground Wires	Flashed Insulators	Tripouts	No. of Insulator Units
1	WT	4–5	26	−10,000	260	Yes	No	No	14–16
2	WT	8–4	8	−23,000	184	Yes	No	No	14–16
3	WT	8–5	7	−27,000	189	Yes	No	No	14–16
4	WT	12–4	1	− 8,000	8	Yes†	No	No	14–16
5	SR	2–1	15	−34,000	360	Yes	SI	No	14
6	SR	2–4	10	−22,000	220	Yes	No	No	14
7	SR	2–5	5	−10,000	50	Yes	No	No	14
8	SR	4–2	8	−Trace*	32	Yes	No	No	14
9	SR	4–3	19	−Trace*	76	Yes	No	No	14
10	SR	4–4	19	−19,000	360	Yes	No	No	14
11	WT	27–6	58	−36,000	2,088	No	Yes	15	14–16
12	WT	28–1	45	−Trace*	180	No	Yes	15	14–16
13	WT	28–4	19	−12,000	228	Yes**	Yes	14	16
14	SR	7–1	17	−Trace*	68	No	Yes	5	14
15	SR	7–2	12	−12,000	144	No	Yes	5	14
16	SR	8–1	34	−12,000	408	No	Yes	7	14
17	SR	8–2	23	− 8,000	184	No	Yes	7	14
18	SR	9–3	28	−10,000	280	No	Yes	9	14
19	SR	19–3	45	−26,000	1,170	No	Yes	‡	14
	SR	24–1	48	None	None	No	Yes	10	14–16
20	SR	24–2	20	−12,000	240	No	Yes	10	14–16
21	SR	27–4	11	− 5,000	55	No	Yes	17	14–16
22	SR	31–3	34	−41,000	1,390	No	Yes	‡	14–16
23	SR	7–4	19	−Trace*	76	No	No	No	14
24	SR	8–4	20	−33,000	660	No	No	No	14
25	SR	9–2	15	−12,000	180	No	No	No	14
26	SR	20–1	30	−Trace*	120	No	No	No	14
27	SR	21–2	20	−30,000	600	No	SI	No	14
28	SR	26–2	20	+Trace*	80	No	No	No	14–16
29	SR	27–3	15	−Trace*	60	No	No	No	16
30	SR	31–4	14	− 8,000	112	No	SI	No	14–16
31	SR	32–2	13	−12,000	156	No	No	No	16
32	SR	32–3	27	− 4,000	108	No	No	No	14–16

* A trace corresponds to about 4,000 amp.
** Stroke probably occurred to open line beyond this tower (WT—28–4).
† Counterpoise installed.
‡ One of these flashovers caused tripout No. 11.
WT—Wallenpaupack tap. SR—Siegfried-Roseland line.
SI indicates surge indicator operation but no flashed insulators.
Insulator flashover voltages: 14 units, 1 x 5-μsec wave, 1,565 kv; 14 units 1.5 x 40-μsec wave, 1,265 kv; 16 units, 1 x 5-μsec wave, 1,775 kv; 16 units, 1.5 x 40-μsec wave, 1,425 kv.

Table II—Surge Crest Ammeter Readings, Flashovers, and Tripouts on Glenlyn-Roanoke 132-Kv Line During 1933

Item No.	Tower No.	No. of Towers Involved	Footing Resistance, Ohms	Tower Current* Amperes	Product IR × 10^{-3}	Flashed Insulators	Tripout	No. of Insulator Units**
1	12 G.	1	80	−23,400	−1,900	Yes	No	12
3	21 G.	3	140	−26,000	−3,640	Yes	Yes	12
13	53 G.	6	35	−55,800	−2,000	Yes	Yes	12
5	61 G.	1	17	−10,000	− 170	No	No	10
6	121 R.	1	5	−10,000	− 50	No	No	12
8	16 G.	1	18	− 9,600	− 170	No	No	12
9	79 G.	1	10	−11,200	− 110	No	No	10
10	90 G.	1	9	−63,200	− 570	No	No	10
11	91 G.	1	8	−12,000	− 100	No	No	10
12	93 R.	1	13	−11,200	− 145	No	No	12
13	94 R.	1	22	− 6,800	− 150	No	No	10
21	62 G.	1	6	−14,000	− 85	No	No	12
23	80 G.	2	6	−10,800	− 65	No	No	10
25	114 R.	2	20	−12,000	− 240	No	No	10
25	84 R.	1	12	− 7,200	− 87	No	No	10
26	91 R.	1	5	−22,600	− 113	No	No	10
28	104 R.	2	13	−20,400	− 265	No	No	12
29	34 R.	1	19	−18,000	− 340	No	No	10
31	88 R.	1	12	− 9,600	− 115	No	No	10
32	83 R.	1	12	−16,000	− 192	No	No	12
33	80 R.	1	10	−12,800	− 128	No	No	12
35	80 G.	1	20	− 8,800	− 175	No	No	10
36	101 R.	1	10	+ 7,600	+ 76	No	No	10

* Where more than one tower is involved, data are given in this table for only the tower with highest current.
** 4¾-in. spaced units.
Insulator flashover voltages: 10 units, 1 x 5-μsec wave, 960 kv; 10 units, 1.5 x 40-μsec wave, 795 kv; 12 units 1 x 5-μsec wave, 1,135 kv; 12 units, 1.5 x 40-μsec wave, 930 kv.

ground wires; flashover and tripout took place in all cases. Three of the products of current and resistance were high and of the order of the insulator flashover voltage for standard test waves; the other products were 400 kv or less. In this section a stroke to a conductor could result in insulator flashover regardless of the tower footing resistance. Only for strokes to towers would footing resistance determine flashover. In the ground wire section, however, for strokes to both towers and ground wires, flashover would be determined by the tower footing resistance.

The third group, items 23 to 32, inclusive, occurred in the section without overhead ground wires where there were no flashovers or tripouts (2 surge indicator operations were recorded). For all these readings, the product of current and resistance was less than 700 kv.

Tower currents varied from 4,000 to 40,000 amp. All currents were negative except item 28, which showed a trace of positive current.

In Table II are listed 23 lightning disturbances on the Glenlyn-Roanoke line. This line is equipped throughout with one overhead ground wire. A total of 32 registrations by the surge crest ammeter was recorded, but only one item in each group involving several towers is listed in Table II (that is for the tower showing highest current). Flashover of insulators occurred with the first 3 items and tripout with 2 of the 3 items. The product of current and tower footing resistance in these items exceeded the flashover voltage of the insulators with standard test waves. In the remaining items there was no flashover or tripout and all products of current and footing resistance were less than 600 kv.

Tower currents ranged from 6,800 to 63,200 amp, and all currents were negative except one, item 36, which indicated 7,600 amp of positive polarity.

Table III—Flashover of Towers, Insulator Assemblies, and Spillway Gaps on Wallenpaupack-Siegfried 220-Kv Line

Year	Flashed Towers	Flashed Insulator Assemblies	Spillway Gap Flashovers
1926	18	24	
1927	15	25	1
1928	100*	128*	0
1929	75	90	9
1930	50	56	4
1931	37	38	4
1932	17	22	2
1933	26	34	1
Total	338	417	21

* Includes carry-over from 1926 and 1927.
Spillway gap flashover voltages: 1 x 5-μsec wave 880 kv; 1.5 x 40-μsec wave 690 kv.

Table IV—Flashed Towers on Wallenpaupack-Siegfried 220-Kv Line Tabulated With Respect to Overhead Ground Wire Construction and Method of Grounding

			Overhead Ground Wires			
Year	Unknown	No Overhead Ground Wires	Standard Grounding	Tower-to-Tower Counter-poise	Radial Counter-poise	Total
1926		18				18
1927	11	4				15
1928	22	74	4*			100
1929	0	71	4	0		75
1930	0	45	3	0	2	50
1931	0	36	0	0	1	37
1932	0	15	0	0	2	17
1933	0	25	1	0	0	26
Total	33	288	12	0	5	338
Miles†		37.5	1.0	2.6	23.6	64.7

* One flashover on reduced insulation.
† Present mileage of each item. This mileage has changed from time to time as construction has been changed.

Table V—Tripouts Caused by Lightning on Pennsylvania-New Jersey 220-Kv Interconnection

Year	No. of Circuit Miles: With O.G.W.	No. of Circuit Miles: Without O.G.W.	No. of Tripouts: With O.G.W.	No. of Tripouts: Without O.G.W.	No. Tripouts per 100 Circuit Miles: With O.G.W.	No. Tripouts per 100 Circuit Miles: Without O.G.W.	Estimated Lightning Severity
1928	187	41	6	13	3.2	32	100
1929	187	41	5	37	2.7	90	130
1930	191	37	8	23	3.1	62	100
1931	263	37	5	20	1.9	54	70
1932	309	37	9	9	2.9	24	50
1933	309†	37*	8	14	1.6	38	70
Total			36‡	116‡			
Average					2.5	50	

O.G.W. = Overhead Ground Wires.
* All on Wallenpaupack-Siegfried line.
† Mileage distributed as follows: Wallenpaupack-Siegfried 27 miles; Siegfried-Plymouth 49 miles; Bushkill-Roseland 46 miles; Roseland-Plymouth 72 miles; Conowingo-Plymouth 114 miles.
‡ The locations of 49 tripouts were not known definitely, but these have been assigned to section with or without ground wires in accordance with correlated information.

Table VI—Effect of Tower Footing Resistance on Flashed Towers on Wallenpaupack-Siegfried 220-Kv Line, 1929–1933, Inclusive

Resistance Range, Ohms	No. of Towers: Flashed	No. of Towers: Total No.	Ratio Flashed to Total Towers
A. Overhead Ground Wire Section			
1— 12	0	36	0.00
13— 65	10	100	0.10
66—120	2	4	0.50
1—120	12	140	0.09
B. Section Without Overhead Ground Wires			
1— 10	14	14	1.00
11— 65	134	148	0.91
66—330	23	30	0.77
1—330	171	192	0.89

Flashovers and Tripouts as Affected by Overhead Ground Wires

Table III shows the number of flashovers on towers, insulator assemblies, and spillway gaps on the 220-kv Wallenpaupack-Siegfried line for 8 years, 1926 to 1933, inclusive. The spillway gaps are at the line terminals and are set at approximately 50 per cent of the flashover voltage of the line insulators.

Data for the 338 flashed towers shown in Table III are analyzed in Table IV with respect to the overhead ground wire construction of the line. It was not possible to classify 33 flashed towers; of the remaining 305, 288 were on the 37.5 miles without overhead ground wires and the remaining 17 occurred on the 27.2-mile ground wire section. None of the flashovers has occurred on the tower-to-tower counterpoise section since the counterpoise was installed, although 29 insulator assembly flashovers occurred in this section in the 3 years prior to installation of counterpoise wires. While the radial counterpoise does not show up as well as the tower-to-tower counterpoise, it must be remembered that the radial arrangement consists of only 200 ft of cable in 4 50-ft lengths, and the tower footing resistance is not nearly as low (5 to 75 ohms) as in the tower-to-tower counterpoise section (1 to 1.5 ohms). Also, of course, about 9 times as much line is equipped with the radial as with the tower-to-tower counterpoise.

Table V summarizes the tripout situation on the entire 220-kv Pennsylvania-New Jersey interconnection, consisting of approximately 346 miles of line. Tripouts are shown to be approximately 20 times as frequent on the line without overhead ground wires as on the lines with overhead ground wires.

Table VI shows the effect of tower footing resistance on tower flashover for the Wallenpaupack-Siegfried line during the 5-yr period, 1929–33, inclu-

Table VII—Lightning Tripouts on Typical Transmission Lines With Overhead Ground Wires

Company and Line	Kv	No. of Miles	No. of Insulator Discs	No. of Ground Wires	Height of Ground Wires Above Conductors at Tower	Distance Between Outside Conductors	Distance Between Ground Wires	No. of Tripouts	No. of Years	Tripouts per 100 Miles per Year
Pa. Power & Light Co. Wallenpaupack-Siegfried	220	27	14–16	2	10.5–11.5	45.3	22.5	4	6	2.47
Pa. Power & Light Co. and Philadelphia Elec. Co. Siegfried-Plymouth	P. P. & L. section 220	49	14	2	13	52.5	26	6	6	2.04
	Phila. Elec. section 220		16	2	16	51	25.5			
Philadelphia Elec. Co. Conowingo-Plymouth (No. 1)	220	57	14	2	16	51	25.5	8	6	2.34
Conowingo-Plymouth (No. 3)	220	57	14	2	16	51	25.5	8	6	2.34
Public Service Gas & Elec. Co. Bushkill-Roseland	220	46	16–18	2	18	57	28.5	1	2	1.00
Public Service Gas & Elec. Co. Roseland-Plymouth	220	72	16–18	2	18	57	28.5	8	3	3.7
Pa. Water & Power Co. Safe Harbor-Westport	220	70	20*	2	26	56.5	42.25	1	2	0.7
Philadelphia Elec. Co. Philadelphia-Chester**	66	14	8*	2	11	17.25	17.25	1	16	0.45
N. Y. Power & Light Co. Greenbush-Pleasant Valley**	110	64	11	2	8.3	28	22	3	2.25	2.08
N. Y. Power & Light Co. N. Y. Edison Co. Pleasant Valley-Millwood**	132	40.5	12	2	11.75	30.5	36	2	2	2.47

* 5-in. spacing; other lines 5½-in. spacing.
** Double-circuit vertical; other lines single-circuit horizontal arrangement.

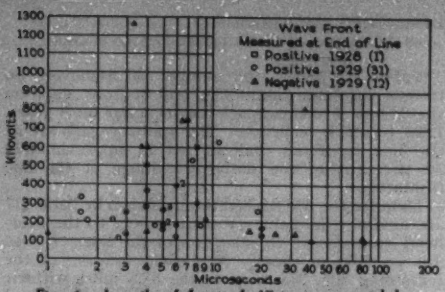


Fig. 1. Length of front of 45 waves caused by lightning on the 220-kv Wallenpaupack-Siegfried line as recorded at end of line by cathode ray oscillograph

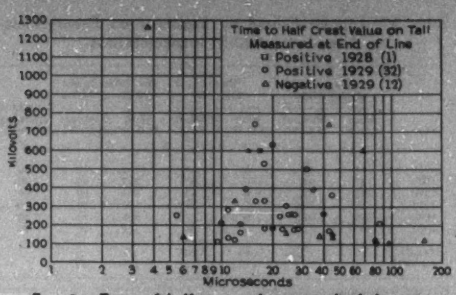


Fig. 2. Time of half crest value on tail of the 45 waves whose lengths of front are shown in Fig. 1

sive. In this period it was possible to locate the flashovers fairly accurately. For the overhead ground wire section the ratio of flashed to total towers is about 1 in 10; for the section without overhead ground wires the ratio is about 9 in 10. For the overhead ground wire section there were no flashed towers where the grounding resistance is 12 ohms or less, regardless of the manner of grounding. For the section without overhead ground wires the tower footing resistance apparently is immaterial. This may be because in this section many of the strokes are direct to the conductor; for such strokes tower footing resistance has no effect on flashover.

From the data here presented, it is evident that the overhead ground wire is effective in preventing line flashover, that it is more effective the lower the tower footing resistance, and that this particular line is immune from flashover if the tower footing resistance is 12 ohms or less.

Calculations have been made for the location of overhead ground wires to take care of direct strokes.[6] These calculations are based upon assumptions as to the lightning potential at the instant of contact with the overhead ground wire, such assumed values varying from 5,000 to 20,000 kv, and also upon assumptions as to the steepness of wave front of the lightning stroke. These values have not been substantiated by measurements of stroke potential and wave front at or near the point of contact of the stroke. The recommended height of ground wires above conductors varies from 20 to 50 ft, depending upon the assumptions.

It is useful to review the data secured by the cathode ray oscillograph concerning length of front and duration of waves on transmission lines; this will be done in a later section. It is useful also to review the ground wire arrangements now in use on practical lines and to see how these lines have operated.

In Table VII are listed several 220-kv lines in Pennsylvania, New Jersey, and Maryland, also a 66-kv line in Pennsylvania and 110- and 132-kv lines in New York. Data are given as to the line insulation, distance between conductors, distance between ground wires, and height of ground wires above conductors, also as to the number of tripouts and tripouts per 100 miles of line per year. It is not apparent from this tabulation that line construction or location of overhead ground wires accounts for the difference in performance of these lines. It is probable that 2 factors missing from the tabulation, namely, tower footing resistance and storm severity, together with line insulation, are the important factors that account for most of the differences in line operation.

Length of Wave Front and Duration of Waves on Transmission Lines

During the years 1928 and 1929 a laboratory with cathode ray oscillographs was located within 300 ft of the Wallenpaupack Station of the Wallenpaupack-Siegfried line, and in 1930 the laboratory was located at Cherry Valley, about 42 miles south of Wallenpaupack. In Fig. 1 are plotted the wave front (time from beginning to crest) against kilovolts for 45 waves of which cathode ray oscillograms were secured at Wallenpaupack in 1928 and 1929, and in Fig. 2 are plotted the time to half crest value on the tail (measured from the beginning) against kilovolts for the same waves.

In Fig. 3 are plotted the wave fronts against kilovolts for 16 waves the oscillograms of which were secured at Cherry Valley in 1930, and in Fig. 4 the time to half crest value on the tail against kilovolts for the same 16 waves. One oscillogram (Fig. 5) taken at Cherry Valley is not plotted. This was a direct stroke that flashed over the line insulators at approximately 3,000 kv on the front of the wave; therefore, this wave could not be included on the same basis as the others.

These figures show that in general the waves at the mid-point of the line are shorter, both as to front and duration, than the waves at the end of the line. Possibly the difference in length may be accounted for by the waves being recorded nearer their origin at Cherry Valley than at Wallenpaupack. The waves recorded at the latter place would tend to attenuate and lengthen out both on the front and tail by travel over the transmission line. At the end of the line the waves may reflect and increase in voltage; this increased voltage would tend to arc

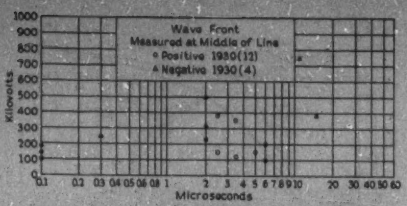


Fig. 3. Length of front of 16 waves caused by lightning on the 220-kv Wallenpaupack-Siegfried line as recorded at midpoint of line by cathode ray oscillograph

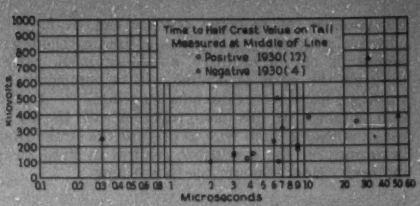


Fig. 4. Time of half crest value on tail of the 16 waves whose lengths of front are shown in Fig. 3

over the oscillograph trip-gap oftener, thus giving more records.

Mechanism of Flashover

Many helpful studies of lightning tripouts of transmission lines have been made in an effort to reduce the problem to one of engineering calculation. However, inasmuch as great uncertainty has existed regarding the actual electrical mechanism of the lightning stroke and the manner in which it builds up flashover voltage across insulators after striking the line, most of these studies have been based upon assumptions which have made conclusions questionable.

Somewhat in disagreement with the usual conception of the stroke as a traveling wave advancing from the cloud to the line, it has been pointed out that the stroke actually begins at the line and advances upward toward the cloud.[7] Considerable laboratory and field experience appear to substantiate the latter viewpoint. Recently a valuable photographic study of lightning[8] has resulted in the conclusion that after a downward leader or dart stroke provides an ionized pathway for the main discharge current, the main stroke follows immediately, passing upward from ground to cloud. The polarities found were cloud base negative and ground positive, which is in agreement with the surge crest ammeter findings given in this paper.

One cathode ray oscillogram of conductor potential was obtained for a direct stroke to the conductor[9] on the Wallenpaupack-Siegfried line. This section of line was without overhead ground wires and the stroke hit the conductor within a span (1,000 ft) of the oscillograph. The oscillogram shows a time from the beginning of the voltage rise on the conductor to flashover of about 5 μsec (Fig. 5). The conductor potential at the point of measurement built up slowly to 1,000,000 volts in about 4 μsec, then more rapidly to 3,000,000 volts at the end of 5 μsec. A velocity of propagation of the lightning stroke upward of approximately 150 ft per microsecond[8] would indicate that the main streamer had progressed less than 1,000 ft toward the cloud. The 3,000-kv conductor potential, assuming a surge impedance of 300 ohms, indicates a current of 10,000 amperes, which should be at least doubled to account for current flowing in both directions in the conductor. Assuming as indicated by crest current records that this stroke current was at least 60,000 amp, the total time element involved in the current wave front would be 8 or 10 μsec and the upward penetration of the main streamers would have reached approximately 1,500 ft in this time. The time required to reach the cloud would be at least 30 μsec assuming the cloud height to be about 4,500 ft. A total time for stroke duration might be about 100 μsec, during the last 70 of which the current dropped from 60,000 amp to zero.

In view of this order of current variation, and in connection with strokes to the tower structure, it is interesting to recognize that the tower and counterpoise are short in time length. With the lightning current rising slowly at first as the stroke proceeds upward, then more rapidly, but never at such a rate as to give important potential differences along the tower, counterpoise, or in the ground due to distance, the tower potential can rise to insulator flashover levels only by virtue of resistance potential drop in the tower footing. Lightning stroke recorder readings of potential across 35 to 40 ft of vertical tower structure have had an upper limit of approximately 40,000 volts. This shows the impedance drop along the tower structure to be unimportant as regards flashover. The problem of limiting tower potentials therefore becomes one of limiting tower footing resistance. This is accomplished by reducing the high current densities at the immediate tower footing through the use of buried counterpoise wires which carry the current away from the tower structure.

This way of looking at the situation means that

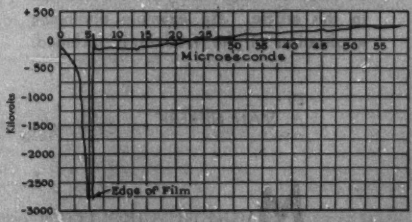


Fig. 5. Reproduction of oscillogram of a direct stroke at Cherry Valley laboratory, Wallenpaupack-Siegfried 220-kv line, July 24, 1930

the problem of reducing outages can be handled effectively merely as a problem of limiting the tower potentials on an ordinary resistance basis, rather than on the basis of dealing with a complexity of traveling wave reflections and couplings.[6,10] A solution obtained on this basis, together with the use of the overhead ground wire to prevent the stroke from beginning on the conductor, assures in most cases immunity from tripouts due to lightning.

References

1. Surge Voltage Investigation on Transmission Lines, W. W. Lewis. A.I.E.E. Trans., v. 47, 1928, p. 1111–21. Lightning Investigation on Transmission Lines, W. W. Lewis, and C. M. Foust. Part I, A.I.E.E. Trans., v. 49, p. 917–28; part II, A.I.E.E. Trans., v. 50, p. 1139–46; part III, A.I.E.E. Trans., v. 53, p. 475–81.

2. Lightning Investigation on the 220-Kv System of the Pennsylvania Power and Light Co. (1931–33), Edgar Bell. Elec. Engg., v. 53, Aug. 1934, p. 1188–94.

3. The Surge Crest Ammeter, C. M. Foust and H. P. Kuehni. *G. E. Review*, v. 35, Dec. 1932, p. 644–8.

4. Lightning Experience on 132-Kv Transmission Lines of the American Gas and Electric Company System (1930–31), Philip Sporn. A.I.E.E. Trans., v. 52, 1933, p. 482–90.

5. The Expulsion Protective Gap, K. B. McRachron, I. W. Gross and H. L. Melvin. A.I.E.E. Trans., v. 52, 1933, p. 884–91.

6. Critique of Ground Wire Theory, L. V. Bewley. A.I.E.E. Trans., v. 50, 1931, p. 1–18.

7. Direct Strokes to Transmission Lines, W. W. Lewis and C. M. Foust. *G. E. Review*, v. 34, Aug. 1931, p. 452–8.

8. Progressive Lightning, B. F. J. Schonland and H. Collens. *Proc.* of the Royal Society, series A, v. 143, p. 654–74.

9. Lightning Investigation on the 220-Kv System of the Pennsylvania Power and Light Company (1930), Edgar Bell and A. L. Price. A.I.E.E. Trans., v. 50, 1931, p. 1101–10.

10. The Lightning Stroke, L. V. Bewley. *G. E. Review*, Dec. 1933. Lightning Computations for Transmission Lines With Overhead Ground Wires, C. A. Jordan. *G. E. Review*, v. 37, 1934: March, p. 130–7; April, p. 180–6; May, p. 243–50.

11. Lightning Investigation on Transmission Lines, Part III, W. W. Lewis and C. M. Foust. A.I.E.E. Trans., v. 52, 1933, p. 478–81.

Analytical Representation of a Magnetizing Curve

A method of representing approximately an empirical magnetizing curve is outlined in this article. An example illustrating application of the method is included.

By
A. VAN NIEKERK
ASSOCIATE A.I.E.E.

Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.

MAGNETIC CIRCUITS of commercial electrical apparatus usually are more or less saturated at the normal operating voltages, and the magnetizing or saturation curves of such apparatus

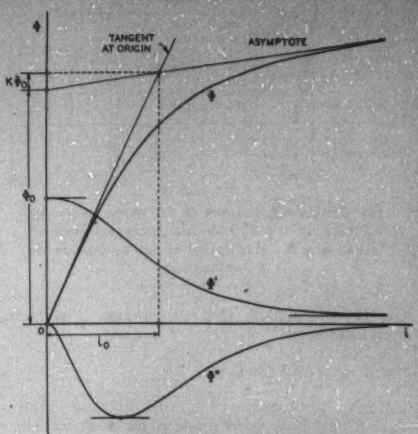


Fig. 1. Magnetizing curve, $\Phi = f(i)$, its first derivative, $\Phi' = f'(i)$, and its second derivative, $\Phi = f''(i)$. The tangent at the origin and the asymptote of the curve determine the constants i_o, Φ_o, and k, as indicated

expressing the relationships between the magnetic flux and the magnetizing current can be represented only by empirical curves that are obtained point by point either from design calculations or from test data. As a consequence, in several instances the solution of equations expressing certain characteristics of electrical apparatus and containing terms representing the flux cannot be found analytically, because it is not possible to eliminate the flux terms from such equations and introduce instead terms designating the magnetizing current. In such cases methods of graphical solution must be resorted to.

If, however, an investigation involving magnetic saturation is of a more or less general character, it appears desirable to indicate the general equation of an analytical curve containing one or more parameters; to these parameters such values must be attributed as to make the analytical curve represent with reasonable accuracy the empirical magnetizing curve of an electric apparatus, because such an equation makes it possible to eliminate the flux terms from the equations previously referred to. A method of representing approximately an empirical magnetizing curve (for instance, the saturation curve of a d-c generator) is outlined in this article.

When a magnetizing curve the equation for which is $\Phi = f(i)$, and curves for the first derivative $\Phi' = f'(i)$ and the second derivative $\Phi'' = f''(i)$ are examined (see Fig. 1) it becomes evident that it should be possible to approximate the (negative) ordinates of the Φ'' curve by a product of 2 factors; the first of these factors is proportional to the square of the abscissa, and the second to a power of ϵ (the base of Naperian logarithms) containing in the exponent the abscissa with negative sign. It should

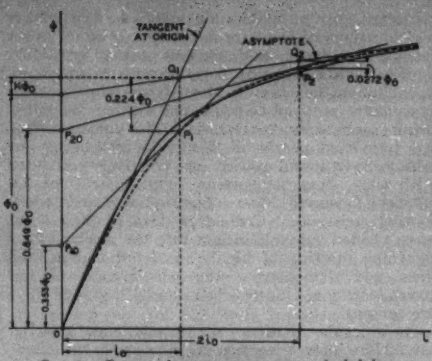


Fig. 2. Empirical magnetizing curve (solid line curve) and its analytical approximation (dotted line curve)

be possible, therefore, to adopt for the Φ'' curve the equation:

$$\Phi'' = -ai^n \cdot e^{-\frac{i}{b}} \tag{1}$$

in which a and b are 2 positive constants (parameters). Like the empirical Φ'' curve, the curve representing this equation has a minimum for a positive value of i, whereas the axis of abscissas is both a tangent at the origin and an asymptote of the curve. The adoption of the equation just given offers certain advantages from a mathematical standpoint, because, in general, any function $i^n e^{ci}$ can be integrated readily for all integral values of n, although a series representation of the integral function is necessary when $n = -1$.

The equation for Φ is obtained from eq 1 by integrating twice; consequently, the equation for Φ will contain, in addition to the 2 parameters a and b, 2 constants of integration, that is, a total of 4 constants. These 4 constants can be determined by imposing the conditions that the analytical Φ curve must pass through the origin O, and must have the same tangent at the origin and the same asymptote as the empirical magnetizing curve. The data (i_0, Φ_0, and $k\Phi_0$) determining this tangent and this asymptote are indicated in Fig. 1.

The result of twice integrating eq 1, and of introducing the proper values for the 4 constants in line with the foregoing, will not be given in the form $\Phi = f(i)$, because it is more advantageous to introduce the ratios:

$$x = \frac{i}{i_0} \qquad y = \frac{\Phi}{\Phi_0}$$

in which case (provided that x is positive) the *characteristic equation of the magnetizing curve* appears in the form:

$$y = kx + 1 - \left(\frac{3}{2}x^3 + 2x + 1\right) \cdot e^{-3x} \tag{2}$$

This equation contains only one parameter, k.

Example

An example, showing how this method of approximating a given magnetizing curve by means of an analytical curve as per eq 2 should be applied in a concrete case, is given in Fig. 2. First, the tangent at the origin and the asymptote for the given curve must be drawn; second, i_0, Φ_0, and $k\Phi_0$ must be determined from the diagram thus obtained, so that the magnitudes of i_0, Φ, and k become known (in Fig. 2, $k = 0.075$). Equation 2 then gives y as a known function of x, and, as a consequence, Φ becomes a known function of i.

In Fig. 2, the empirical (given) curve is indicated by a heavy line and its analytical approximation by a dotted line, thus clearly revealing the discrepancies between the 2 curves. By slightly varying the inclinations of tangent and asymptote (these 2 lines cannot be drawn with absolute accuracy anyway) an equation (2) can be found for which these discrepancies will remain within reasonable limits. In order to obtain some idea about the degree of approximation, the analytical curve should be plotted so that it can be compared with the empirical curve; it should be emphasized, however, that not many points of the analytical curve need to be calculated for this purpose. In general, it will be sufficient to determine, in addition to the tangent at the origin and the asymptote which can be considered as given, 2 points of the analytical curve and the tangents at these points. For instance, the points P_1 and P_2 (see Fig. 2) with abscissas i_0 and $2i_0$, can be chosen for this purpose; for any value of k, the locations of these points are determined by:

$$Q_1P_1 = 0.224\,\Phi_0 \qquad \text{and} \qquad Q_2P_2 = 0.0272\,\Phi_0$$

whereas the tangents $P_{10}P_1$ and $P_{20}P_2$ are determined by:

$$OP_{10} = 0.353\,\Phi_0 \qquad \text{and} \qquad OP_{20} = 0.849\,\Phi_0$$

(These relations can be derived easily from eq 2.) This means that, when applying the method and after drawing the tangent at the origin and the asymptote, the points P_1 and P_2 can be located directly, the tangents $P_{10}P_1$ and $P_{20}P_2$ drawn, and the analytical curve traced.

When problems involving a reversal of field (magnetizing) current must be dealt with, it should be remembered that eq 2 applies only for positive values of x; for negative values of x (negative branch of the magnetizing curve) the following characteristic equation must be used instead:

$$y = kx - 1 + \left(\frac{3}{2}x^3 - 2x + 1\right) \cdot e^{+3x}$$

When the residual magnetism of apparatus must be taken into account (for instance, in problems dealing with self-excited d-c generators) eq 2 can be used without modification, provided that in Fig. 1 the portion of the axis of ordinates now designated by $k\Phi_0$ is put equal to $k(\Phi_0 - \Phi_r)$ and that, instead of the ratio $y = \frac{\Phi}{\Phi_0}$, the ratio $y = \frac{\Phi - \Phi_r}{\Phi_0 - \Phi_r}$ is introduced, where Φ_r designates the residual flux of the apparatus.

Lightning Investigation on a 220-Kv System

Investigation of the effects of lightning discharges on the 220-kv transmission lines of the Pennsylvania Power and Light Company has been continued over a period of several years; results obtained during the period 1931–33 are reported and analyzed in this paper. By the use of the "distribution ratio method" of locating faults nearly all 220-kv faults causing line tripouts were found quickly and positively correlated with time, dynamic current, lightning current, insulator flashovers, line construction, and tower footing resistance.

By
EDGAR BELL
ASSOCIATE A.I.E.E.

Pennsylvania Pwr. and Lt. Co., Hazleton, Pa.

LIGHTNING RESEARCH has been conducted on the Pennsylvania-New Jersey 220-kv interconnection for the past several years for the purpose of obtaining knowledge of the magnitude of lightning, and of its distribution and effects on high voltage transmission lines of various types of construction; also to investigate the effects of low tower footing resistance and special grounding devices such as continuous counterpoise and tower footing grounding cables. This paper briefly describes the research conducted during 1931–33 by the Pennsylvania Power and Light Company with the coöperation and assistance of the General Electric Company and the Electric Bond and Share Company, which was confined largely to the former Wallenpaupack-Siegfried 220-kv line; the paper includes also line tripout and flashover data from all 220-kv lines of the interconnection.

Research conducted up to and including 1930 has been reported previously.[1, 2, 3] During the period 1931–33, this work has consisted chiefly of the acquisition and study of operating records (flashovers, tripouts, and magnetic oscillograms of fault currents), line betterment (performance of counterpoise, etc.), and field research (lightning strokes and lightning severity). Plentiful results of diverse nature have been obtained, including records of lightning strokes, structure current magnitude and polarity, number and locations of insulator flashovers, effect of tower footing resistance and various tower grounding devices, lightning storm severity records, and so on. A technique has been perfected whereby locations of dynamic arcs can be estimated within a few miles, using graphic ammeter records. This unique method has permitted nearly all 220-kv faults causing line tripout to be found quickly and positively correlated with time, dynamic current, lightning current, insulator flashover, line construction, and tower footing resistance. Correlated data of these kinds have yielded valuable insight into the mechanism of lightning faulting of highly insulated transmission lines and demonstrate the effectiveness of low tower footing resistance when overhead ground wires are present.

As far as the circuits of the Pennsylvania-New Jersey 220-kv interconnection are concerned, the following conclusions seem justified:

1. Conventional overhead ground wires provide protection against most of the direct strokes encountered.

2. Most lightning tripouts result from single-phase-to-ground faults.

3. Insulator flashovers causing line tripouts usually involve but one phase. When overhead ground wires are present, the majority of flashovers occur on one structure only, and when absent, the majority of flashovers involve several adjacent structures (usually 2).

4. Records of structure current resulting from lightning are practically all of negative polarity. Magnitudes as great as 41,000 amperes have been registered.

5. Tower footing resistances of less than 13 ohms appear to enable the overhead ground wires of the Wallenpaupack-Siegfried line to protect the line against all strokes of lightning. This tentative value of resistance appears to be independent of special tower footing grounding cables and counterpoise.

Description of Line

Although a description of the former Wallenpaupack-Siegfried line has been given elsewhere, it is believed worth while to present here a brief review of its design, history, and present status. The circuit comprising the former Wallenpaupack-Siegfried line is 65 miles long and of steel-tower, single-circuit, horizontal-configuration design. Conductors are 795,000-cir-mil A.C.S.R. (aluminum conductor steel reinforced), are spaced 22 ft $7^1/_2$ in. apart, and are supported by 16 (or 14) insulator units spaced $5^3/_4$ in. Two overhead ground wires of 184,000-cir-mil A.C.S.R. spaced 22 ft 7 in. apart and about 10 ft 6 in. to 11 ft 6 in. above the line conductors, were installed over 37 per cent of the line after $1^1/_2$ years of operation. Two sections, one about $19^1/_2$ miles long and extending south from Wallenpaupack, and one about $4^1/_2$ miles north from Siegfried, were so equipped. Flashovers still occurred on these sections of line, especially over High Knob (a rocky prominence 12 miles south of Wallenpaupack); consequently, early during 1929 a counterpoise consisting of a single continuous 2/0 copper cable was installed for a distance of 2.6 miles over this ridge. It was bonded to 2 footings of each of the 14 towers which it connected, was trenched in the earth and loose rock where this was possible and terminated at either end in a network of driven rods. Tower foot-

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. Pacific Coast Convention, Salt Lake City, Utah, Sept. 3–7, 1934. Manuscript submitted April 12, 1934; released for publication May 28, 1934. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

ing resistances which formerly varied from 50 to 150 ohms were reduced to about 1 to 1.5 ohms.

During 1930 the remaining $16^1/_2$ miles of overhead ground wire section near Wallenpaupack, and during 1931 the $4^1/_2$-mile section near Siegfried, were equipped with a less costly though less effective means of tower footing groundings. Groups of 4 buried 50-ft cables, perpendicular to each other and extending radially outward at 45 deg to the direction of the line were installed, each cable being bonded to its tower footing. These installations did not produce the extremely low resistance of the counterpoise, but effected reductions of about 50 per cent over former values. New resistances range from 3 to 85 ohms, with an average of 32 ohms.

During 1930 special overhead ground wires of 180,000-cir-mil A.C.S.R. were installed over a $3^1/_2$-mile section of line about 21 to $24^1/_2$ miles south of Wallenpaupack. These lightning stroke diverting[4] cables are supported on wood poles about 35 ft above the tower bridge, and anchored to earth by 4 (or 6) "copperweld" steel guys per structure. The 2 overhead cables are cross-bonded at each structure and are insulated from the tower tops by the long wood poles; they are grounded by means of the guys and are bonded to the tower footings through buried return cables similar to the tower footing grounding cables, but necessarily much longer.

During April 1932, a 220-kv tie[5] from Bushkill, Pa., to Roseland, N. J., was placed in service forming a Y-shaped line having terminals at Wallenpaupack, Siegfried, and Roseland and lengths of 28, 37, and 46 miles, respectively. The latter (new) section is completely covered by 2 overhead ground wires.

The circuit comprising the former Wallenpaupack-Siegfried line extends from Wallenpaupack, Pa., through Bushkill to Siegfried, Pa. The 83-mile circuit from Siegfried to Roseland is now called the Siegfried-Roseland line, and the 28-mile circuit from Wallenpaupack to Bushkill is called the Wallenpaupack tap. Since in general the research still has been conducted on the circuits comprising the former Wallenpaupack-Siegfried line, they accordingly will be designated by that name in this paper.

Field Research Methods and Devices

Records of line tripouts, insulator flashovers, and magnetic oscillograms have been kept regularly as well as field records from specialized devices, particularly on the former Wallenpaupack-Siegfried line. The *surge indicators*[6] installed on that line during 1930 have proved valuable in locating flashovers. These devices, one of which is coupled to each insulator assembly, are operated by surge current in the tower bridge, particularly that flowing over an insulator assembly when flashed by lightning. After operation, a yellow semaphore target is exposed and can be seen by a patrolman on the ground.

During 1929, a partial installation of *lightning stroke recorders*[7] was made. These instruments, which are inherently voltage-measuring devices utilizing Lichtenberg figures on camera film, record the polarity and approximate crest voltage of surges. They are used to measure the voltage drop across a section of tower when lightning current flows through the structure. The few installations of this device in 1929 spanned about 30 to 35 ft on the outside of one tower leg only, instead of reaching from the bottom of one leg to the top of the diagonally opposite leg as in certain other investigations. During 1930 each of the 314 line structures was equipped, and later during that season the installations were improved by substituting a longer and more rigid lead. During 1931 improved moisture-proof film packets of increased sensitivity replaced the former paper packets, and have been used each year since. During the 4-yr period 1930–33, 352 records have been secured.

During 1932, a different device, utilizing laminated steel links of high retentivity which are magnetized by the field surrounding a current carrying conductor, and designed to measure the polarity and crest magnitude of nonoscillatory structure currents, was proposed; 33 of these devices were installed. These *surge crest ammeters*,[8] as they are called, yielded no records, probably because of insufficient sensitivity. During 1933, all 314 towers were equipped with devices of improved design and about double the former sensitivity; 32 records were obtained.

During 1930, the *lightning severity meter*[6] was first tried in a limited way. This is a small integrating camera-like device, containing a gaseous glow tube connected in series between a 30-ft vertical antenna and ground. Electrostatic charges which collect upon the antenna (such as those from charged clouds) are discharged suddenly through the tube when the surrounding atmospheric field suffers a reduction in intensity from a lightning discharge in the vicinity. Successive discharges cause a cumulative darkening of the stationary film, which is left exposed for a period of one week.

Because the lightning severity meter records a phenomenon that is affected by conditions within a somewhat extensive area, is cumulative in action, and records all disturbances great and small over a weekly period, its story cannot be correlated satisfactorily with specific occurrences such as known lightning strokes, insulator flashovers, etc. It seems to possess merit as a "lightning survey" meter in selecting between alternative routes for future transmission lines.

Results—General

It is not possible to present in detail all data secured since 1930. The plan used includes summaries of data obtained during these and prior years, specific detailed samples, and statistical tables. Valuable insight into the mechanism and results of lightning influence on this line has been obtained from correlated data of different kinds, all relating to a single series of occurrences, and the use of these facilities has reduced the amount of line patrolling formerly necessary after storms. For example, assume a given storm causing 2 line tripouts. Associated in time with the relay and oil switch operations are magnetic oscillograms and graphic ammeter records, and dynamic arcs somewhere on the line. The approximate location of these arcs is estimated[11] from recorded values of line residual or transformer

bank neutral currents, and the phase or phases involved are determined from the same oscillograms. Consequently, patrolling usually is necessary only within about 5 miles each way from each estimated location, to permit discovery of the surge indicator operations and flashed insulators, and collection of lightning stroke recorder film packets and magnet links. Complete line patrols and changes of all film packets and magnet links are made at intervals of 2 months. Table I presents typical information secured concerning a line tripout.

Correlated information has permitted determination of the locations of 72 tripouts on the Wallenpaupack-Siegfried line. Since 1930, all but 2 of the 45 tripouts have thus been located. Prior to and including 1930, when technique was less developed, 29 out of 98 tripouts definitely were identified.

Lightning Severity; Lightning Stroke Records

Results obtained with the lightning severity meter have been reported in terms of "index numbers" and also "charge numbers." An index number is the $\log_2$ of the corresponding charge number. The latter represents the total charges summed up over the period of a week. Both numbers have been used as a means of comparing lightning severity at different sites. Table II lists season averages of index numbers and charge numbers for the past 3 years from 11 sites in Pennsylvania, the last 4 being adjacent to, or near the terminals of, the former Wallenpaupack-Siegfried line.

Typical weekly records for the 1933 season from sites 1, 7, and 9 representing severe, moderate, and mild exposures, are shown as Fig. 1.

Most of the lightning stroke records from this line have been obtained from the lightning stroke recorder, which apparently is quite sensitive to voltage disturbances. Besides recording most of the direct strokes to the tower to which the recorder is coupled, the instrument is affected by other disturbances which perhaps result from strokes to nearby objects and/or induced strokes. The records cannot always

Table I—Representative Line Tripout Data—Former Wallenpaupack-Siegfried Line

Date and time	June 3, 1933, 4:55 p.m.	
Line name and tripout no.	Siegfried-Roseland No. 5	
Phase or phases involved	Y (single phase to ground)	
Initial residual amperes and breaker operating times: Wallenpaupack	320 amp., 121 cycles	
Initial residual amperes and breaker operating times: Siegfried	1,740 amp., 29 cycles	
Initial residual amperes and breaker operating times: Roseland	430 amp., 81 cycles	
Estimated fault location	about 7.2 miles north of Siegfried	
Towers affected	SR 7-1	SR 7-2
Flashed insulators	Yes	Yes (1 unit broken)
Did surge indicators work?	Yes	Yes
Lightning stroke recorder polarity	Negative	Negative
Surge crest amperes	—Trace	—12,000
Overhead ground wires	No	No
Tower footing resistance, ohms	17	12

Table II—Lightning Severity at Typical Sites

Site No.	Location	Season Averages: Index Numbers 1931	Index Numbers 1932	Index Numbers 1933	Charge Numbers 1931	Charge Numbers 1932	Charge Numbers 1933
1	Jordan Valley	7.0	4.6	7.1	138	24	138
2	Blue Mountain Summit	4.7	3.4		26	11	
3	Lizard Creek Valley	5.0	3.2	5.5	32	9	45
4	South Tamaqua	7.6	6.2	8.2	195	74	295
5	Locust Mountain	5.7	3.9		52	15	
6	Broad Mountain	5.4	3.2	2.6	42	9	6
7	Frackville	4.6	3.6	4.9	24	12	30
8	High Knob Summit	6.1	6.5		69	91	
9	Cherry Valley	1.2	0.6	2.5	2	2	6
28	Siegfried			2.7			28
29	Wallenpaupack			3.1			31

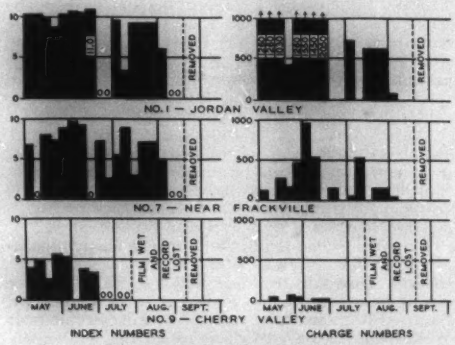


Fig. 1. Typical weekly records of lightning severity data obtained at 3 sites during 1933

These records, from top to bottom, are representative of those obtained at sites of severe, moderate, and mild exposure to lightning

Table IV—Comparison of Corresponding Registrations From Lightning Stroke Recorders and Surge Crest Ammeters

Device	Negative	Positive	Others	Total	% Negative
Lightning stroke recorder	25	2	3	30	83–93
Surge crest ammeter	29	1	0	30	96

Table III—Lightning Stroke Recorder Registrations on the Wallenpaupack-Siegfried Line

Polarity	Total Recorder Registrations 1930**	1931	1932	1933	Total	Apparent Strokes* 1930**	1931	1932	1933	Total
Negative	26	85	48	58	217	16	30	11	25	82
Positive	0	16	31	26	73	0	0	1	0	1
Others***	3	19	19	21	62	2	2	6	2	12

* In classifying records into "strokes," other data also have been used, such as insulator flashovers, surge (flashover) indicator operations, etc.
** The 1930 records were obtained from now obsolete, rather insensitive, paper film packets.
*** Many of these records have been classed as oscillatory, but they may have been caused by 2 or more successive and/or nonassociated disturbances. Some recorde are too small for polarity interpretation.

Table V—Correlated Lightning Surge Data for Former Wallenpaupack-Siegfried Line

Item No.	Line Name	Tower No.	Footing Resistance, Ohms	Surge Crest Ammeter Readings, Amperes	Products IR × 10^{-3} (See Note)	Overhead Ground Wires	Flashed Insulators and Phases	Trip-out No.	Lightning Surge Recorder Record
1	WT	4-5	26	−10,000	260	Yes	No	None	Neg.
2	WT	8-4	8	−23,000	184	Yes	No	None	Neg.
3	WT	8-5	7	−27,000	189	Yes	No	None	Neg.
4	WT	12-4	1	− 8,000	8	Yes†	No	None	Neg.
5	SR	2-1	15	−24,000	360	Yes	SI	None	Neg.
6	SR	2-4	10	−22,000	220	Yes	No	None	+ and −
7	SR	2-5	5	−10,000	50	Yes	No	None	Neg.
8	SR	4-2	8	−trace*	32	Yes	No	None	Neg.
9	SR	4-3	19	−trace*	76	Yes	No	None	Neg.
10	SR	4-4	19	−19,000	360	Yes	No	None	+ and −
11	WT	27-6	58	−36,000	2,088	No	Yes, 1	15	Neg.
12	WT	28-1	45	−trace*	180	No	Yes, 1	15	Neg.
13	WT	28-4	19	−12,000	228	Yes**	Yes, 1	14	None
14	SR	7-1	17	−trace*	68	No	Yes, 1	5	Neg.
15	SR	7-2	12	−12,000	144	No	Yes, 1	5	Neg.
16	SR	8-1	34	−12,000	408	No	Yes, 1	7	Neg.
17	SR	8-2	23	− 8,000	184	No	Yes, 1	7	Neg.
18	SR	9-3	28	−10,000	280	No	Yes, 1	9	Neg.
19	SR	19-3	45	−26,000	1,170	No	Yes, 3	‡	Neg.
	SR	24-1	48	None	None	No	Yes, 1	10	Neg.
20	SR	24-2	20	−12,000	240	No	Yes, 1	10	None
21	SR	27-4	11	− 5,000	55	No	Yes, 1	17	Neg.
22	SR	31-3	34	−41,000	1,390	No	Yes, 3	‡	Neg.
23	SR	7-4	19	−trace*	76	No	No	None	Neg.
24	SR	8-4	20	−33,000	660	No	No	None	Neg.
25	SR	9-2	15	−12,000	180	No	No	None	Neg.
26	SR	20-1	30	−trace*	120	No	No	None	Neg.
27	SR	21-2	20	−30,000	600	No	SI	None	Neg.
28	SR	26-2	20	+trace*	80	No	No	None	Neg.
29	SR	27-3	15	−trace*	60	No	No	None	?
30	SR	31-4	14	− 8,000	112	No	SI	None	Neg.
31	SR	32-2	13	−12,000	156	No	No	None	Pos.
32	SR	32-3	27	− 4,000	108	No	No	None	Pos.

* A trace corresponds to about 4,000 amps. ** Stroke probably occurred to open line between towers WT 28-3 and 28-4. † Counterpoise installed.
‡ One of these flashovers caused tripout No. 11. No estimate of location could be made because of a lack of residual current.
WT—Wallenpaupack tap; SR—Siegfried-Roseland line; see text, "Description of Line."
SI—Indicates surge indicator operation but no flashed insulators.
NOTE: IR × 10^{-3} is the product of columns 4 and 5 divided by 1,000, and represents apparent kilovolts across the tower footing resistance. Flashover can occur (a) when the line conductor is struck, and (b) when the tower or overhead ground wire is struck and the product IR × 10^{-3} combined with the impedance drop (in kilovolts) through the tower structure exceeds the flashover strength of the line insulation, or between 1,400 and 2,300 kv. In case (a) flashover occurs from line conductor to tower and in (b) from tower top to line conductor. Items 13–18 and 20–21 apparently are examples of case (a) and items 11, 12, 19, and 22 of case (b).

be classified positively as having been caused by direct strokes although a judicious classification yields results probably not far from the truth. During 1933, some additional information was obtained from the surge crest ammeter.

To present in detail the large amount of data obtained is obviously impracticable. In general, records obtained since 1930 are similar though more numerous than those shown in Table V of the 1930 paper.[8] Existing records are summarized in Table III.

Corresponding to the 105 lightning stroke records obtained during 1933, there were 32 surge crest ammeter records. One reason for this small number of records is that the lightning stroke recorder responds to influences other than impedance drop resulting from direct strokes, whereas the surge crest ammeter is affected only by current. Another factor is that the latter devices were not in service as long as the former, nor were they serviced as frequently. Of the 32 records obtained, 30 have been correlated with lightning stroke recorder registrations. The remaining 2 records are associated with lightning strokes that yielded no lightning stroke recorder records. This peculiar characteristic of Lichtenberg figure cameras occasionally failing to yield a record[9] has been observed for some years though the reason is not known. In these 2 cases, insulators were flashed and line tripouts occurred. Surge crest ammeters in each case yielded records of 12,000 amp, negative. Table IV shows the excellent correlation between polarity of records from the 2 devices.

Surge crest ammeter records from the Wallenpaupack-Siegfried line have ranged in value from a trace (about 4,000 amp) to 41,000 amp. (Records of currents as great as 63,200 amp[10] have been obtained from the Glenlyn-Roanoke, Va., 132-kv line of the American Gas and Electric Company.) Table V presents detailed data and correlating information.

Counterpoise and Tower Grounding Cables

It has been mentioned that the counterpoise has effected an enormous reduction in tower footing resistance, and that about 50 per cent reductions have been obtained with tower footing grounding cables. Of more importance is the fact that no flashovers have occurred on the counterpoise section of line since the counterpoise cables were installed. Lightning severity data from High Knob previously shown indicates greater than usual lightning severity in that region. Prior to the installation of the counterpoise, 13 towers had been flashed over in that short 2.6-mile section. At least 2 of these occurred after overhead ground wires were in use.

The record of the tower footing grounding cables is not quite as good. Four towers have been flashed, resulting in at least one tripout. Nevertheless, the performance appears to have been improved, as Table VI shows.

Line Insulator Flashovers

Table VII lists the numbers of towers on which insulator flashover has occurred; these are designated as flashed towers. Usually, the flashover involved but one phase to ground. This compilation shows that from 85 to 95 per cent of all flashovers have occurred on the open sections of line and that on a comparable mileage basis, only about 11 per cent as many towers have been flashed on the sections protected by overhead ground wires as on open line.

Table VIII compares the numbers of flashed towers with the numbers of flashed insulator assemblies and surge indicator operations, and indicates that most flashovers involve only one phase.

Line Tripouts

Table IX lists the numbers of tripouts that have occurred on the open and overhead ground wire sections of line, as well as those the locations of which could not be determined with certainty. Of the 143 tripouts listed, the exact location of the fault and the number of circuit phases involved are known in 72 cases. Table X shows the numbers of phases involved in these tripouts.

Records from other 220-kv lines equipped with overhead ground wires involving 18 more tripouts show that the proportional numbers of faults affecting 1, 2, and 3 phases are 68, 23, and 9 instead of 50, 25, and 25 as shown in Table X; this demonstrates that for horizontally configurated lines of these types single-phase faults are in the great majority.

Magnetic oscillograms have been invaluable in several respects. One use has been to facilitate estimating fault location[11] when the fault involved only 1 or 2 phases and residual currents were measured. Other uses have been to show the phase (or phases) involved in a flashover, changes in current magnitude and direction of power flow, times of relay and breaker operation, and the few cases where single-phase-to-ground arcs changed into 2-phase-to-ground arcs. Table XI shows the segregation of 90 tripouts on the 220-kv Pennsylvania-New Jersey interconnection (of which the numbers of phases involved and actual locations are known) into those involving 1, 2, or more adjacent structures.

It has been shown previously that most faults in

Table VI—Results of Wallenpaupack-Siegfried Line Betterment

Line Section	Miles	Years	No. Towers Flashed	No. Line Tripouts	Flashed Towers** per 100 Circuit Miles per Year	Tripouts per 100 Circuit Miles per Year
Counterpoise (1929–33)	2.6	.5	0	0	0	0
Diverting cables (1930–33)	3.7	.4	0	0	0	0
Tower footing grounding cables (1930–33)	21*	.4*	5†	2	4.8†	1.2‡
Standard overhead ground wires (1927–29)	22*	2.5*	12	3	20.0	5.5
Open line (1926–33)	43.8*	.8*	228	87	65.0	24.8

* Approximate values.
** A flashed tower is that on which one or more insulator assemblies has flashed over, and which may have involved 1, 2, or 3 phases. If the same tower was reflashed later it has been counted as 2 towers, and so on.
† Only 4 of these 5 items can be charged to failure of the tower footing grounding cables, and the figure of 4.8 is on this basis. Tower footing resistances were 13 15, 34, and 56 ohms.
‡ Only one of these 2 items can be charged to failure of these cables, and the figure of 1.2 is on this basis. The tower footing resistance was 13 ohms. Surge indicator operations occurred at this and 2 adjacent towers and lightning stroke records at this and the next tower.
Note: The extra flashed tower and line tripout is included in the open line data.

Table VII—Flashed Towers* on the Wallenpaupack-Siegfried Line

Construction	Year 1926	1927	1928	1929	1930	1931	1932	1933	Total	Per Cent	No. per 100 Circuit Miles per Year
Overhead ground wire**		0	4	4	5	1	2	1	17	5.0	9.3
Open line†	18	4	74	71	45	36	15	25	288	85.2	82.8
Unknown	0	11	22	0	0	0	0	0	33	9.8	

* Towers on which one or more insulator assemblies have been flashed. ** Average mileage, 6.5 years, 28.3. † Average mileage, 8 years, 43.5.

Table VIII—Flashed Towers and Insulator Assemblies, and Surge Indicator Operations on the Wallenpaupack-Siegfried Line

	Year 1926	1927	1928	1929	1930	1931	1932	1933	Total
Flashed towers	18	15	100	75	50*	37	17	26	338**
Flashed insulator assemblies	24	25	128	90	56*	38	22	34	417**
Surge indicator operations					38*	56	42	56	192**

* 29 flashed towers and 34 flashed assemblies correlate with the 38 surge (flashover) indicator operations.
** 109 flashed towers and 128 flashed assemblies correlate with the 192 surge (flashover) indicator operations.

Table IX—Tripouts on the Wallenpaupack-Siegfried Line

Construction	Year 1926	1927	1928	1929	1930	1931	1932	1933	Total	Average per 100 Circuit Miles per Year
Overhead ground wire		0	1	1	1	0	1	0	4	2.2
Open line	15	4	2	10	14	20	9	13	87	35.0
Unknown		3	11	27	9	0	0	2	52	

Table X—Phases Affected in Tripouts on the Wallenpaupack-Siegfried Line

No. of Faulted Phases	Overhead Ground Wire Section		Open Line Section		Total	
	No.	%	No.	%	No.	%
1	2	50	55	81	57	79.2
2	1	25	7	10	8	11.1
3	1	25	6	9	7	9.7
Total	4	100	68*	100	72	100.0

* Although at least 87 open line tripouts have occurred, only 68 have been positively located.

Table XI—Phases and Towers Involved in 220-Kv Faults

		220-Kv Tripouts			
		Open Line Section		Overhead Ground Wire Section*	
		Number	Per Cent	Number	Per Cent
Single-phase faults	total	55	81	15	68
	involving 1 structure	20	29	12	54
	involving 2 structures	31	46	2	9
	more than 2 structures	4	6	1	5
Multiphase faults	total	13	19	7	32
	involving 1 structure	4	6	7	32
	more than 1 structure	9	13	0	
		68	100	22	100

* Only 4 of these 22 tripouts occurred on the former Wallenpaupack-Siegfried line.

volve but one phase conductor. Table XI shows also that when overhead ground wires are present, most of the few faults involve but one structure; but when they are absent, most of the large number of faults involve 2 adjacent structures. The 22 tripouts on sections of line equipped with overhead ground wires occurred over a 6-yr period (1928–33) on 241 miles (average) of circuit, whereas the 68 tripouts on lines not so equipped occurred during the same 6-yr period on 38 miles (average) of circuit. Reduced to a more comparable basis, there were 29.8 tripouts (average) per 100 circuit miles per year on open line and only 1.5 on line equipped with ground wires.

Tower Footing Resistance

It would be very helpful if the secret of how much and why tower footing resistance affects the operation of transmission lines could be made clear. Results usually are masked by many other effects, such as insulation strength of line, clearances and configuration of ground wires, season lightning severity and variations between routes of different lines, whether or not the resistances were measured with overhead ground wires disconnected from and insulated from the tower under measurement, presence of special grounding networks such as a counterpoise, and other factors. Overhead ground wires alone reduce frequency of flashover very greatly and the reason for the few remaining flashovers becomes difficult of solution. Assuming that the overhead ground wire has intercepted a stroke and is attempting to conduct it to earth, the suggestion has been made that flashover results when the product of structure current and tower footing resistance exceeds the insulation strength of the line. The problem is not as simple as that, however. It is evident that complications are introduced by surge wave front, reflections from tower top and tower footing, tower and ground wire impedance, and other factors; further complications result because of uncertainty as to how much the tower footing resistance at the time of a stroke differs from the ordinary "meggered" value, and because of the small amount of structure current data available.

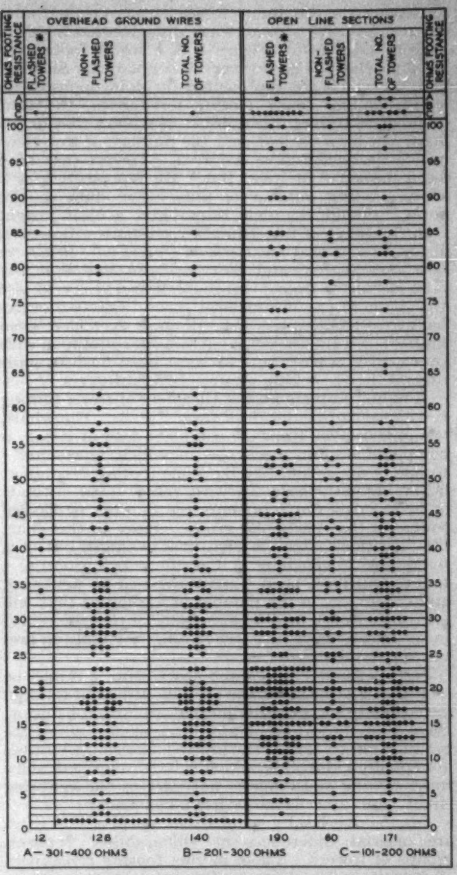


Fig. 2. Tower footing resistance and flashover data for the Wallenpaupack-Siegfried 220-kv line during the 5-year period 1929–33

*A flashover involving one or more phases of one tower is counted as one flashed tower; if reflashed later, it is recounted

Data on flashed insulators for 5 years have been employed to indicate the effect of tower footing

resistance on this line. Resistances were measured by megger with ground wires disconnected from the tower under test. Figure 2 is a tower footing resistance chart of the former Wallenpaupack-Siegfried line on which are represented by dots opposite the corresponding tower footing resistances, the total number of towers, the number of towers that as yet have not been flashed, and the number of towers on which flashovers have occurred. Towers that have been flashed 2 or more times are represented by a corresponding number of dots. The data in this form, although complete, do not give a clear insight into the effect of tower footing resistance; however, it can be seen that *few overhead ground wire structures have been flashed*, and that *few open line structures have not been flashed*. An inspection will reveal also that none of the 36 overhead ground wire structures having resistances less than 13 ohms ever have been flashed. Of the 19 such structures not equipped with overhead ground wires, 14 have been flashed, some several times, making a total of 25 flashovers.

A more complete idea of the effect of tower footing resistance can be obtained from Fig. 3. This chart, which is derived from the complete data of Fig. 2, is composed of dots each one of which represents 4 towers of approximately the same footing resistance, beginning with those of lowest value. The ordinate or height of a dot represents the number of flashed towers in that particular group. Since in this chart the "location factor" is fairly well averaged out, it is reasonable to conclude that in time each group of 4 towers will have been equally exposed to lightning, and differences in the number of flashovers that will have taken place will be a measure of the differences in the effectiveness of tower footing resistance in preventing flashovers.

Figures 2 and 3 represent 5 years' data. It may be seen that for the open line section, although random variations exist between different groups of 4 towers, there is no indication of any fundamental difference between towers of high and low resistances. All towers are equally vulnerable, which is to be expected, since tower footing resistance is not part of the lightning circuit until after flashover has taken place.

For the overhead ground wire section of line there are marked differences in vulnerability between groups of towers. Those having footing resistances of less than 13 ohms so far have been immune.

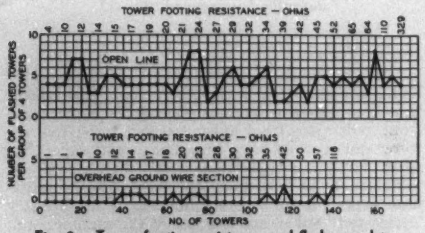


Fig. 3. Tower footing resistance and flashover data of Fig. 2 plotted in curve form; each dot represents 4 towers of approximately the same footing resistance

Those having resistances of more than 13 ohms are flashed occasionally although for resistances of less than 60 ohms not more than 1 tower in 4 is so characterized; between 60 and 118 ohms this number is increased to 2. The curve of these data shows that above 13 ohms there is a slight increase in vulnerability as resistances increase.

Similar data[12] from South Africa have been arranged by the writer into a chart similar to Fig. 3. These data show more clearly than the Wallenpaupack-Siegfried data the increased vulnerability of the higher resistance towers and the existence of a maximum safe value of tower footing resistance. For the Victoria Falls-Transvaal 132-kv lines, this value is 6 ohms, compared with 12 ohms for the Wallenpaupack-Siegfried 220-kv line. Between 7 and 24 ohms the maximum number of flashed towers per group of 5 towers is 1; above 24 ohms this number increases to 2 and ultimately to 3.

Figure 3 is presented not as a solution of the problem, but to stimulate more interest in the subject. It has been shown that of 2 lines of approximately similar construction and length, but having different average tower footing resistances, the one having the lower resistance will have a correspondingly better flashover and tripout record.[13] A study made by the writer on several pairs of lines of different voltage ratings and locations, suggests that the reason low resistance lines show improved performance is in the increased number of towers having resistances less than a "critical value" for the particular type of construction involved. Apparently for 3 pairs of medium voltage lines having one overhead ground wire, the critical resistances range in value from 2 to 7 ohms, whereas for a 230-kv line the value may be as great as 32 ohms; for the former Wallenpaupack-Siegfried line it appears to be about 12 ohms.

References

1. Surge Voltage Investigation on the 220-kv System of the Pennsylvania Power and Light Co., N. N. Smeloff. A.I.E.E. Trans. v. 47, 1928, p. 1140.

2. Lightning Investigation on the 220-kv System of the Pennsylvania Power and Light Co. (1928 and 1929), N. N. Smeloff and A. L. Price. A.I.E.E. Trans., v. 49, 1930, p. 895.

3. Lightning Investigation on the 220-kv System of the Pennsylvania Power and Light Co. (1930), Edgar Bell and A. L. Price. A.I.E.E. Trans., v. 50, 1931, p. 1101.

4. Diverting Direct Strokes, A. E. Silver. *Elec. World*, Aug. 16, 1930.

5. Switching at Richmond Station, Raymond Bailey and F. R. Ford. Elec. Engg., Jan. 1934, p. 156 (Fig. 1).

6. Instruments for Lightning Measurements, C. M. Foust. *G. E. Review*, April 1931.

7. Lightning Investigations on Transmission Lines, 1929, W. W. Lewis and C. M. Foust. A.I.E.E. Trans., v. 49, July 1930, p. 917.

8. The Surge Crest Ammeter, C. M. Foust and H. P. Kuehni. *G. E. Review*, Dec. 1932.

9. 1930 Lightning Investigations on the Transmission System of the American Gas and Electric Company, Philip Sporn and W. L. Lloyd, Jr. A.I.E.E. Trans., v. 50, 1931, p. 1111. (Table IV, item 21).

10. Lightning Investigation on Transmission Lines—IV, W. W. Lewis and C. M. Foust. Elec. Engg., v. 53, Aug. 1934, p. 1180–86.

11. Locating Grounds by Distribution Ratio Method, W. F. Dunkle and J. S. DeShazo. Elec. Engg., v. 53, Feb. 1934, p. 258.

12. An Analysis of the Lightning Faulting Characteristics of the 132-kv Lines of the Victoria Falls and Transvaal Power Co., Ltd., E. F. Rendell and H. D. Gaff. *Trans.* of South African Inst. of Elec. Engrs., Nov. 1933.

13. Lightning Experience on 132-kv Transmission Lines of the American Gas and Electric Co. System, 1930–1931, Philip Sporn. A.I.E.E. Trans., v. 52, 1933, p. 482. (Figs. 3, 4, and 5).

Lightning Performance of 132-Kv Lines

Lightning performance of the 132-kv transmission lines of the American Gas and Electric Company during 1932–33 is reported in this paper. Analysis of lightning performance of these lines, records of which have been kept for the past 9 years, has resulted in definite progress being made in understanding the lightning problem and also in definite conclusions regarding many aspects thereof.

By
PHILIP SPORN
FELLOW A.I.E.E.

I. W. GROSS
ASSOCIATE A.I.E.E.

Both of the American Gas & Electric Co., New York, N. Y.

ALTHOUGH the first 132-kv line on the present 132-kv network of the American Gas and Electric Company was placed in service in 1917, not until the lightning season of 1925 when 4 additional lines were in service did the importance of the lightning problem to the successful operation of such lines become apparent. The destructive effects on one of these lines that year already have been reported.[1] From that time on a careful record of the lightning performance of all lines on the 132-kv system has been kept yearly, studied, and correlated with pertinent features of the lightning protective problem as applied to transmission lines. Analyses of these records have been presented to the Institute in the past[2, 3, 4, 5, 6, 7] in the light of the knowledge, theory, and opinions on lightning prevalent at the time. It is the purpose of this paper to present and discuss the operating performance under lightning conditions during 1932 and 1933 of the lines of this 132-kv network which now comprise some 1,450 miles of tower lines.

Transmission System

The extent of the 132-kv network, country traversed, and type of construction, which have been described before,[8] were practically the same in 1932 and 1933 except that the single-circuit lines 8, 9, and 10 (Table III) were double-circuited during most of the 1933 lightning season. All the lines, except 60 miles of wood pole line, are of steel tower construction; all steel tower lines are equipped with 1 ground wire at the tower peak, and a few with 2 ground wires.

A general summary of the types of lines is given in Table I, the 60-cycle and impulse flashover voltages of the insulators in Table II, and more details concerning each line and their detailed operating performances in Table III.

Line Outages and Lightning Storm Data

Line outages for the various classifications of lines are given in Table IV, and have been plotted together with lightning frequency and severity in Figs. 1 and 2. Lightning frequency is the yearly number of storms reported at 8 stations distributed over the system; lightning severity is the visual classification of storms by observers at these stations.

Outstanding features regarding outages (Table IV) are:

1. Outages on this system, averaging 10.6 to 12.4 per hundred miles of line per year, were practically the same for single- and double-circuit line during 1932 and 1933. This record differs from the situation in 1928 to 1931[6] when for the first 2 years 2-circuit outages were the greater, and for the second 2 years 1-circuit outages were greater (all on 100-mile-per-year basis).

2. Lines equipped with 2 ground wires had about 80 per cent of the outages experienced by lines with 1 ground wire.

3. Wood pole lines with no ground wires had approximately 50 per cent more outages than steel tower lines with ground wires.

4. Steel-tower ground-wire lines insulated for 132 kv, but operated at 33 to 44 kv, have in the order of 60 per cent of the outages of simi-

Table I—Miles of Line of 132-Kv Construction Operating on the American Gas & Electric Company System in 1933

Line right of way	1,457.2
3-phase circuit	2,484.4
2-circuit line	1,027.2
1-circuit line	430.0
Wood pole line	60.3
Line with 1 ground wire	1,247.0
Line with 2 ground wires	149.9
Line with no ground wire	60.3

Table II—Approximate Flashover Characteristics* (Kv) of Line Insulators

Insulator Units		60-Cycle	Minimum Impulse Values	
No.	Spacing (In.)	Dry (Crest)	1x5-μsec Wave	1½x40-μsec Wave
10	4¾	640	880	680
11	4¾	700	980	750
12	4¾	780	1,080	830
10	5½	680	950	730
11	5½	765	1,050	810
12	5½	850	1,150	890
9	5¾	680	950	730
10	5¾	760	1,040	860
12	5¾	895	1,250	1,025
10	6⅞†	1,010	1,400	1,070

* Based upon "Flashover Voltages of Insulators and Gaps," ELECTRICAL ENGINEERING, June 1934, p. 882–6, and effective spacing one unit less because of grading shields.
† No grading shields used.

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. Pacific Coast convention, Salt Lake City, Utah, Sept. 4–7, 1934. Manuscript submitted May 26, 1934; released for publication May 29, 1934. *Not published in pamphlet form.*

1. For all numbered references see bibliography at end of paper.

1		2	3	4	5	6	7	8	9	10	11	12	13	14
Item		Beaver Creek Hazard	Deepwater Bloomsburg	Ft. Wayne Marion Muncie	Glenlyn Roanoke	Glenlyn Bellingham	Howard Ashland	Howard Fostoria	Line Wilmington	Line Fostoria	Logan Spring(1)	Marion Kokomo	Muncie Anderson	Philo Zanesville
Length of line	Miles	28.4	46.2	80.6	65.0	30.0	20.9	44.8	63.2	45.6	21.0	20.8	18.5	73.0
Insulators per Suspension String	No.-Space	10-5-1/8	10-4-3/4	10-5-1/8	10-4-3/4	11-5-1/8(2)	10-5-1/8	10-5-1/8	9-5-3/4	12-4-3/4(2)	10-5-7/8	10-5-1/8	10-5-1/8	11-4-3/4(2)
Operating Voltage	K.V.	44	66	132	132	132	132	132	132	132	132	132	132	132
Ground Wire	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Grading Shields (1)	Type	R & R	R & R	R & R	R & R	R & R	R & R	R & R	R & R	None(11)	None	R & R	R & R	R & R
Height of Tower Peak (Standard)	Ft.	72	77	97	97	97	97	97	97	97	95(7)	97	97	97
Average Tower Foot Resistance	Ohms	-	45.5(8)	-	18.9	31.5	9.4	9.4	9.4	21.0	-	-	5.0	7.8
Average Towers per Mile	No.	3.74	3.66	3.68	4.13	4.28	5.05	4.79	4.78	4.79	7.76	5.69	5.74	4.07
Number of Circuits	No.	2	2	2	2	2	1	1(9)	1 (9)(10)	1(9)(10)(14)	1	1	1	2
1932 LIGHTNING PERFORMANCE														
Tripouts - One Circuit Only		0	5	3	4	0	1	1	3	0	2	0	1	3
" Both Circuits		-	3	2	2	-	-	-	-	-	2	-	-	1
Damaged Insulators (Towers Affected)		0	0	4	0	0	0	0	3	-	2	-	-	0
" Conductors " "		0	1	2	2	0	0	0	1	-	2	-	-	1
Burned Arcing Rings " "		0	0	8	27	2	0	0	0	-	-	-	-	4
Total Cases of Damage (Towers Affected)		0	0	9	29	2	0	0	4	-	10	-	-	6
Cases of Damage per Line Outage		-	1.13	2.25	4.75	-	0	0	1.33	-	5	-	-	1.20
Lightning Strokes Reported per Year														
Lightning Strokes per Line Tripout														
1931 LIGHTNING PERFORMANCE														
Tripouts - One Circuit Only		2	2	9	5	2	0	4	5	1	4	0	0	2
" Both Circuits		-	2	2	2	4	-	1	1	-	-	0	0	4
Damaged Insulators (Towers Affected)		2	0	3	1	0	0	0	2	-	-	-	-	2
" Conductors " "		2	0	3	1	0	0	0	1	-	-	-	-	2
Burned Arcing Rings " "		2	0	15	6	2	0	0	2	-	-	-	-	8
Total Cases of Damage (Towers Affected)		2	0	19	8	2	0	0	3	-	-	-	-	8
Cases of Damage per Line Outage		2.5	0	1.8	1.8	0.84	-	0	0.8	2	-	-	-	1.33
LINE TRIPOUTS PER 100 MILES OF LINE PER YEAR														
1932		7.1	7.0	13.6	10.8	20.0	0.0	11.1	2.5	2.2	19.0	0.0	0.0	5.1
1933		9.0	14.1	8.0	9.2	0.0	4.8	2.2	28.5	6.0	33.3	0.0	5.4	6.8
1931		28.2	10.5	3.5	46.1	26.6	9.6	13.4	28.5	19.7	33.3	0.0	1.4	11.0
1930		10.6	14.1	71.2	16.9	16.7	4.8	4.5	1.2	2.2	33.3	5.4	1.4	3.5
1929		-	-	7.5	46.8	33.3	-	-	8.9	8.9	76.0	3.5	-	15.8
1928		-	-	-	16.8	6.7	-	-	-	8.9	42.0	-	-	14.4
1927		-	-	-	33.6	-	-	-	-	8.8	33.3	-	-	3.5
1926		-	-	-	16.8	-	-	-	-	19.8	33.3	-	7	20.3
Average		11.5	11.4	8.0	27.1	17.2	4.8	8.0	10.3	8.0	34.1	2.0	6.8	11.1
Ratio, Maximum to Average		2.5	1.2	1.7	1.8	1.9	2.0	1.7	2.8	2.5	2.2	3.3	2.4	1.9

(1) R & R means Ring & Ring
R & R means Ring & horn
(2) One less unit on Bottom Conductor
(3) Wood Pole Line
(4) Two less units on Bottom Conductor
(5) No. 2 Circuit R & R
(6) R & R on #1 Circuit - R & R on #2
(7) Height of Steel Crossarm
(8) After Installing Ground Rods - Before Counterpoises
(9) Two Circuit Since June 5, 1933
(10) Part of Howard-Fostoria Line Since June 5, 1933
(11) R & R on New Circuit June 5, 1933
(12) Two Line Sections Since 1931, but Treated as One Line
(13) 10 - 5-1/8" Units on New Circuits
(14) 10 - " " " " " " and R & R
(15) 10 - 5-1/8" and R & R on 2nd Circuit

lar lines operated at 132 kv. Similar better performance is shown on the one line operated at 66 kv, although in 1932 the outages were abnormally high because of several flashovers on the graded section of this line which should not be included in the over-all *line* performance.

The salient characteristic of line performance brought out in Figs. 1 and 2 is that line outages vary in unison with both the *total* storms observed (lightning frequency) as well as the number of very severe storms only; they do not correlate with either the number of *light* or *severe* storms alone.

Two-Circuit Outages

The use of 2-circuit lines as a means of improving continuity of service in our 132-kv network, until a year or so ago, has been fundamental. Two-circuit outages caused by lightning on such lines are shown in Fig. 3. These outages steadily increased from 1926 to 1932 as the system capacity grew and as the transmission system was extended through mountainous lightning-infested territory, rising from 15 per cent of the total line outages on 2-circuit lines in 1926 to 43.5 per cent in 1932. During 1933, however, these 2-circuit outages showed a decrease to 38 per cent, although 1933 was a worse year than 1932 in total storms and severe storms recorded, and also in total line tripouts.

This better 2-circuit performance in 1933 has been attributed to 3 causes: (1) The introduction of carrier current relaying to some 2-circuit lines thus eliminating some outages that may have resulted from through line fault currents; (2) the extensive application of high speed circuit breakers which

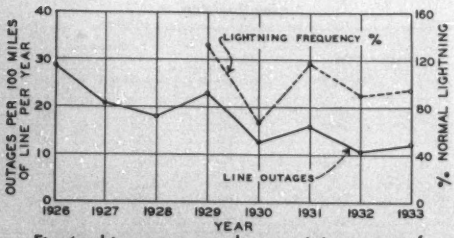


Fig. 1. Line outages on the transmission system of the American Gas and Electric Company compared with lightning frequency (per cent of average)

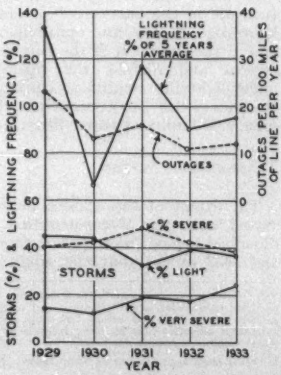


Fig. 2. Lightning frequency and severity as recorded at 8 stations compared with line outages

15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Phila Jacksville Draywville	Phila So. Point Turner	Phila Ham.(5	Roanoke Roanoke(12)	Roanoke Roanoke	Saltville Kingsport	So. Bend Michigan City	So.Point Portsmouth	Springfield Dearborn Creek(1)	Switchback Logan	Switchback Saltville	Turner Cabin Creek	Turner Lonza	Twin Br. Boston-Barker	Twin Br. Fla.Water	Twin Br. Stanwood	Windsor Oxford
15.4	16.2	80.7	98.3	43.0	56.0	40.0	34.6	76.3	50.0	38.0	31.6	40.2	38.0	65.4	4.5	72.0
11.4-3/4	11.4-3/4(15)	10.5-1/8	11.1-1/8(2)	13.4-3/4(4)	10.5-1/8	9.5-3/4	10.5-1/8	10.5-3/4	10.5-1/8	10.5-1/8	18.5-1/8	12.4-3/4	10.5-1/8	9.5-3/4	9.5-3/4	12.4-3/4
132	132	132	132	132	132	132	33	132	132	132	132	132	132	132	132	132
1	1	1	1	1	1	1	6	1	1	1	1	1	2	1	1	1
R A M(5)	R A M(6)	R A M	R A M	R A M	R A M	R A M	R A M	Home	R A M	R A M	R A M	R A M	R A M	R A M	R A M	Home
97	97	97	97	97	97	97	97	9	97	97	97	97	97	97	97	78
3.0	3.7	1.0	2.5	2.5								10.2		2.5		10.0
4.95	4.10	4.93	4.47	4.65	4.15	4.59	4.43	5.52	3.78	4.59	4.23	3.38	5.49	4.61	4.9	3.34
2	2	1	1	2	1	1	2	1	1	1	2	2	2	1	2	2
0	8	3	24	4	7	5	2	2	8	16	1	2	2	7	2	1
1	1	-	-	2	-	-	2	-	8	-	1	0	2	-	1	0
1	2	1	2	1	0	7	2	2	7	0	1	2	3	13	4	-
0	2	0	2	2	1	0	0	0	1	0	0	1	3	2	1	-
1	28	0	28	21	2	3	1	-	12	16	1	2	7	8	2	1
1	20	0	23	21	2	3	1	2	12	16	1	2	7	24	2	1
1.0	1.54	0.67	0.96	2.1	0.76	1.6	1.25	1.14	0.89	1.00	1.00	3.0	1.75	3.43	1.67	1.00
1	10	9	11	3	6	11	4	7	6	9	1	11	5	6	0	3
1	4	1	-	2	-	-	3	-	7	-	3	3	4	-	0	0
-	0	1	-	-	0	0	3	-	-	1	-	3	2	10	4	-
-	12	0	-	-	1	0	1	5	-	1	-	9	0	3	4	-
-	13	7	-	-	18	1	8	7	-	11	-	18	2	9	1	-
-	13	7	-	-	18	1	8	7	-	11	-	11	3	21	8	-
-	7.93	0.78	-	-	1.67	0.91	3.0	1.0	-	1.22	-	0.79	0.33	3.68	-	-
13.0	5.4	11.2	11.2	11.6	10.8	27.6	28.3	17.8	26.0	20.2	17.0	26.4	23.7	9.2	6.0	1.8
8.0	5.8	3.7	24.4	23.3	13.7	13.5	11.2	17.8	32.0	40.3	8.5	5.0	18.5	10.7	61.0	1.8
2.0	10.4	6.3	26.6	28.5	16.1	17.0	28.1	43.2	14.5	57.5	17.0	34.5	20.8	15.1	9.0	3.4
4.7	10.1	3.7	46.7	25.0	12.5	2.5	0	28.0	36.0	32.3	12.7	12.5	7.9	4.5	20.4	8.0
13.0	7.7	-	32.5	37.2	23.2	22.5	-	-	40.0	34.8	29.5	17.4	-	10.7	61.2	3.4
13.0	5.9	-	29.8	8.9	8.9	17.5	-	-	36.0	10.9	-	12.1	-	-	40.8	3.4
19.5	10.2	-	32.6	37.2	-	10.0	-	-	-	-	-	24.2	-	-	41.0	3.4
-	-	-	-	34.2	-	-	-	-	-	-	-	24.2	-	-	0.0	0.0
8.1	10.2	4.8	28.0	27.1	14.0	15.4	14.5	26.7	30.6	36.7	17.0	30.1	13.3	10.1	23.0	4.8
2.4	1.8	1.3	1.7	2.2	1.7	1.2	1.8	1.5	1.3	2.5	1.7	1.9	1.8	1.5	2.7	4.2

sometimes probably cleared the trouble on one circuit before it could be communicated to the second circuit; (3) the application of expulsion protective tubes to one 2-circuit line, for which the records show that in at least 3 instances the protected circuit cleared the line of lightning without circuit interruption.

Effect of Tower Footing Resistance

Benefits of low tower footing resistances in reducing lightning flashovers of lines having overhead ground wires have been discussed in the past on theory, and investigated to some extent by analyzing operating experience. The 2 years' operating record presented here gives supporting data to existing evidence.

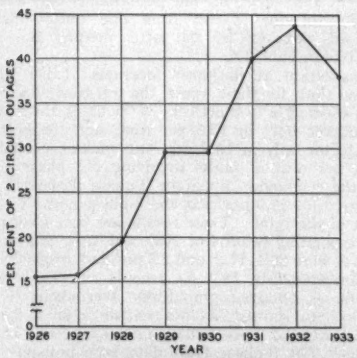


Fig. 3. Per cent of 2-circuit outages of 2-circuit lines during 1926–33

The effect of low average tower footing resistance on line outages is shown in Fig. 4. The drop from 30 outages per year to 8, as the average tower footing resistance falls from 80 to 5 ohms is too definite to be anything but conclusive. Although the plotted points are somewhat scattered, as might be expected from the different types of territory and variety of soil involved (the record covers 4 years' experience on 15 different lines), the trend in reduction of outages is clearly defined.

The magnitude of tower footing resistance required to make a line practically lightning proof has been much discussed, but rarely stated with any assurance; 10 ohms and 5 ohms have been mentioned as possibilities. Some light may be thrown on this by the data presented in Fig. 5. Here it is shown, that of the 86 towers flashed over in 1932 and 1933 on 5 typical lines, 57 per cent had a footing resistance of 10 ohms or less, 44 per cent 5 ohms or less, and 10 per cent 1 ohm or less.

While Fig. 4 shows the benefits of low tower footing resistance in reducing line outages, it is clear from Fig. 5 that tower footing resistances in the order of 5 or 10 ohms have little prospect of rendering practical conventional 132-kv lines of the type described herein lightning proof, but undoubtedly will make them more lightning resistant. Further analysis of Fig. 5, given in Table V, shows that

Table IV—Outages per 100 Miles of Line (Right of Way) per Year

	1932	1933
Total line outages	155	180
Average all lines	10.6	12.4
2-circuit lines, 1 ground wire	10.1	12.2
1-circuit lines, 1 ground wire	11.5	12.6
Lines with single ground wire	10.7	12.4
Lines with 2 ground wires	8.8	9.4
Wood pole lines, no ground wire	14.9	18.2
Lines insulated for 132 kv, but operated at 33 and 44 kv	5.7	9.1
Lines insulated for 139 kv, but operated at 66 kv	14.1	7.0

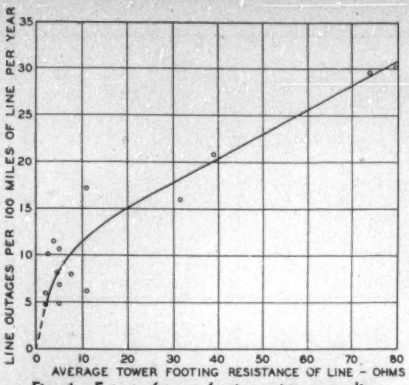


Fig. 4. Extent of tower footing resistance on line outages (4-year average on 15 lines, 1930–33)

considering the 86 flashed towers and one tower each adjacent, in 31 per cent of the cases the tower having the lowest resistance flashed, and in 37 per cent of the cases the tower having the highest resistance flashed.

Counterpoise Performance

On sections of 2 lines where the normal tower footing resistances were high, counterpoises were installed as previously described.[6] These line sections were too restricted in extent and have been in service too short a time to enable comprehensive conclusions to be drawn regarding the benefits of counterpoises in general. Observed flashovers on these line sections, however, have decreased since the installation of the counterpoise wires, as indicated in Table VI. On the Glenlyn-Roanoke (Va.) line, which in the past has had a bad lightning record, flashovers on the protected towers were reduced more than 50 per cent; on the Deepwater-Pleasantville (N. J.) line the reduction was 70 per cent.

Line Damage

Records of these lines since grading shields were installed, as in the past, show no serious damage to conductors, insulators, or hardware. No line has been out of service because of its inability to be placed back into service. The summarized record is shown

Table V—Towers Flashed Over on 4* 132-Kv Line 1932 and 1933 (Refer to Fig. 5)

	No.	Per Cent
Total towers flashed over (at insulator assemblies)	86	100
Towers flashed over where footing resistance was lowest of 3 consecutive towers (considering 1 tower each side of flashed tower)	27	31
Ditto, highest tower footing resistance	32	37

* Philo-Canton, Rutland-South Point-Turner, Roanoke-Roxboro, and Turner-Logan lines.

in Table VII; of the flashover marks observed (number of towers involved) 75 per cent was found on grading shields, 22.8 per cent affected conductors, and 29.5 per cent involved insulators. These percentages, while an average for the 2 years, are almost exactly the same for each year individually. The lesser number of observed flashovers in 1933, although a worse lightning year than 1932, is probably because complete inspections of all lines after the 1933 season have not been reported.

The "towers flashed over per line outage"—numerically 1.54 in 1932—seems to indicate that, on the average, in about 50 per cent of the cases the lightning disturbance has affected 2 towers. The corresponding figure of 0.84 for 1933 has been discounted because of the lack of complete line inspection, as indicated in the preceding paragraph.

Phase Location of Line Flashover

An analysis of the positions on the towers of conductors on which flashovers have occurred gives results that are interesting to interpret in the light of both lightning protection to the line and system stability as affected by single or multiphase faults.

Table VI—Flashovers on Counterpoise Sections of Line

Line	No. of Towers With Counterpoises	Towers Flashed Over: Before Counterpoises Were Installed	Towers Flashed Over: After Counterpoises Were Installed
Glenlyn-Roanoke 132 kv	40	6.2 (yearly avg)	3.0 (1 yr)
Deepwater-Pleasantville 132/66 kv	100	5.0 (yearly avg)	1.5 (2-yr avg)

Such an analysis has been made for several lines, using 2 methods: first, by flashover marks observed on tower climbing inspection on 5 lines (Table VIII); and second, by automatic oscillograph (Hall recorder) recording line voltage at a cardinal point on the system, thus observing line performance over a large section of the system from one central point. Records obtained by the latter method are summarized in Table IX.

Inspection at flashover locations (Table VIII) shows that, for the 2 years, the top conductor only was affected in 54.3 per cent of the cases, the middle conductor only in 15.5 per cent, and the bottom conductor only in 13.3 per cent, making a total of 83.1 per cent of faults involving one phase only. Of the remainder, apparent 2-phase flashovers accounted for 12.9 per cent and 3-phase faults 4.0 per cent of the total. These results are very similar to corresponding records of 1930 and 1931[8] where the figures were 86.4, 11.3, and 2.3 per cent, respectively.

Corresponding 1932–33 records of (Table IX) faults, as obtained graphically over about $^1/_3$ of the system, showed 77.0 per cent single-phase faults, 13.4 per cent 2-phase faults, and 9.6 per cent 3-phase faults. The 3-phase fault data here probably err on the high side as nearly all were interpretations of oscillographic records of line disturbances where

little voltage drop was recorded, and the faults were remote from the points of observation. The 1930–31 record in Table IX obtained on one line close to an automatic current recording oscillograph showed only 6.6 per cent 3-phase faults, a figure which is probably more trustworthy, and more in line with the record obtained by physical inspection.

While diverse interpretation of the data in Tables VIII and IX may permit the justification of any existing theory of how lightning gets on the lines of this system, there seems to be no evidence, from the data, that any one theory can be set up to the entire exclusion of any other. One outstanding point is the record of single-phase faults on middle conductors of vertically configurated lines, which comprise 15.5 to 25 per cent of the total faults. Similar past records[5,6] give results of the same order. It is clear that 2 ground wires—the normal ground wire, together with the top line wire (considered a ground wire for flashovers on the middle phase only)—with the conductor configuration employed on these lines, does not give complete shielding from lightning.

Table VII—Line Damage

	1932	1933
Tower flashovers (insulators)	71	44
Towers with burned conductors	60	31
Tower flashovers (grading shields)	181	111
Total flashovers (towers affected)	242	149
Total line flashovers	157	180
Flashed over towers per line outage	1.54	0.83

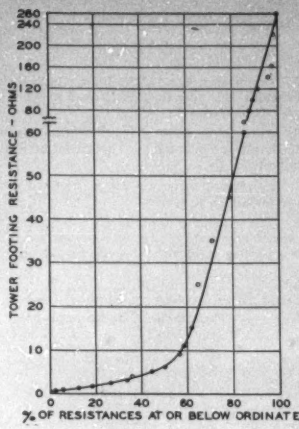
One interesting point brought out by the oscillograph records (Table IX) is that 7.8 per cent of the faults that start as single-phase develop into 2-phase faults; and 1.6 per cent of faults starting as 2-phase develop into 3-phase faults.

Apparatus Damage

Although station apparatus is not part of the lines, the operating record of such apparatus under lightning conditions is associated so closely as to be of interest. During 1932, 2 large 132-kv power transformers failed at stations equipped with lightning arresters, and graded insulation at line entrances. During 1933, there were failures of one power transformer where no lightning arrester or graded insulation existed, one lightning arrester (reduced to 50 per cent) but without other failure in the station, one cable capacitor, and an insulator on a lightning arrester.

Fig. 5. Effect of tower footing resistance on line flashover (86 towers where flashover was observed during 1932–33)

Data obtained on Philo-Canton, Roanoke - Roxboro, Philo - Howard, Philo - Rutland, So. Point, and Turner-Logan lines



Summary and Conclusions

Analysis of data presented in this and previous papers on the same 132-kv system, leads to the following conclusions:

1. Very definite decrease in lightning outages of transmission lines is effected by the use of a ground wire; a reduction in the order of 30% being indicated for 1932 and 1933.

2. Low average tower footing resistance of a line is productive of low lightning outages. Below 10 ohms the reduction is very pronounced.

3. Flashovers occur even at towers having low footing resistance; low resistance reduces outages but does not eliminate them.

Table VIII—Location of Flashed Over Insulator Assemblies by Tower Climbing Inspection

Line	1932 T	1932 M	1932 B	1932 T & M	1932 T & B	1932 B & M	1932 T, M, & B	1933 T	1933 M	1933 B	1933 T & M	1933 T & B	1933 B & M	1933 T, M, & B
Philo-Canton	5	0	0	1	0	0	1	6	1	0	0	0	0	0
Roanoke-Roxboro								2	8	7	4	1	1	0
Philo-Rutland-So. Point	14	0	2	1	1	0	1	11	1	1	0	0	0	0
Philo-Howard	0	0	0	1	0	0	1	3	2	1	0	1	0	0
Turner-Logan	3	0	0	1	0	0	1	5	2	1	0	1	0	0
Totals	22	0	2	4	1	0	4	26	14	10	4	3	0	0
Yearly %	66.7	0	6.1	12.1	3.0	0	12.1	45.6	24.6	17.5	7.0	5.3	0	0
Totals 1932 & 1933	48	14	12	8	4	0	4							
% of Totals	54.3	15.5	13.3	8.9	4.0	0	4.0							

	1932–33	1930–31
% Single phase	83.1	86.4
% 2 Phase	12.9	11.3
% 3 Phase	4.0	2.3

T, M, and B represent top, middle, and bottom assemblies, respectively.

4. It is impossible, practically, to overinsulate a line to prevent lightning outages. Overinsulation in the order of 3 or 4 to 1 for $^{33}/_{66}$ kv lines indicates a reduction in outages ranging as high as 50%.

5. On present day 132 kv lines, physical damage resulting from lightning flashover is of little concern where grading shield arcing protection is used.

6. From 75 to 85% of lightning troubles on these lines result in single phase faults only. The spread of trouble to other phases is infrequent.

7. Continuity of service can be bettered some 60% by the use of two circuit construction.

8. The possibility of producing a lightning proof line by the use of expulsion protective gaps at insulator assemblies, with our type of line construction, without going to additional ground wires, insulation, conductor clearances, or reduction in tower footing resistance seems possible, based on actual operating experience obtained on one line last year. Detailed results of this installation will be reported at a later date.

9. Although not directly brought out by the data in the paper, there is still another possibility of producing a high tension transmission line with the equivalent of lightning-proof performance and that is by the use of a high speed opening high speed reclosing breakers reclosing possibly in 10 cycles or less after the flashover, so that the net effect will be no loss of synchronism and no interruption of service to even the most sensitive equipment. Some development work on that idea now started will be reported on at a later date.

10. The effect of lightning on a transmission line is distinctly local, extending over only a very few towers, frequently not more than two, and in many cases only one.

11. Line outage performance follow both total storm frequency, as well as frequency of severe storms. This may be of value in predicting line performance.

12. Graphic automatic recording instruments have been of great benefit in studying the lightning performance and characteristics of these lines; as they show definitely, in many cases, what has taken place.

13. The benefits of counterpoises in reducing line outages due to lightning are indicated in a recorded reduction in flashed over towers in the order of $^1/_3$ to $^2/_3$.

The analysis of lightning performance of the 132-kv lines of the American Gas and Electric Company system which has been continued for the past 9 years has resulted in some very definite progress being made in understanding the lightning problem and also definite conclusions on many aspects thereof. The progressive stages of development of the more important ideas have been summarized in Table X. It may be noted that many of the controversial points have been settled, at least to the authors' satisfaction at the present time. Consequently, in the future attention will be concentrated on those phases of the lightning problem that remain unanswered or in controversy. There is, no intention, however, to discontinue or to relax in the thoroughness with which operating performance records on this system have been gathered and analyzed over almost a decade.

Table IX—Location of Flashed Over Line Conductors by Automatic Oscillograph-Hall Recorder

1932–1933							
Total records obtained	72						
Records indefinite	8						
Indefinite phase indication because of 2-line trouble	10						
Analyzed for flashover phase location	52						
	T	M	B	T & M	T & B	B & M	T, M, & B
Totals	17	13	10	2	3	2	5
Per cent	32.7	25.0	19.3	3.8	5.8	3.8	9.6

	1932 & '33	1930 & '31
% 1-phase faults	77.0	73.8
% 2-phase faults	13.4	19.6
% 3-phase faults	9.6	6.6
No. of 1-phase faults developing into 2-phase faults	5	7.8%
No. of 2-phase faults developing into 3-phase faults	1	1.6%

T, M, and B represent top, middle, and botton assemblies, respectively.

Bibliography

1. Lightning and Other Experience With 132-Kv Steel Tower Transmission Lines, Sindeband and Sporn. A.I.E.E. Trans., v. 45, 1926, p. 770.

2. 1926 Lightning Experience on 132-Kv Transmission Lines, Philip Sporn. A.I.E.E. Trans., v. 47, 1928, p. 668.

3. 1927 Lightning Experience on 132-Kv Transmission Lines, Philip Sporn. A.I.E.E. Trans., v. 48, 1929, p. 480.

4. 1928 Lightning Experience on 132-Kv Transmission Lines of the American Gas and Electric Company, Philip Sporn. A.I.E.E. Jl., June 1930, p. 432.

5. 1929 Lightning Experience on the 132-Kv Lines of the American Gas and Electric Company, Philip Sporn. A.I.E.E. Trans., v. 50, 1931, p. 574.

6. Lightning Experience on 132-Kv Transmission Lines of the American Gas and Electric Company—1930–31, Philip Sporn. A.I.E.E. Trans., v. 52, 1933, p. 482.

Table X—Progress in Reaching Conclusions on Lightning Performance of 132-Kv Lines of American Gas & Electric Company

Ref. No.	Features Considered	Status in Year Indicated 1926	1927	1928	1929	1930 1931	1932 1933	Proved or Not Proved
1.	One ground wire effective in reducing lightning outages	A	C	P	C	C	C	P
2.	Two ground wires more effective than one in reducing lightning outages		D	D	P	C	C	P
3.	Low tower footing resistance reduces lightning outages	A	D	D	D	P	C	P
4.	Tower footing resistance must be considerably less than 20 ohms—in the order of 5 ohms suggested				D	C	P	P
5.	Low tower footing resistance does not make line *lightning proof*				A	D	P	P
6.	Grading shield protection of insulators render line damage of minor importance	A	D	P	C	C	C	P
7.	Grading shield protection reduce number of lightning flashovers			X	C			
8.	Effects of lightning on line is localized near point of origin (effect at stations not included)		A	D	P	C	C	P
9.	Lightning storm data—frequency and severity—must be evaluated in considering outage data		A	D	P	C	C	P
10.	Two-circuit lines improve continuity of service, but do not make lines lightning proof	A	D	P	C	C	C	P
11.	Continuity of service greatly enhanced by expulsion tube protection—lightning proof line seems possible						D	NP
12.	Overinsulating line, although improving performance, does not make line lightning proof					A	P	P
13.	Impulse insulation strength of wood does not give the great freedom from line outages predicted					D	D	NP
14.	Protection against induced lightning voltages is important	A	D	D	D	C	C	P
15.	Direct lightning strokes play vital part in producing line outages				D	C	C	P
16.	Lowering tower footing impedance by counterpoises beneficial—probably more so than low resistance					D	D	NP
17.	Installation of high speed tripping and reclosing circuit breakers						A	

A—idea advanced; C—confirmed; D—discussed; P—proved to authors' satisfaction; X—discarded. NP—Not proved.

Incandescence—
Some Theoretical Aspects

Some theoretical considerations involved in incandescent phenomena, with particular reference to incandescent illumination, are discussed briefly in this paper. In spite of the recent remarkable achievements in luminescent illumination, the incandescent lamp still is believed to await a genuine challenge.

By
SAMUEL G. HIBBEN
ASSOCIATE A.I.E.E.

Westinghouse Lamp Co.,
Bloomfield, N. J.

THE 2 CLASSES of radiation pertinent to a discussion of illumination are incandescence and luminescence. Many light sources fall partially into both classes, and therefore the line of demarcation is not always obvious. Indeed, it is believed that fundamentally they are identical, merely being different manifestations of energy release from atomic systems, disturbed by chemical, electrical, thermal, or other means. All electrons presumably have specific wave lengths at which they radiate. In solids and liquids, however, the molecules are packed so closely that they cannot vibrate in their proper periods. Just when one is beginning to emit regular vibrations, another knocks against it, and the vibrations become irregular. This results in vibrations of every wave length, our so-called continuous spectrum. Gas and vapor molecules being relatively free are not disorganized thus, and therefore the spectra of these are seen as series of lines (Fig. 1). If the pressure of the gas be increased enormously, it is conceivable that a continuous spectrum also might be produced, probably with the characteristic line spectrum superimposed on it.

The specific field of this paper is incandescence, frequently called temperature radiation. As already noted, this type of radiation is characteristic of solids and liquids, and is characterized by continuous spectra. Only a few solids are known that are exceptions to this general rule of a continuous spectrum, and only one or 2 gases are known that at temperatures attainable in the laboratory will give forth radiation in the visible region through incandescence. All substances in the solid or liquid state start emitting visible radiation at temperatures just above 500 deg C, the exact temperature varying with the substance. At low temperatures, the maximum energy radiated is somewhere in the infra-red region; as the temperature is increased, the maximum shifts to a shorter and shorter wave length, theoretically reaching the visible or ultra-violet regions (Fig. 2). This was postulated originally by Wien, and now is known as Wien's displacement law.

For purposes of discussion, some standard is advisable, which, for temperature radiation, is called a "black body." This may be defined as a substance capable of absorbing every incident radiation in the ultra-violet, visible, and infra-red regions ranging from about 300 A to 3,000,000 A. (A is the abbreviation for Ångström unit, a unit used for expressing wave lengths of light; it is equal to 1 cm $\times$ 10^{-8}.) Actually, there is no such substance, since everything reflects some energy—from such things as lampblack and platinum black which are about 99 per cent perfect, to newly polished silver which is only a few per cent perfect. The carbon filament, which was used for many years in incandescent lamps, is also very nearly the equal of the black body standard. However, experimental artifices such as internally blackened spheres with minute observation hole may be used to reproduce black body phenomena even more closely than actual substances will. The obvious question that follows is why a standard of absorption should be chosen to discuss radiation.

Very early in the scientific history of light it was realized that some important relation existed between the absorption and emission of a body. It remained for Kirchhoff and Balfour Stewart, working independently just prior to 1860, to reduce this relation to a definite law, now named for the former. It may be expressed as follows: At a given temperature, the ratio between the emissive and absorptive power for a given wave length is the same for all bodies:

$$\frac{E_{\lambda T}}{A_{\lambda T}} = \text{constant}$$

Stated in another way, this means that any body that is a good absorber is a good radiator, and in just the same proportion. Fundamentally, Kirchhoff's law

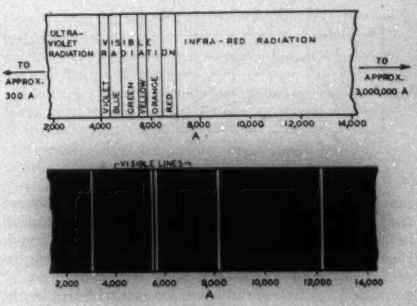


Fig. 1. Continuous spectrum of typical incandescent source (above) and (below) line spectra of typical luminescent source (sodium)

Full text of a paper recommended for publication by the A.I.E.E. committee on production and application of light, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted June 15, 1934; released for publication July 6, 1934. *Not published in pamphlet form.*

proves that at a given temperature no substance can emit more light of a given wave length than a perfect black body at the same temperature. This does not necessarily mean that no substance may be more efficient than a black body as a light source, as may be seen in a later discussion. A second important conclusion from this law is that a body cannot emit those rays for which it is transparent, or for which its surface acts as a perfect mirror. Since the ratio of emission to absorption must remain a finite number, the substitution of zero for $A_{\lambda T}$ (the condition of perfect transparency or perfect reflectivity) must be followed by the substitution of zero for $E_{\lambda T}$. Still another conclusion is that when a body is capable of emitting certain radiations, it absorbs these same radiations when it is irradiated by them. It may absorb other radiations also, as is illustrated by the selective absorption of colored substances.

Mere radiation of energy, however, does not make a good light source. The effectiveness of visible radiations is wholly dependent on the mechanism of the eye. The average human eye has a very definite sensitivity curve which reaches its maximum at 5,560 A, but drops off very quickly to small values at the limits of the visible spectrum. This is shown by Fig. 3. Any radiations beyond these limits, of course, are worthless for vision, and within the limits are effective only in proportion to the ordinates of the curve.

As previously pointed out, the maximum energy radiated is at its peak in the infra-red regions at low temperatures. As the temperature increases this peak comes nearer and nearer to the peak of maximum eye sensitivity; if the latter peak could be reached, there would be obtained for any particular

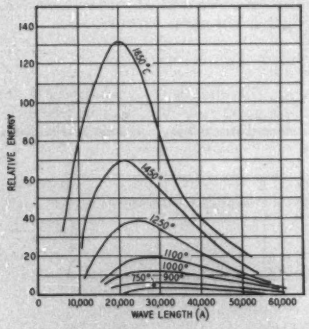


Fig. 2. Energy curves for radiations from a black body at various temperatures

material the most efficient incandescent light source that could be constructed. It is characteristic of all materials, however, that they do not absorb, and, therefore, *do not radiate,* energy at all wave lengths except, of course, a black body which does so by definition. Carbon radiation for example, is different from tungsten radiation which in turn is different from that of iron. This characteristic of individual materials is called selective radiation and is a very important factor in determining the effectiveness of a light source.

To these 2 light-source criteria of incandescence—good absorption (or good radiation) and selective radiation—must be added practical considerations. The material chosen must be capable of withstanding high temperatures for long periods of time and must be susceptible to processing for manufacture. A review of the history of incandescent sources will help to understand the full scope of the problems involved.

Almost all early forms of illumination were produced by chemical means—the burning of wood, of vegetable and animal oils, and later of mineral oils and gas. In the final analysis, these are forms of incandescence, usually of minute particles of carbon, although sometimes the phenomenon of luminescence also occurs. Naturally elementary incandescence was known through the process of putting a bar of metal into a fire until it became white-hot, and glowed upon removal; but the problem of maintaining the glow except by a fire that would give off more light than the indirectly heated bar was not solved until the advent of electricity.

As far as is known, the first application of electricity to produce incandescence was made by Sir Humphry Davy in 1802. By passing a heavy current through thin strips of metal, light was produced. He found only one metal, platinum, that would last long enough at an incandescent temperature to be called a light source. This was the forerunner of the modern filament lamp. Thereafter, for a period of 75 years, endless experimenters worked on this problem with 2 materials in especial favor as filaments, carbon, and platinum. Then came the first real success—Edison's carbon filament lamp. While contemporaries of Edison, working independently, achieved simultaneous or even prior results, his work on all phases of the problem even to that of designing constant voltage distribution systems, marked the start of the electric light industry.

Edison's lamp patents were based on 4 things: a high resistance filament operating in a vacuum maintained by a one-piece glass globe having all joints sealed by fusion of the glass. All except one of these are still primary considerations; that one, the vacuum, merely changed so that it might be better expressed as keeping deleterious gases or vapors away from the filament.

Naturally, as with any definite product, continuous efforts were made to improve its value. These efforts extended in many directions—from glass problems, manufacturing economies, and exhaust perfection to the ever-present question, the filament. Efforts were made not only to improve carbon, but also to find substitutes for it. The first of these was osmium, an extremely rare metal, developed as a filament material in Austria and Germany. Its improved efficiency was of the order of 75 per cent, but its scarcity and its fragility prevented its use from becoming universal. Next in line was tantalum—not as efficient as osmium, but more practical. Then came tungsten with an early efficiency of 7.5 lpw (lumens per watt) or more than double the efficiency of the carbon lamps then in use (1907).

In tungsten, a metal was discovered which was entirely practical. Abundant, it did not present any insurmountable difficulties toward purification and processing; and thus far, considered practically as well as scientifically, in spite of an intensive and systematic research during the past 25 years to which

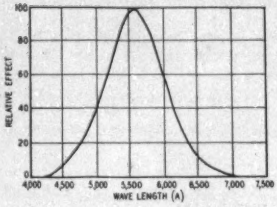


Fig. 3. Eye sensitivity for equal mounts of radiant energy

few products have been subjected, no other known material will do as well.

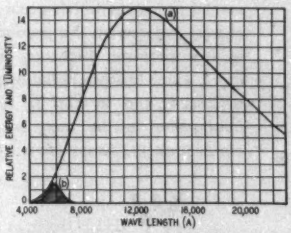
The filament material is, of course, the vital point of all incandescent lamp manufacture. However, other factors have great importance, some only because tungsten is used, others regardless of the material. Consider, for example, the question of high vacuum—a vital feature because oxygen, carbon dioxide, and water vapor must be kept away from the filament. After tungsten was adopted as a filament material, however, it was realized that the vacuum could be replaced by inert gases and definite improvement obtained. The presence of the gas retarded the evaporation of the tungsten, and thereby permitted the use of higher temperatures. At these higher temperatures, greater radiation in the spectral region is obtained. Greater heat losses (through conduction and convection) seemed imminent at first, but it was found that these heat losses even though greater were more than compensated by the additional light obtained, except in lamps of low wattage.

Assuming that tungsten is the best filament material available today, and that all major fields incident to its use have been explored and utilized, what is there to look forward to in efficiency? To raise the temperature of the filament increases its efficiency, but simultaneously shortens its life. From a practical standpoint, a life of about 1,000 hr for general service lamps seems to be desirable. At this standard, lamp efficiencies vary from 10 to 20 lpw. This seems to be unreasonably low when a theoretical computation based upon the mechanical equivalent of light indicates that the efficiency of a perfect light source would be in the neighborhood of 670 lpw. A study of the eye sensitivity curve (Fig. 3) indicates one aspect of this great difference. Let it be assumed that a light source were obtainable that would radiate wholly within the visible region. If this radiation were uniform in this narrow band, the illumination effect would be only in proportion to the ordinates of this curve, and therefore the efficiency would be about 220 lpw. Only a green light source radiating at 5,560 A could approach the figure of 670 lumens per watt; for a red light at 7,300 A, a perfect light source might have an efficiency only of the order of 20 or 30 lpw.

To speak of a practical light source radiating wholly within the visible spectrum is to speak of Utopia. Let the equivalent of an eye sensitivity curve (a spectral luminosity curve) be superposed on the complete radiation curve of a standard incandescent lamp (Fig. 4). A totalization of the areas enclosed under the curves indicates that an efficiency of 50 lpw would be excellent for tungsten temperatures a few hundred degrees less than its melting point of 3,650 deg C. In this connection it is interesting to observe that a black body would reach its maximum of luminous efficiency (approximately 90 lpw) at the temperature of 6,250 deg C; above this temperature, too much radiation is in the ultraviolet region, and below it too much in the infra-red. Even though many non-black bodies have a better selective radiation than a black body, a temperature of 6,250 deg C is so far beyond the limits of practice that approximately 50 lpw must be accepted as a theoretical peak efficiency for incandescent tungsten. Between this figure and the achieved 20 lpw illumination, engineers must look for improvement and explain the losses. Convection and conduction losses through the inert gases, the heating of lead wires and supports, absorption of light by the glass bulb—these are very appreciable factors, and apparently

Fig. 4. Spectral energy curve of a standard incandescent lamp (a) and spectral luminosity curve (b)

Area enclosed under the curve beyond the limits of the diagram is equivalent to approximately 30 squares



ones that in the weighing of lamp costs versus operating costs are at present in a state where only radical discoveries would make it economically wise to alter present lamps greatly.

However, progress is by no means at a standstill. Ever since the adoption of tungsten the efficiencies of incandescent lamps have risen. During the present period they are taking an important step upward through the success of coiled-coil filaments. Just as the original coiled filament allowed higher temperatures, so the present development of a filament first wound as a simple helix, and then as a compound helix, is expected to increase efficiencies as much as 10 per cent by minimizing heat losses and allowing more radiant energy to be emitted in the spectral region.

In the face of remarkable achievements here and abroad in the field of luminescent light sources, most of them by the same manufacturers engaged in the

production of the filament lamp, incandescence might be thought to be on the defensive. A cold analysis, however, indicates that much greater progress than now even visioned must be made before the incandescent lamp ever can be regarded as a "back number." First of all, the purpose of any artificial source is merely to replace the light produced by the sun. It, too, is an incandescent source, probably with an efficiency equivalent to 50 or 60 lpw, and with the continuous spectrum common to all incandescent sources. With its endless possibilities of size and types, with its great simplicity of installation and operation, with its low cost, the incandescent lamp still awaits a genuine challenge.

Low Pressure Gaseous Discharge Lamps—Part I

By
SAUL DUSHMAN
ASSOCIATE A.I.E.E.

General Elec. Co., Schenectady, N. Y.

Radiation and conduction phenomena in low pressure gaseous discharge lamps are discussed in this paper. Results of measurements on the variables in a discharge are given, and an attempt is made to correlate them with the concentration of atoms at different energy levels, and with the luminous efficiency. An insight into the fundamental processes which occur in a gas discharge and govern the production of light in low pressure discharges are given. In Part I, which follows, radiation processes are discussed, and in Part II, scheduled for publication in the next issue, electrical conduction processes are covered.

WHILE the light from an incandescent solid, such as a tungsten filament, is characterized by a continuous type of spectrum, that is, one in which radiations of all wave lengths in the visible range are present, that from a gas or vapor has a characteristic line type of spectrum. As a result, the latter usually exhibits a distinct color due to the predominant intensities of radiations of certain wave lengths. The efficiency of such a light source depends upon both the intensities and the visibility factors of the most prominent lines.

In Fig. 1[1] are shown the spectra, as observed by passing the light through a prism spectroscope, of those gaseous discharges which have been utilized for purposes of illumination. The figure also gives the values of the visibility factor V_λ for the most intense lines in these spectra, and there is also shown a plot of V_λ as a function of λ. The light output L in lumens per unit area of a source is given by the relation

$$L = 621 \int_{\lambda_1}^{\lambda_2} V_\lambda E_\lambda d\lambda \tag{1}$$

where $E_\lambda d\lambda$ denotes the energy radiated in watts per square centimeter in the range λ to $\lambda + d\lambda$, and 621 is the maximum luminous equivalent per watt of radiated energy (corresponding to radiation of wave length $\lambda = 5{,}550$ A $= 555.0$ millimicrons). (One Ångström unit $= 1$A $= 10^{-8}$ cm $= 0.1$ mμ. One micron $= 1\mu = 10^{-4}$ cm.) The limits λ_1 and λ_2 for visible light may be assumed, for all practical purposes, to be $\lambda 4{,}100$ and $\lambda 7{,}200$. For any source, the specific luminous efficiency L_s is thus defined by the relation

$$L_s = \frac{L}{W} = \frac{621 \int_{\lambda_1}^{\lambda_2} V_\lambda E_\lambda d\lambda}{\int_0^\infty E_\lambda d\lambda} \tag{2}$$

where W is the total energy radiated.

For any given source of light there also exists an optimum luminous efficiency L_0 which represents the efficiency of a fictitious source which has the same energy distribution in the visible region, but which emits no energy whatever outside the visible region. This is defined by the relation

$$L_0 = L/W_L = L/\int_{\lambda_1}^{\lambda_2} E_\lambda d\lambda \tag{3}$$

and determines the maximum attainable efficiency for a light of a given energy distribution in the visible range.

Table I gives data on the luminous efficiencies (lumens per watt) of a number of light sources including the different types of gaseous discharges which are of practical interest. The last column gives the energy utilization ratio

$$\eta = L_s/L_0 = W_L/W \tag{4}$$

for each case.

Full text of Part I of a paper recommended for publication by the A.I.E.E. committee on production and application of light, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22-25, 1935. Manuscript submitted June 7, 1934; released for publication July 6, 1934. *Not published in pamphlet form.*

1. *G. E. Rev.*, v. 37, 1934, p. 260-8.

For helium and carbon dioxide no data are available for making an estimate of the value of L_0, but undoubtedly the value of η for both cases is less than 0.05. The value of L_s for cadmium is typical of results obtained with other metal vapors such as those of lithium, potassium, rubidium, caesium, zinc, and magnesium. Of the rare gases, only neon and helium give sufficient light in the visible range to be of interest.

Only in the case of carbon dioxide is the light actually white, so that the use of this gas discharge has been suggested for true color rendering. In fact, it was used by D. McFarlan Moore in his tube lighting introduced about 1906. However, the use of gases, such as carbon dioxide, nitrogen, and hydrogen, has not proved practical because of the 2 disadvantages: first, the relatively low luminous efficiencies; and, second, the phenomenon of "clean up" which leads to a rapid disappearance of the gas during the operation of the discharge.

Table I—Luminous Efficiencies of Various Sources of Light

Source	Color	L_0	L_s		100η	
Black body at T = 6,500	White	218.5	86.3		39.5	
Sun	White	250[a]	100		40	
Tungsten (gas filled)	White	143[a]	15	− 30	10	−20
Flaming arc	White	220[b]	27	− 45	12	−20
Sodium vapor	Yellow	475[c]	50	−100	10	−21
Mercury, low pressure	Blue-green	248[d]	15	− 20	6	− 8
Mercury, high pressure	Blue-green	298[a]	30	− 35	10	−12
Neon	Orange-red	198[d]	15	− 40	7.5	−20
Helium	Yellow-white		4	− 10		
Carbon dioxide	White		2	− 4		
Cadmium	Blue		0.5	− 1		

a. Values given by L. J. Buttolph, paper read before Am. Electrochem. Soc., April 1934.
b. Assuming that most of the light is due to the carbon crater, the temperature of which corresponds to that of a black body at 4,000–5,000 deg K.
c. Based on $V\lambda$ for the D-lines.
d. Values calculated by F. A. Benford from measurements under operating conditions.

Origin of Spectral Lines

When a discharge is passed in sodium vapor at low pressure (0.0005 to 0.005 mm of mercury), the spectrum is obtained as a result of the impact on sodium atoms of electrons which have acquired kinetic energy from the electric field between the cathode and anode. If e denotes the charge on an electron, and V the potential difference through which the electron has traveled before collision with a sodium atom, the kinetic energy acquired is given by the relation

$$\frac{1}{2} mv^2 = Ve \tag{5}$$

where m = mass of electron and v = velocity.

For a potential fall of one volt, the velocity attained is 5.935×10^7 cm per second, and the kinetic energy is 1.591×10^{-12} ergs.

The complete arc spectrum of sodium is obtained only if the value of V exceeds that of the ionizing potential V_i, which in the case of sodium is 5.12 volts. At lower voltages than this, fewer spectral lines are obtained, and if the electron energies are reduced to some value corresponding to that between 2.10 and 3.18 volts only the 2 D lines (λ5,890 and λ5,896) are obtained. Collisions of sodium atoms with electrons having an energy below 2.10 volts are absolutely ineffective in producing any radiation from the sodium atoms.

The interpretation of these observations on the basis of the Bohr theory of atomic energy levels is illustrated by reference to Fig. 2. An electron of kinetic energy less than 2.10 volts suffers an *elastic* collision with a sodium atom, so that the electron loses only an insignificantly small fraction of its energy. On the basis of ordinary dynamics it is readily shown that this loss is $2m/M$ of the total energy of the electron, where M/m denotes the ratio of the mass of the atom to that of the electron. For sodium, $2m/M = 4.8 \times 10^{-5}$ volts. When the energy of the electron exceeds 2.10 volts, an *inelastic* collision occurs, and if the kinetic energy is less than 3.18 volts, there is a transfer of energy

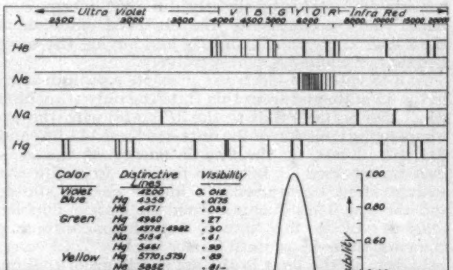


Fig. 1. Some typical line spectra and visibility curve

to the atom corresponding in amount to 2.10 volts, while the excess over this value is retained by the electron as kinetic energy. The energy imparted to the sodium atom is used to excite it to the *first excited state*, which is designated spectroscopically as the $3P$ state. When the atom is in such a high energy state, it tends to return *spontaneously*, within an interval of approximately 10^{-8} sec, to the normal state, and in this process the excess energy is radiated as a monochromatic radiation of frequency, ν, determined by the relation

$$\nu = \frac{Ve}{h} = 2.43 \times 10^{14} \text{ per volt} \tag{6}$$

where h is Planck's constant (6.547×10^{-27} erg-sec),

and the corresponding wave length in Ångströms is

$$\lambda = \frac{c}{\nu} = \frac{12{,}336}{V} \tag{7}$$

where c = velocity of light.

Thus for $V = 2.10$ volts, λ, calculated from eq 7, has the value 5,890. Actually the $3P$ state of sodium

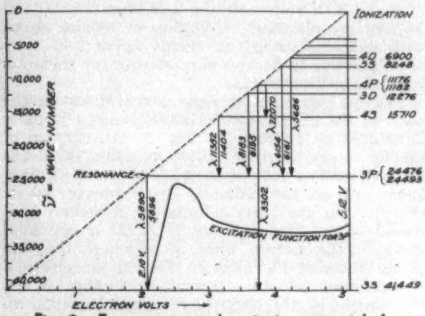


Fig. 2. Energy states and excitation potentials for sodium

consists of 2 states of slightly different energy contents. This accounts for the observed emission of the 2 lines known as D_1 and D_2, and having the wave lengths 5,896 and 5,890, respectively.

At 3.18 volts, the electron can excite a sodium atom to the $4S$ state and from this state the only transition which can occur is that to the $3P$ state, with the accompanying emission of the infra-red lines λ11,382 and λ11,404. Thus, as the kinetic energy of the electron is increased, it becomes possible to excite the sodium atom to successively higher energy states, and the spectrum changes from the simple doublet consisting of the 2 D lines to a spectrum containing more and more lines, until finally for $V = 5.12$ volts, or higher, all the lines in the arc spectrum of sodium appear. At this voltage, the atom becomes ionized, forming Na^+, and hence 5.12 is designated as the ionization potential (V_i).

While Fig. 2 shows the voltages at which the different energy states are produced, Fig. 3 shows, in a more customary form, the "energy levels" and the spectral lines corresponding to transitions between these levels. For reasons which need not be discussed here, transitions can occur only between levels in adjacent columns and not between those in the same column. Even before Bohr suggested his theory, spectroscopists had observed that in the simpler spectra it was possible to represent the reciprocal of the wave length of any line (wave number) as the difference between 2 wave numbers in the form

$$\frac{1}{\lambda} = \bar{\nu}_1 - \bar{\nu}_2 \tag{8}$$

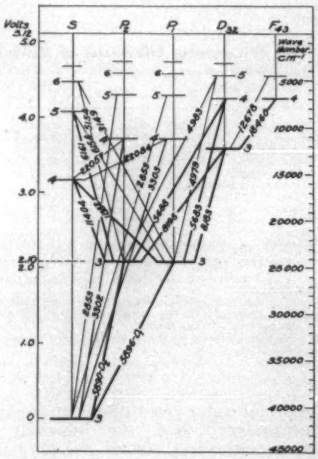
where $\bar{\nu}_1$ is the wave number of the *lower*, and ν_2 that of the upper level. For members of the same series ν_1 is a constant, while ν_2 decreases as the limit of the series is approached. In Figs. 3 and 4 the wave numbers of the different levels have been indicated, and from the difference in wave numbers of any 2 levels, the corresponding electron volts may be derived by means of the relation

$$V = \frac{\bar{\nu}_1 - \bar{\nu}_2}{8{,}106} \tag{9}$$

Resonance Radiation and Resonance Potential

An interesting phenomenon observed with the D-line radiation of sodium is the "reversal" of these

Fig. 3. Energy levels and lines in arc spectrum of sodium



lines if a heated bulb containing sodium vapor is interposed between the sodium lamp and the observer. Similar reversal of spectral lines has been observed in the spectrum of the sun (Fraunhofer lines) and the explanation in both cases is the same. A sodium atom may be excited to the $3P$ state not only by collision with an electron of the requisite kinetic energy, as discussed above, but also by *absorption of light* of the same frequency as that emitted by the transition from $3P$ to the normal state. The absorbed energy is then reëmitted when the atom returns to the normal state, and in the case of a bulb containing sodium vapor, there is perceived in a direction at right angles to that of the incident light from the discharge, a faint yellow glow. The analogy with resonance phenomena in other fields of physics has led to the designation of this radiation as of the resonance type, and hence the corresponding excitation voltage, 2.10 volts for sodium vapor is known as the resonance potential (V_r).

This "absorption" of the D-lines by sodium thus is not a true absorption in which the radiation is converted into energy of a longer wave length, but rather

a scattering of the incident light. We may regard the phenomenon as one in which a photon, or light particle, of magnitude $h\nu_0$ (where ν_0 = frequency of D-lines) is passed on from one sodium atom to another, causing successive excitation and reëmission of the lines until finally the radiation is emitted at the surface of the discharge tube. From this point of view the phenomenon has been designated as "imprisonment of radiation."

Similarly a sodium atom in an excited state higher than $3P$ could be excited to a still higher state by absorption of radiation of frequency ν_{kj} where k designates the upper level j, the lower level, and ν_{kj} is the frequency of light emitted by a transition from the upper to the lower level. In a subsequent section this phenomenon will be discussed in greater detail because of its importance in determining the luminous efficiency of a light source.

The remarks have been limited so far to a discussion of the processes which lead to the production of radiation from sodium vapor, but this case has been used merely as an illustration of the type of mechanism by which the line spectra of all the elements are produced. During the past 20 years, since Bohr first postulated his theory, an enormous number of investigators have succeeded in interpreting the spectra of nearly all the elements, both in the normal state (arc spectra) and in the ionized state (spark or enhanced spectra); for an atom in the ionized state may be excited by impact of electrons to emit a characteristic spectrum, and in some cases it has been possible to determine the spectra of the atom in a number of stages of ionization. However, since these spectra are always in the ultraviolet region and require special conditions for their production they are not of interest as sources of light and will not be discussed further.

Various methods have been used to determine the energy levels in the arc spectra of the elements. In many cases the values of the potentials have been measured at which electrons lose discrete amounts of kinetic energy by collision with the atoms. Such measurements have yielded values known as critical potentials. A determination of the resonance lines by absorption measurements has made it possible to determine in some cases the energy values of the lowest excited states (V_r) and from these in turn the accurate values of the ionization potentials (V_i). This method has been used especially in the case of the rare gases and of a number of metallic vapors. Finally, an analysis of the arc spectra themselves combined with experiments on critical potentials have enabled spectroscopists to deduce the corresponding energy level diagrams.

As a result there is now available a great deal of information on the type of spectrum obtainable from each element and its system of energy levels. From an inspection of such energy level diagrams, as that shown in Fig. 3 for sodium, it is possible therefore to deduce some conclusions regarding the probable characteristics of any element as a source of light. (The theory of the origin of spectral lines is discussed in any treatise on modern physics. A very complete bibliography of papers published during 1920–1931 on line spectra of the elements is given in a paper by R. C. Gibbs.[2] Energy level diagrams of a number of elements are also given in a book by W. Grotrian.[3] See also review by S. Dushman.[4])

In Fig. 4 is shown the energy level diagram for the arc spectrum of mercury. The levels are arranged in columns according to spectral type, and the potentials required to excite these levels are indicated at the left, while the corresponding wave numbers are indicated along the line which divides the "triplet" system of levels from the "singlet" system. There are 2 respects in which the spectrum of mercury differs from that of sodium. First, the resonance lines, λ2,537 and λ1,850, are in the ultra-violet region, and lines in the visible range are produced only by transitions from higher levels to the lowest excited levels. Hence, in order to obtain λ5,461, an intense line in the green which is most efficient because of its high value of V_λ, it is necessary to

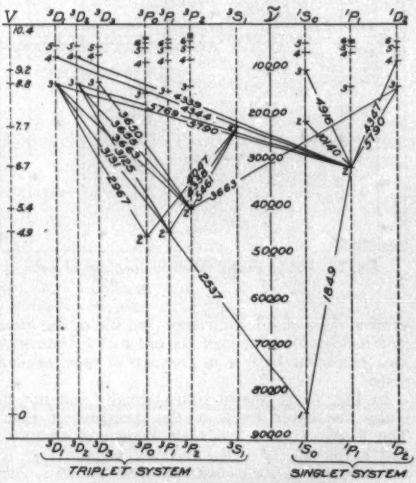


Fig. 4. Energy levels for mercury

impart to an electron a kinetic energy corresponding to 7.7 volts, while the radiation emitted corresponds to 12,336/5,461 = 2.26 volts. On the other hand, in the case of sodium, the kinetic energy of a 2.10 volt electron may be converted quantitatively into the radiation λ5,890, λ5,896.

Second, while in the case of sodium (and other alkali metals) all the energy states are of such a nature that a transition to a lower state may always occur with accompanying emission of radiation, there are certain energy levels in the case of mercury from

2. *Rev. of Modern Physics*, v. 4, 1932, p. 278.
3. "Graphic Representation of the Spectra of Atoms and Ions With One, Two, and Three Valence Electrons" (a book). Julius Springer, Berlin, 1928.
4. "Line Spectra and the Periodic Arrangement of the Elements." *Chem. Rev.*, v. 5, 1928, p. 109.

which no transitions occur with emission of radiation. Such are the states designated spectroscopically in Fig. 4 as 2 $^3P_0$ and 2 $^3P_2$, which are adjacent to the level 2 $^3P_1$ from which the transition λ2,537 occurs. These are known as metastable states and while the normal atom may be excited to one of these states by impact of an electron having the

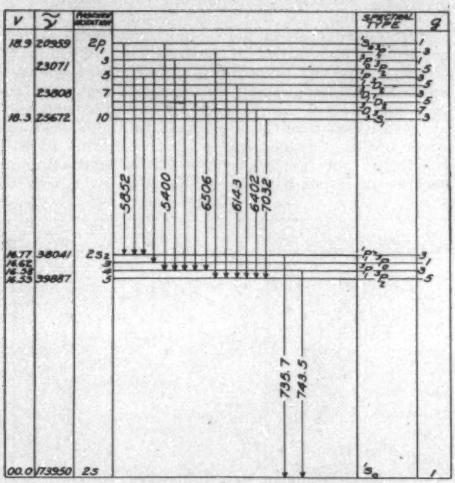


Fig. 5. Lower energy levels in spectrum of neon

proper value of kinetic energy, the life of the atom in a metastable state is of the order of 10^{-3} to 10^{-4} sec, instead of 10^{-8} as in the case of other excited states.

In Fig. 5 are shown (schematically and not to scale) the lower levels in the spectrum of neon. The lowest excited levels are known as s_5, s_4, s_3, and s_2 (or $^3P_2$, $^3P_1$, $^3P_0$, and $^1P_1$, respectively), of which s_5 and s_3 are metastable, while s_4 and s_2 give rise to the 2 resonance lines λ743 and λ736 which are in the far ultra-violet. The combination of these 4 levels with the 10 higher p levels give rise to about 30 spectral lines which impart to neon its red-yellow light. Here, as in the case of mercury, it is evident that the electron must acquire about 18.5 volts in order to excite a neon atom to a level from which transitions (corresponding to about 2 volts of kinetic energy) can occur with emission of visible light.

Finally, Table II gives values of V_i and V_r for a few of the gases and vapors of interest in the production of light, also the resonance lines (λ_r) and, in the column under V_m, the metastable levels.

From this table it is evident that of the different alkali metals, sodium is the only one which has resonance lines in the visible range. Also, while the resonance lines for the other alkali metals are in the near infra-red, the corresponding lines for all the other gases and vapors are in the ultra-violet. Since, under the usual operating conditions, the most intense lines in the arc spectrum of any element are the resonance lines, it follows that sodium must be more efficient as a source of light than any of the other elements. The other interesting fact, emphasized by the data in Table II, is the presence of metastable states in all other spectra than those of the alkali metal.

Probability of Excitation and Ionization

The various factors which govern the intensity and efficiency of light produced from an electrical discharge in a gas will now be considered. The intensity of any spectral line depends in the first place upon the rate at which transitions occur from some excited state k to a lower state j. Under stationary conditions, the rate at which atoms in state k revert to state j will be equal to the rate at which they are formed. Therefore the intensity of light must vary with both the electron current (I_e) and the concentration of atoms in the lower state j, (N_j), since the number of collisions per unit time per unit volume will vary with the product $N_j \cdot I_e$. However, not all collisions between sodium atoms and electrons of kinetic energy 2.10 volts (or higher) are effective in producing excited atoms in the $3P$ state. The probability that a collision will result in a transfer of energy is a function of the velocity (or kinetic energy) of the electron. It is customary to define the probability of excitation P_e, as the number of excited atoms formed per unit electron current per unit length of path, per unit pressure at zero deg C. For each energy level in any given spectrum, the manner in which P_e varies with V (i.e., with the kinetic energy of the electron) may be quite different. In Fig. 2 there is shown a plot of this function for the $3P$ state of sodium,[5] from which it is seen that the maximum probability of excitation

5. L. E. Loveridge, quoted by R. B. Brode, *Rev. of Modern Physics*, v. 5, 1934, p. 269.

Table II—Critical Potentials, Resonance Lines, and Metastable Levels

Atom		V_r	λ_r	V_m	V_i
Lithium	(Li)	1.84	6,708		5.37
Sodium	(Na)	2.10	5,890; 5,896		5.12
Potassium	(K)	1.60	7,645; 7,699		4.32
Rubidium	(Rb)	1.56	7,800; 7,948		4.16
Caesium	(Cs)	1.38; 1.45	8,521; 8,943		3.87
Helium	(He)	20.91	592	19.77	24.47
		21.12	584	20.55	
Neon	(Ne)	16.58	744	16.53	21.47
		16.77	736	16.62	
Argon	(A)	11.56	1,067	11.49	15.69
		11.77	1,048	11.66	
Krypton	(Kr)	9.98	1,236	9.86	13.94
		10.59	1,165	10.51	
Xenon	(Xe)	8.39	1,469	8.28	12.08
		9.52	1,295	9.40	
Zinc	(Zn)	4.01	3,076	3.99	9.36
		5.77	2,139	4.06	
Cadmium	(Cd)	3.78	3,261	3.71	8.96
		5.30	2,288	3.93	
Mercury	(Hg)	4.87	2,537	4.64	10.38
		6.67	1,850	5.44	
Thallium	(Tl)	3.27	3,776	0.96	6.07
		4.46	2,768		

occurs for electrons of 2.5 volts, approximately. In the case of the $2\,^1P_1$ state of mercury (corresponding to V_r = 6.67 volts), P_e increases from zero at 6.67 volts to a maximum value at 6.8 volts and then decreases with further increase in voltage.[6]

In a similar manner, the probability of ionization, P_i, is defined as the number of ions formed per unit electron current, per unit path length, per unit pressure at zero deg C. For values of V less than about 4 V_i, P_i increases linearly with V according to a relation of the form

$$P_i = C(V - V_i) \tag{10}$$

From the results obtained by I. Langmuir and H. A. Jones,[7,8] the following values of the constant C are derived for helium, neon, argon, and mercury. The value for sodium has been taken from a paper by M. J. Druyvesteyn and N. Warmoltz.[9]

Helium	(He)	0.035
Neon	(Ne)	0.034
Argon	(A)	0.33
Mercury	(Hg)	0.69
Sodium	(Na)	0.66

As has been shown by C. G. Found,[10] eq 10 is valid even for cumulative ionization (see discussion below) if V_i is replaced by V_r.

Intimately connected with the probability of excitation is the optical excitation function, F_e, which gives the intensity of any spectral line as a function of the kinetic energy of the incident electron, and which may be determined quite readily experimentally. This concept was first suggested by R. Seeliger[11, 12, 13] and determinations of F_e for a number of lines in different spectra have been carried out by several investigators, notably by W. Hanlé and K. Larche.[14] In Fig. 6 are shown curves obtained by the latter for the 3 lines in the spectrum of cadmium, $2^3P_2 - 2^3S_1$; $2^3P_1 - 2^3S_1$; and $2^3P_0 - 2^3S_1$ which correspond, respectively, to the lines λ5,461, λ4,358, and λ4,047 in the spectrum of mercury (see Fig. 4).

If the probability of a transition from state k to state j is designated by A_{kj}, then it is evident that the function F_e is given by the relation

$$F_e = P_e A_{kj} \tag{11}$$

which states that the intensity of any spectral line, ν_{kj}, varies with both the probability of excitation of the level k and the probability of transition from this level to state j.

A further consideration of the excitation function shows that this involves implicitly another quantity, the probability of a collision (P_e) between an electron of kinetic energy, V, and a molecule of the gas. (Since only monatomic gases and vapors are being considered the terms atom and molecule are evidently synonymous.) Actually the probability of a collision is also a function of V, as shown in Fig. 7[15] for collisions of electrons with atoms of the alkali metals.

The function P_e is defined as the number of collisions per unit electron current per unit length of path per unit pressure at zero deg C.

The functions P_e, P_i, and P_s each determine a mean free path which is derived as follows:[8]

The probability of a collision in a distance dx in a gas at a pressure p is $P_e p\,dx$. A current of electrons of strength I passing through the layer dx is decreased by

$$dI = -IP_e p\,dx$$

Hence

$$I = I_0 e^{-P_e x p} \tag{12}$$

where I_0 is the initial electron current in the beam and I is the

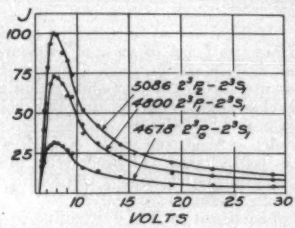


Fig. 6. Intensities of lines in spectrum of cadmium as functions of electron volts

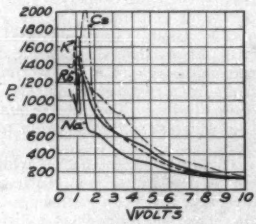


Fig. 7. Collision probabilities for electrons in alkali metal vapors, as functions of velocity

electron current after passing a distance, x, through the gas at a pressure, p.

The mean free path L is the average distance traveled before colliding and is given by

$$pL = 1/P_e = L_0$$

the free path at unit pressure.

From the value of L or L_0

the effective area of a single atom, q, is found by dividing P_e by the number of atoms per unit volume per unit pressure. If the unit of pressure is one millimeter of mercury at zero deg C, and the unit of volume is one cubic centimeter, then

$$q = 0.281 \times 10^{-16} P_e \text{ cm}^2 \tag{13}$$

The radius r of a circle of this area may be described as the effective radius of the atom for collision and is given approximately by

$$r = 0.3 \times 10^{-8} \sqrt{P_e} \text{ cm} \tag{14}$$

Table III gives values of mean free paths for electrons (L_e) and molecules (L_m), also values of $1/L_e$ and $1/L_m$, the number of collisions per centi-

6. W. H. Brattain, *Phys. Rev.*, v. 34, 1929, p. 474.
7. *Phys. Rev.*, v. 31, 1928, p. 357.
8. K. T. Compton and I. Langmuir, *Rev. of Modern Physics*, v. 2, 1930, p. 123.
9. *Phil. Mag.*, v. 17, 1934, p. 1.
10. *Phys. Rev.*, April 15, 1934.
11. *Ann. d. Physik*, v. 59, 1919, p. 613.
12. *Physikal. Zs.*, v. 22, 1921, p. 610.
13. "Gasentladungen," R. Seeliger, p. 32.
14. *Zs. f. Phys.*, v. 67, 1930, p. 440.
15. R. B. Brode, *Rev. of Modern Physics*, v. 5, 1934, p. 269.

meter path, for a few gases at one millimeter pressure and 25 deg C.[16] According to the kinetic theory of gases $L_s = 4\sqrt{2}L_m$.

Table III—Kinetic Theory Values of L_s, L_m, and their Reciprocals at p = One Millimeter and 25 Deg C

Gas		L_s	L_m	$1/L_s$	$1/L_m$
Mercury*	(Hg)	0.0149 cm	0.00263 cm	67.0	380.0
Argon	(A)	0.0450	0.00795	22.2	125.9
Neon	(Ne)	0.0787	0.01390	12.7	72.0
Helium	(He)	0.1259	0.02221	7.95	45.0

* The vapor pressure of mercury at 25 deg C is 0.00184 mm. Hence the values of L_s and L_m at this temperature should be multiplied by $1/_{0.00184}$ = 544.

If these values be regarded as the significant ones from the point of view of collision, then the values of $L_sP_s = L_s/L_0$, and L_sP_i are to be considered as measuring the probability that excitation or ionization shall occur at any one collision. Thus for electrons of kinetic energy corresponding to 22.0 volts in neon, the value of $1/P_i$ = 59 cm, while L_s = 0.0787 cm. Therefore the probability that an electron of this energy will ionize a neon atom at a single collision is 0.0787/59 = 0.00134, or one collision out of 750 is effective in producing ionization. For sodium vapor at 365 deg C (vapor pressure = 0.15 mm of mercury, number of sodium atoms per cubic centimeter = 2.2×10^{18}) L. S. Ornstein and B. Baars[17] have deduced a value for L_s of 0.5 cm. From this they derive for the atomic radius the value $r = 1.7 \times 10^{-8}$ cm, and they conclude from measurements on the intensity of the D lines produced that at the maximum, 5 per cent of the collisions are effective in producing D-line radiation.

It should be noted that while $1/L$ gives the number of collisions per centimeter path, the actual direction between collisions is quite random and therefore the number of collisions per unit length in a given direction is $1/L^2$. An electron traveling a distance of one centimeter in neon at one millimeter pressure and 25 deg C makes $(12.7)^2$ = 162 collisions with neon atoms.

Life of Excited Atoms

(A very full discussion of the life of excited atoms, and related topics has been given by A. C. G. Mitchell and M. W. Zemansky, see reference 18.)

As has been mentioned previously, the intensity of a spectral line of frequency, ν_{kj}, corresponding to a transition from state k to state j, depends not only upon the probability of excitation from the lower to the upper state (P_s), but also upon the probability of occurrence of a transition from k to j. This probability is usually designated by A_{kj}, and the reciprocal, τ_{kj}, is a measure of the average life of the excited state k with respect to the radiation ν_{kj}.

The physical significance of τ_{kj} may be stated thus: Given a certain number (n_0) of excited atoms in state k at $t = 0$, the number at the end of interval, t, providing that the rate of generation of excited atoms is zero, is given by

$$n = n_0 e^{-t/\tau} \tag{15}$$

According to classical physics, the "damping factor," $1/\tau$, of a linear harmonic oscillator emitting radiation of frequency ν_0 (and wave length λ_0 in Ångström units) is given by the relation

$$\tau = \frac{3mc^3}{8\pi^2 e^2 \nu_0^2} = 1.131 \times 10^{-8} \left(\frac{\lambda_0}{5{,}000}\right)^2 \text{ sec} \tag{16}$$

where

c = velocity of light
m = mass of electron
e = charge on electron

On the other hand, the quantum theory point of view leads to a relation between the value of τ_{kj} and the absorption coefficient, α, of the resonance radiation of frequency, ν_{kj}. If I_0 designates the intensity of the radiation at $x = 0$, the intensity of the light passing through a thickness x of the absorbing atoms is given by

$$I = I_0 e^{-\alpha x} \tag{17}$$

From measurements of α for any resonance radiation, the value of τ may be derived by means of a relation of the form

$$\alpha = \frac{K \cdot n \cdot \lambda_0^2}{\tau\sqrt{T}} \tag{18}$$

where K is a constant for the transition k to j; λ_0 is the wave length of the resonance line; n is the number of absorbing atoms per cubic centimeter, and T is the absolute temperature (in degrees Kelvin). Actually the absorption is observed for a radiation extending over an interval $\Delta\nu$ of frequencies, and the measurements give α as a function of ν over this range, so that the above relation applies strictly only to the center of the range which is at ν_0 (or λ_0).

The magnitude of the absorption for the resonance lines of sodium is evident from the measurements of W. Zehnden,[19] which are shown in Table IV. The relative intensity of the radiation after passing through a thickness of 1.492 cm of sodium vapor at the absolute temperature T is given under I/I_0. The last 2 columns give the values of α calculated by eq 17.

Table IV—Absorption for the Resonance Lines of Sodium

T	n	I/I_0 for D_1	I/I_0 for D_2	αD_1	αD_2
416.5	8.32×10^{10}	0.701	0.518	0.238	0.441
431.0	2.24×10^{11}	0.424	0.236	0.575	0.968
445.9	5.90×10^{11}	0.183	0.111	1.14	1.47

Extrapolation to T = 503, that is, 230 deg C, shows that at this temperature (at which $n = 1.25 \times 10^{12}$), the value of I/I_0 for the D_2 line decreases

16. K. T. Compton and I. Langmuir, *Rev. of Modern Physics*, v. 2, 1930, p. 208.
17. *Proc.* Amsterdam Acad. Sciences, v. 34, 1932, p. 1,259.
18. "Resonance Radiation and Excited Atoms," A. C. G. Mitchell and M. W. Zemansky. The Macmillan Company, 1934.
19. *Zs. f. Phys.*, v. 86, 1933, p. 555.

to 0.1 in a distance $x = 0.74$ cm. The value of τ deduced from these measurements of α is 1.5×10^{-8} sec.

The absorption of mercury vapor for its resonance line λ2,537 is so great that, as R. W. Wood has shown, a shadow is cast by a quartz bulb filled with mercury vapor at room temperature (pressure = 0.001 mm, approximately) when illuminated by the resonance radiation. A depth of 0.5 mm of the vapor at 0.001 mm of mercury pressure reduces the intensity of a beam of resonance radiation to $^1/_3$ its initial value[20].

Just as atoms in the normal state absorb radiation of the frequency corresponding to the transition from the lowest excited state, metastable atoms may be excited to higher energy states by absorption of radiation. For instance, the metastable neon atoms in state s_5 (see Fig. 5) may be excited to one of the p-states by absorption of λ6,402, which is one of the most intense lines in the spectrum of the gas.

It is evident, as mentioned in a previous section, that the reciprocal of the absorption coefficient, that is, $1/\alpha$, may be regarded as the mean free path for the collision of light corpuscles (energy quanta or photons) with normal or excited atoms in the gas. Equation 17 shows that the magnitude $1/\alpha$ is a measure of the distance in which the light intensity is decreased to $1/\epsilon$ of its original value. Hence the light intensity is reduced to ϵ^{-2}, that is, to 0.135 of its original value in traveling a distance $2/\alpha$ and the number of collisions in that distance is 2α. In the case of the resonance radiation of sodium, $1/\alpha$ is equal to 0.32 for a pressure of sodium vapor of 0.00063 mm (at 230 deg C). Hence the resonance radiation originating at the center of a 2-cm diameter tube is absorbed and reëmitted 10 times before reaching the walls. Values of τ for the resonance lines of a number of atoms have been derived from observations on α and also by other methods. Table V shows some of the results obtained, and for comparison there are given in the last column, values of τ calculated by means of eq 16.

Table V—Average Life of Excited Atoms

Atom		λ in A	τ in Sec	τ (Calc.) in Sec
Lithium	(Li)	6,708	2.7×10^{-8}	2.04×10^{-8}
Sodium	(Na)	5,896, 5,890	1.48×10^{-8}	1.57×10^{-8}
Potassium	(K)	7,699, 7,665	2.7×10^{-8}	2.67×10^{-8}
Caesium	(Cs)	8,944	3.8×10^{-8}	3.62×10^{-8}
		8,521	3.3×10^{-8}	3.29×10^{-8}
Mercury	(Hg)	2,537	1.08×10^{-8}	2.91×10^{-8}
		1,849	1.30×10^{-8}	1.55×10^{-8}
Cadmium	(Cd)	3,261	2.5×10^{-8}	4.81×10^{-8}
		2,288	2.0×10^{-8}	2.37×10^{-8}

Cumulative Ionization

An atom in an excited state, B, may be raised to a still higher energy state, C, by 2 methods.

1. It may absorb radiation of wave number $\tilde{\nu}_B - \tilde{\nu}_C$ by a process similar to that by which absorbed resonance radiation brings about a transition from the normal to the first excited state—a process which has been discussed in the previous section.

2. The excited atom may collide with an electron from which it will receive the energy corresponding to $V_C - V_B$, where V_C and V_B are the excitation potentials of the 2 states. By successive impacts the atom may thus be excited to continuously increasing energy states until finally it becomes ionized.

This latter process of excitation and ionization by electrons in successive stages is designated as the *cumulative* type and plays an important rôle in all hot-cathode, low-voltage arcs, such as those in sodium vapor, neon, helium, or mercury vapor. It is possible, for instance, to obtain an arc in sodium vapor with a voltage drop slightly above 2.10 volts and below the actual ionization potential, 5.12 volts. Similarly arcs in mercury vapor may be obtained with a voltage drop less than 10.4.

Obviously the rate of cumulative ionization must increase with both the electron current density and the value of τ, for the longer the "life" of the excited state, the greater the probability of a collision between the atom in this state and an electron.

Since the rate of excitation by absorption of radiation according to process (1) also increases with electron current density and τ, a more detailed investigation is necessary to determine in any given discharge which of the 2 processes is more effective in causing ionization. According to a calculation carried out by K. T. Compton,[21,22] impact by photons is much more important in the case of arcs at low pressures.

Life of Metastable States

In a previous section mention has been made of the existence of metastable states in the case of all monatomic vapors and gases, except those of the alkali metals. By impact of electrons having the necessary kinetic energy, it is possible to excite mercury or neon atoms to these metastable states, but a transition from these states to the normal, which is accompanied by radiation corresponding in frequency to the energy difference involved, is extremely improbable. In fact, according to the older quantum theory, such transitions were "forbidden." But on the basis of the newer quantum mechanics, there does exist a definite probability, extremely small it is true, for such a transition, and this leads to values of τ for metastable states which are of a much larger order of magnitude than those for other excited states.

However, in a discharge, metastable atoms are actually destroyed in a much shorter interval of time, by one or more of the following processes, for each of which there is a high degree of probability of occurrence:

1. The metastable state may be excited to a higher energy state by the process of cumulative ionization.

2. The same result may be secured by absorption of radiation, as mentioned already. Thus in the case of neon, the atom in the metastable state s_5 can absorb λ6,143, λ6,402, or λ7,032. Similarly mercury in the $^3P_2$ state can absorb λ5,461 or λ3,663. In fact, observations on the intensity of absorption of the line λ6,402 have been used by various investigators to determine the concentration of metastable atoms in a neon discharge as well as the duration of existence of atoms in the metastable state.

20. "The Origin of Spectra," F. D. Foote and F. L. Mohler. The Chemical Catalog Company, New York, 1922.

21. *Phys. Rev.*, v. 20, 1922, p. 105.

22. "The Origin of Spectra." F. D. Foote and F. L. Mohler. The Chemical Catalog Company, New York, 1922.

3. An interesting and very important process by which the concentration of metastable atoms may be decreased is that designated as collisions of the second kind. This may be illustrated by referring to the energy level diagram for neon (Fig. 5) and Table II. The metastable state s_5 differs in energy from the resonance level, s_4, by only 0.05 volts. By collision with a neon atom, the atom in state s_5 may acquire sufficient energy to raise it to the state s_4. Similarly the metastable state s_3 may lose 0.04 volt by collision to from the state S_4. Under special conditions such collisions may also occur between ordinary excited atoms and electrons with the result that the kinetic energy of the latter is increased while the excited atom returns to a lower state without emission of energy. This is evidently the reverse process of that by which an electron transfers its kinetic energy to an atom (which is known as a collision of the first kind).

4. If there is present an admixed gas whose atoms have an ionization or excitation potential lower than that of the metastable atoms, the latter may transfer their energy to the former. For instance, in a mixture of neon and argon, the metastable neon atoms (V_m = 16.53 and 16.62) can bring about ionization of argon atoms (V_i = 15.69). Similarly in an argon-mercury mixture, metastable argon atoms may cause ionization of the mercury atoms.

5. Lastly, the metastable atoms are destroyed in a discharge tube by impact on the walls and other surfaces, where they cause emission of secondary electrons. The significance of this phenomenon in a neon discharge has been studied by a number of investigators.[23, 24]

Thus, in actual discharges the life of a metastable atom depends upon the conditions of temperature, pressure, current density, and diameter of tube. Under these conditions it has been found that τ may be expressed in terms of p, the pressure, by a relation of the form

$$\frac{1}{\tau} = \frac{A}{p} + Bp$$

where A and B are constants. The term A/p takes into account the rate of diffusion to the walls, while Bp gives rate of disappearance in the gas volume itself.

While values of τ as high as 0.1 sec have been observed for metastable states, the values obtained in usual type of discharges range from 10^{-2} to 10^{-4} sec at pressures of a few millimeters of mercury and ordinary temperatures. At very low temperatures the value of τ is increased. With increase in pressure from very low values, the value of τ increases at first, and then passes through a maximum beyond which further increase in pressure causes a decrease in τ.[25]

Thermal Excitation and Ionization

The production of spectra in stars is evidence of the excitation and ionization of atoms produced at high temperatures. At these temperatures there exists an equilibrium between the rates of excitation and ionization on the one hand and the rates at which both transitions to lower energy levels and recombinations occur. The relative distribution of atoms in 2 excited states A and B is then given by the Boltzmann relation

$$\frac{n_A}{n_B} = \frac{g_A}{g_B} \cdot \frac{\epsilon^{-V_A e/kT}}{\epsilon^{-V_B e/kT}} = \frac{g_A}{g_B}\, \epsilon^{-(V_A - V_B)e/kT} \qquad (19)$$

where

n_A = number of atoms per cubic centimeter in state A
g_A = "statistical weight" of state A
V_A = excitation potential of state A
with similar meanings for n_B, g_B, and V_B
T = absolute temperature of gas
k = Boltzmann gas constant

As an illustration of the significance of this relation, consider the case of sodium vapor. For the normal state, which will be designated by A, g_A = 1; and for the first excited state, B, g_B = 2. Also $V_B - V_A$ = 2.10 volts. Since e/k = 11,600 deg per volt,

$$n_{Na'}/n_{Na} = 2\epsilon^{-\frac{24,360}{T}} \qquad (20)$$

where Na' denotes excited atoms in the $3P$ state.

Thus at T = 4,872 deg K, the ratio of excited to normal atoms is 0.0134, or 1.3 per cent of the atoms are in the first excited state.

On the basis of the Boltzmann distribution law, as stated in eq 19, Saha derived an equation for the degree of ionization as a function of the temperature. Denoting the concentration of normal atoms by n_a, that of singly charged positive ions by n_p, and that of electrons by n_e, Saha's equation has the form[26,27,28]

$$\log_{10} \frac{n_e n_p}{n_a} = \frac{5,040 V_i}{T} + \frac{3}{2} \log_{10} T + 15.385 \qquad (21)$$

From eq 21 it follows that at any given temperature the degree of ionization is lower the greater V_i. Therefore it is expected that atoms of helium, neon, and argon would be found to be ionized only in the highest temperature stars, while the ionization of caesium would occur in comparatively cold stars.

Probably a considerable fraction of the light obtained from high pressure arcs (such as the flaming and open air type and the mercury arc at high pressure) is due to thermal excitation and ionization followed by transitions to lower levels and recombination. In low pressure discharges the gas is not in thermal equilibrium with electrons and ions and practically all the light is due to excited atoms. The recombination of ions and electrons occurs only on the walls and the energy thus evolved merely raises the temperature of the walls and contained gas to not over a couple of hundred degrees above room temperature.

However, as will be more fully discussed in Part II of this paper, the electrons and positive ions in a low pressure discharge are each characterized by a "temperature" which may range from 5,000 to 50,000 deg K, and even higher.

23. C. G. Found and I. Langmuir, *Phys. Rev.*, v. 39, 1932, p. 237.
24. C. Kenty, *Phys. Rev.*, v. 43, 1933, p. 181.
25. J. M. Anderson. *Can. Jl. Res.*, v. 2, 1930, p. 13; v. 4, 1931, p. 312; v. 7, 1932, p. 434.

26. Equation 21 is given by K. T. Compton and I. Langmuir, *Rev. of Modern Physics*, v. 2, 1930, p. 135.
27. "Statistical Mechanics," R. C. Tolman. The Chemical Catalog Company, 1927, p. 147.
28. "The Origin of Spectra," P. D. Foote and F. L. Mohler. The Chemical Catalog Company, New York, 1922, Chap. VII.

The second and concluding part of this paper on "Low Pressure Gaseous Discharge Lamps" is scheduled for publication in the September 1934 issue of ELECTRICAL ENGINEERING. In the present issue, radiation processes are discussed, and in Part II, electrical conduction processes will be covered.

Insulator Surface and Radio Effects

Because of the rapid extension of police radio systems, and because both electric power lines and police cars occupy the highways, the problem of power line radio influence has acquired an added importance. Insulators coated with dirt, moisture, and hygroscopic salts have been found to cause radio disturbances at voltages much less than those for clean insulators.

By
W. A. HILLEBRAND
MEMBER A.I.E.E.

CHARLES J. MILLER, JR.
ASSOCIATE A.I.E.E.

Both of the University of California, Berkeley

THE high voltage insulator is an essential part of overhead circuits for the transmission or distribution of electric power. The adequacy of such circuits is judged principally by their reliability, which in turn depends largely on the adequacy of the insulator selected. The factors that determine whether or not an insulator is satisfactory are durability, mechanical strength, ability to resist flashover under lightning, ability to resist flashover at the operating voltage when wet and dirty, and freedom from radio effects.

Because of the rapid extension of police radio and because both power lines and police cars occupy the highways, the question of power line radio influence has acquired an added importance that makes it necessary to be able to separate out the causes of such effects and to determine their relative importance.

Since the wet flashover of an insulator and the radio effect which an insulator may cause are both functions of its surface properties, it was thought that a study of such properties should be undertaken with a view of learning more about the mechanism by means of which an arc is or may be established over the wet and dirty surface of an insulator, and of the manner in which the disturbances that affect radio receiving sets may originate. The ultimate objective is an improvement in design, the establishment of economic limits of performance, or both. The authors have been engaged in such a study for nearly 2 years, the results of which are presented in this paper.

The wet arcover of an insulator starts as an arc between liquid electrodes; apparently a current of between 30 and 60 ma is required for this arc to be maintained until the gap between conductor and ground is bridged. Surface resistance must be small enough to permit this current to flow. Initiation of the arc is assisted by electrostatic forces which disrupt water drops and pull conducting material into the arc path. An insulator is most dangerous and most likely to flash over when the water film is thickest. Dirt, moisture, and hygroscopic salts on insulator surfaces increase leakage currents to a hundred or more times the dry value. The resistance drop in potential between conductor and surface film results in breakdown of the neighboring air and in radio disturbances at voltages far less than those at which breakdown would occur if this conducting film were not present.

Wet Arcover of Insulators

Properties of the atmosphere always are considered carefully by both the designer and user of an insulator. However, since wet flashover at operating voltage generally occurs during a fog, it was thought worth while to investigate the dielectric strength of fog laden air to see if it departs from normal and may be a cause of breakdown.

Sparking voltage-distance curves were determined for needle gaps on several different occasions for the dense sea fogs of central California. Observations were made on the summit of Twin Peaks in the western part of San Francisco, about 3 miles from the Pacific Ocean. In each test the curve corresponding to 100 per cent humidity was obtained, indicating that the dielectric strength of air under such conditions is a maximum, and of itself cannot be directly a cause of arcover. This is in agreement with other experimental evidence and with the accepted theory that the otherwise free ions in the atmosphere are trapped by fog and vapor particles and rendered less mobile, with the result that a higher voltage is necessary to cause breakdown.

Initiation of an Arc

A power arcover on a wet and dirty insulator starts as a weak low-current high-voltage arc, the current of which is limited by the ohmic resistance of the water film in series with it. Laboratory experience indicates that about 60 ma is the minimum current at which such an arc will not be blown out automatically. Therefore, for an insulator to be in a dangerous condition, it is necessary that the conductivity of the surface film, as influenced by both its thickness and the presence of dissolved conducting material, be at least sufficient to permit a current of 60 ma to flow. Such an arc also must start at a high resistance point on the insulator surface or between ribs, shells, or petticoats, and generally between boundaries of the water film. This means that the

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. Pacific Coast convention, Salt Lake City, Utah, Sept. 3–7, 1934. Manuscript submitted May 28, 1934; released for publication June 25, 1934. *Not published in pamphlet form.*

arc terminal electrodes are liquid. To what extent the properties of such electrodes may affect the development of an arc is believed to be unknown. To shed some light on this question the following experiment was performed.

The sparking voltage-gap length curve at 60 cycles was determined for an air-gap between 2 horizontal brass strips approximately $^1/_8$ in. thick and

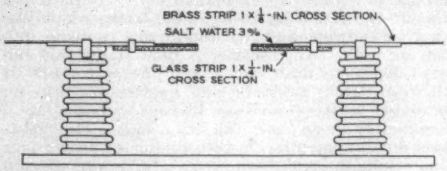


Fig. 1. Arrangement of liquid electrodes

1 in. wide. This same curve then was determined immediately for liquid electrodes of the same dimensions. Liquid electrodes were established by placing thick water films on glass after the manner indicated in Fig. 1. The 2 curves obtained are shown in Fig. 2; they are believed to be significant. In performing this experiment it was discovered immediately that when the voltage is high enough (for these tests about 30 kv) the liquid film at its boundaries is disrupted by electrostatic forces, with the result that conducting material is sprayed into the gap. Beyond this point arcover takes place with a relatively small increase in voltage for increasing gap length. Up to this point the arcover voltage for both liquid and solid electrodes is approximately the same. Further work will include the study of solutions containing materials that lower the surface tension, which should result in arcover taking place at correspondingly lower voltages.

In observing the flashover of a dripping wet suspension insulator the function of water drops as point dischargers is strikingly evident. By allowing a single drop of salt water to roll off the top surface of such an insulator it is easily possible to reduce the arcover voltage by 30 per cent less than that obtained in the standard A.I.E.E. wet test.

As an insulator becomes wet in an approaching fog, there is first a complete redistribution of voltage with the appearance of highly overstressed zones which "spit" vigorously. This is the period of nervousness for an observer but of safety for the insulator because the surface resistance is still too high to permit the development of an arc. As moisture is accumulated the insulator quiets down and may become entirely black with no electrical overstress. Its condition now is dangerous because the surface resistance is low enough to permit the development of an arc, once started.

On a foggy night hot yellow arcs have been observed to flash from a suspension insulator string that was perfectly black and showed no evidence of overstress, travel half the length of the string, and blow out. One of the authors was fortunate enough to observe the flashover in service of a large 4-part bus insulator operated at a line voltage of approximately 66,000 kv, or not more than 38 kv to ground. The nominal wet flashover voltage of this insulator under A.I.E.E. test conditions would have been at least 130 kv. Flashover occurred during a heavy fog when everything was dripping wet. The insulator itself was perfectly dark and showed no sign of overstress, but arced suddenly and without any warning whatsoever.

In summary, it is believed that the flashover of a wet and dirty insulator starts as a weak high-voltage arc, generally between liquid electrodes. The current is limited by the resistance of the surface film, but the disruption of this film at some point by electrostatic forces probably facilitates the initiation of the arc. An insulator is believed to be most dangerous when completely wet and showing no sign of overstress.

Radio Influence

It is a matter of common knowledge that, under certain circumstances, electric power lines may radiate electromagnetic waves that affect radio broadcast reception. The source of such radiation is generally the partial failure of a dielectric, whether it be air, oil, or solid insulation, resulting in a disruptive static discharge. This discharge may occur as corona into the air from conductor and fittings, through oil, through the cracked shell of an insulator, or through partially punctured coil insulation, about the conductor of a dry type bushing, from the cap lips, clevis bolt, or cotter key of a suspension insulator to the shell of the unit above it, as corona about the wire or pin of a pin type insulator, across loose joints in the hardware of wood construction, or over the surface of a dirty insulator in humid weather.

Circuits involved in generating this disturbance are indicated schematically in Fig. 3, in which R is

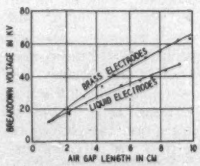


Fig. 2. Air gap-voltage curves for metal and liquid electrodes of similar dimensions

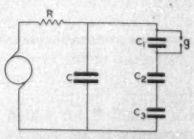


Fig. 3. Schematic representation of the generation of electromagnetic radiations that cause radio effects

the line impedance, C line capacitance, and C_1, C_2, C_3 the successive portions of a series of dielectrics. Upon the breakdown of C_1, represented by the discharge of gap g, capacitance C immediately discharges into capacitances C_2 and C_3 in series, resulting in a sudden change in the electric field that is propagated as an electromagnetic wave.

Experience indicates that, in general, corona into the air will cause very little radio effect, because the

breakdown is gradual, not of the type indicated in Fig. 3, and the rate of energy transfer is small.

Referring again to Fig. 3, if capacitances C_2 and C_3 be shunted by a resistance, the value of which is low in comparison with the impedance of the capacitances, a disproportionate voltage will be thrown upon capacitance C_1 and gap g with the result that the gap will break down at a much lower voltage than if the shunting resistance of capacitances C_2 and C_3 were absent.

In practice, such a condition exists when the surface of an insulator becomes coated with a conducting film. The resistance of this film corresponds to a resistance that has been assumed to be shunting capacitances C_2 and C_3. Capacitance C_1 is represented by the electrostatic capacitance between insulator cap or tie wire and the surface film. A pin type insulator therefore should exhibit corona at the tie wire at a much lower voltage when its surface is coated with a conducting film than when it is not so coated.

Laboratory Experiments

In order to establish the truth or falsity of this conclusion, experiments were performed on glass plates to which were applied electrodes of conventional forms. Insulators near the sea coast were washed, and the wash water carefully was saved and applied to the glass surface so as to deposit thereon the same amount of solid material per unit of area as was found on the insulator.

Since the breakdown over an insulator surface as a cause of radio effect is the subject being studied, the performance of the film coated surface was compared with that of the clean surface by applying voltage to the electrodes and passing the combined leakage and charging current through the primary of a radio frequency transformer, the secondary of which was connected to the antenna circuit of a radio receiving set. The conductivity of the surface film is almost wholly dependent upon the amount of absorbed water, which in turn depends upon vapor tension and atmospheric humidity. Therefore, all tests were performed on both the clean and coated plates enclosed in a box wherein the humidity could be controlled within fairly close limits.

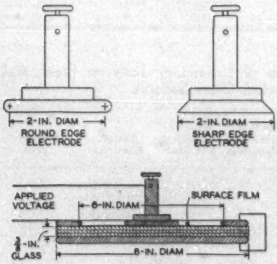


Fig. 4. Inner electrodes (above) and electrode assembly (below) used in laboratory tests

The test specimen consisted of a stack of 3 $^1/_8$-in. glass plates with conventional electrodes on opposite sides. The bottom electrode was a round brass plate, the top one a 2-in. brass disk in the center of a 6-in. annular ring. Electrodes used and their assembly are shown in Fig. 4.

The purpose of the annular ring was to provide a definite path, uniform in all directions, for leakage currents. For one series of tests, the glass surface between the central electrode and annular ring was covered with wash water from dirty insulators taken from a line near the sea coast, so that, when dried, it would have exactly the same quantity of dirt and other material per unit of area as the average for the insulator surfaces in the field. The surface coating of these insulators was analyzed in terms of insoluble, incombustible material, which means sand and clay, and of chloride ion. The relative occurrence of these is: 1.0 milligram of dirt per square inch of surface, and 0.035 milligram of chloride ion. All of the material present on the insulator surface was transferred in proper amount to the glass surface. This gave the opportunity, by making observations with clean and dirty plates, of determining the effect of dirt and salt on the energy of the radio effect and on the voltage at which breakdown occurs.

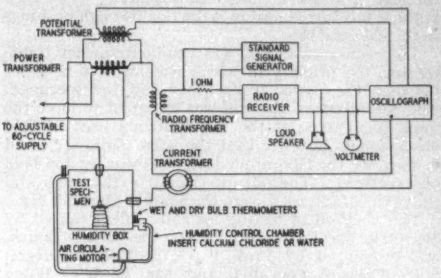


Fig. 5. Schematic diagram showing arrangement of equipment for laboratory tests

The electrostatic capacitance of the electrode assembly with 3 $^1/_8$-in. glass plates is 25 $\mu\mu$f. This is about double that of a standard pin type insulator between the pin as one electrode and conductor and tie wire as the other, so that initial corona for clean surfaces should occur at a lower voltage than for an insulator.

Arrangement of apparatus for these tests is shown schematically in Fig. 5, and a photograph of the actual laboratory set-up in Fig. 6. The humidity control box was cubical, 3 ft on a side, and completely air tight. The air was circulated through an external pipe 3 in. in diameter by a small motor driven fan. The air entering the humidity box was forced through the control chamber in which a wire basket containing lumps of calcium chloride for drying the air could be inserted. Another basket, containing damp rags suspended in water replaced the calcium chloride basket when high relative

humidities were desired. The relative humidity in the box was determined by wet and dry bulb thermometer readings from thermometers inserted in the air pipes at the entrance to and the exit from the box. With this arrangement, relative humidities of from about 20 to 95 per cent are easily obtainable.

The transformer used was a 440/2,400-volt 3-kva power transformer. The power supply was a 220-volt line, which was connected to the transformer through a $1^1/_2$-kva induction regulator. The high voltage was introduced into the box through bushings in the side and top.

The radio pick-up coil was a radio frequency transformer, the primary of which was inserted in series between the power transformer and the specimen. The secondary of the coil was designed to have the same inductance as the loop antenna used in field observations in order that the same radio set could be used for the laboratory tests that was used in field observations. The output circuit of the radio and the oscillograph used were the same in the field tests.

This method of testing for radio effect caused by dielectric breakdown, so far as the writers know, was originated by Prof. F. O. McMillan (Oregon State College, Corvallis) and Mr. R. J. C. Wood (Southern California Edison Company, Los Angeles).

The test procedure consisted in establishing a desired humidity, then applying voltage to the test specimen, measuring the input to the radio set as in the field tests, and taking oscillograms. Surface resistance also was determined with a megger.

Results are given in the oscillograms, in the curve of Fig. 7, which shows the relation between relative humidity and radio effect for the dirty surfaces, and in Tables I and II. A striking difference between the performances of clean and dirty surfaces is illustrated clearly in the observations recorded in Table II.

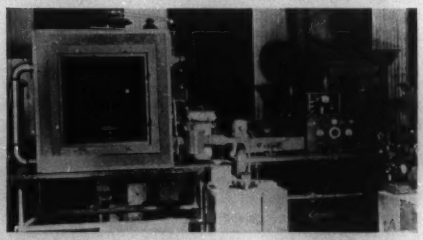


Fig. 6. Laboratory apparatus

Field Measurements

Field measurements of radio influence which, as will be shown later, are correlated closely with the laboratory tests, were made at Muir Beach, Calif., from a tap of the 11-kv Alto-Bolinas circuit of the Pacific Gas and Electric Company. This particular circuit was selected because of its isolation and freedom from many possible sources of disturbance; because at its operating voltage pin-hole and tie-wire corona would be absent if insulators were dry and clean; and because the insulators are exposed to a known type of contamination, salt spray from the ocean. Results of these measurements are given in Table III. The data therein recorded show exactly the same variation of radio effect with humidity as was found in the laboratory tests. Hours are required for the effect of a change in humidity to become manifest so that the 12:15 reading of October 17 still shows some radio effect which entirely disappeared in the subsequent readings at 4:30 and 7:45.

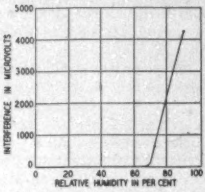


Fig. 7. Effect of relative humidity on interference

Round edge electrodes; 2,500 volts applied

On November 26, insulators were washed by hand. The 12:10 reading was taken immediately before washing. The readings of December 2 show the absence of radio effect with the clean insulators even though the humidity was comparatively high. The reading of May 10 was taken at another part of the line. The effect found at that station probably resulted from one or more cracked insulators. The reasons for believing this to be the case are given later.

With respect to the magnitude of radio influence recorded in Table III, attention is called to the fact that the loop antenna used as a pick-up was within 25 ft of the 11-kv conductors and within 35 ft of the top

Table I—Surface Resistance of Clean and Coated Glass

Surface Condition	Surface Resistance, Megohms	Relative Humidity, Per Cent	Center Electrode
Clean	100+	91	Round edge
Coated, Muir Beach film	0.6	90	Round edge

Table II—The Results of Laboratory Tests on Clean and Coated Glass Surfaces

Surface Condition	Magnitude of Radio Effect, Microvolts	Relative Humidity, Per Cent	Center Electrode	Applied Volts
Coated, Muir Beach film	4,250	91	Round edge	2,500
Clean	0	91	Round edge	2,500
Clean	0	35	Round edge	2,500
Clean	0	29	Sharp edge	2,500
Clean	1,320	48	Sharp edge	7,000
Clean	1,160	85	Sharp edge	7,000

of the transformer pole. In order to obtain readings as large as possible the loop antenna was placed as near the source of disturbance as it was possible to get it.

It is a matter of common experience that power line disturbance diminishes in intensity at a high

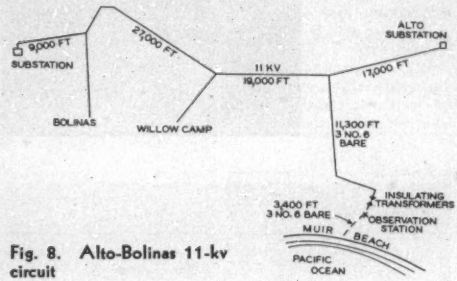


Fig. 8. Alto-Bolinas 11-kv circuit

rate with distance from the line and it is rarely evident at distances greater than 300 ft. That was true in this case and was confirmed by repeated visits to the residences of nearby consumers connected to this circuit. Their receiving sets were much more sensitive than the one used in these measurements. At no time was the effect audible in their sets except when tuned to stations a thousand miles or more distant and then it was of the same order as static from the atmosphere.

An interesting and altogether unexpected discovery is the fact that the radio effect was tuned very sharply at the 5 frequencies recorded in Table III. No explanation for this is offered. On other circuits sharp tuning also has been found, but in no other case within the authors' experience has the effect been limited to so few frequencies.

Had it been possible to continue the tests recorded in the curve of Fig. 7 to 100-per cent relative humidity, the curve would drop from a sharp peak suddenly to zero, for the reason that when the conducting film of moisture became heavy enough to function as a resistance without breakdown where it joins the electrode, all sudden current changes would cease and with them all radio effect. It is characteristic of power line radio influence caused by insulator surface breakdown resulting from dirt and moisture to increase with humidity, reach a maximum, and then decrease as insulator surfaces become thoroughly wetted. This was particularly true of the circuit observed at Muir Beach. In the latter stage, heavy power arcs would occur between shells or between petticoats of the same shell; but, although they occurred repeatedly at Muir Beach and were almost directly overhead, in no case did they cause any disturbance in the radio.

Yager (see "Electrical Leakage over Glass Surfaces," *Bell Laboratories Record*, v. 12, Oct. 1933) gives curves for adsorption on clean glass surfaces and for electrical conductivity that bear a strong resemblance to Fig. 7. He also calls attention to the time required for adsorption to take place. The same effect was observed with dirty film employed in the laboratory tests and in the field observations of October 17, Table III, previously referred to.

Table III—Field Measurements of Radio Disturbance on the Muir Beach Tap Line

Date	Time (p.m.)	Magnitude of Radio Effect at Various Frequencies, Microvolts per Meter					Relative Humidity, Per Cent
		630 kc	720 kc	770 kc	840 kc	1,290 kc	
9-19-33	8:30	650	890	270	240	320	91
	10:00			400	330	410	
	11:00	470		300	430	400	
9-23-33	7:30	390		180		36	82
	8:55				180		88
9-24-33	6:20*	370		100	110	16	87
9-25-33	5:25	100	120	100	55	0	66
	6:25	220	190	250	200	170	100
	7:50	110	180	130	130	0	100
10-1-33	5:25	220	190	160	150	170	97
	9:30	320	280	330	240	150	
10-10-33	6:55	280	360	330	270	280	88
	8:15	320	430	430			
10-17-33	12:15	100	390	200	110	13	19
	4:30	0	0	0	0	0	
	7:45	0	0	0	0	0	65
10-24-33	12:37	57	110	130	240	2	88
	2:25	160	160	130	110	30	81
	3:55	280	160	170	110	120	83
	5:00	320	210	180	270	150	82
	3:30	160	210	120	130	70	90
	7:55	120	140	110	76		
11-6-33	2:30	45	96	830	0	0	82
	3:27	100	160	470	64	10	94
		200		200	70		
		120	280	93	61		
		80					
11-14-33	3:30	100	140	40	43	26	86
	4:25	180	280	110	70	70	
11-26-33	12:10	0	0	0	0	0	37
	5:00	0	0	0	0	0	63
	8:05	0	0	0	0	0	26
12-2-33	12:45	0	0	0	0	0	83
	1:30	0	0	0	0	0	80
	2:00	0	0	0	0	0	
	5:12	0	0	0	0	0	90
3-29-34	5:45	53	64	47	12	0	94
	7:05	77	140	40	12	0	
	9:00	16	71	43	0	0	
5-10-34	3:40		71	60		15	53

* a.m.

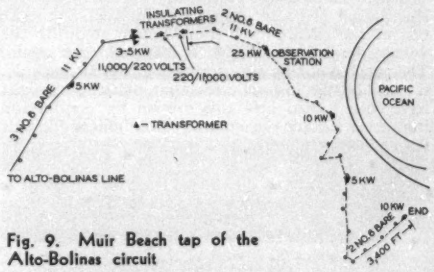


Fig. 9. Muir Beach tap of the Alto-Bolinas circuit

The influence of dirt in the form of finely divided clay or sand has not been determined, but is probably important as establishing points for electrical discharge to take place. On a clear night, with a light dew, 11-kv insulators along the sea coast have been observed to be faintly luminous, silhouetted against the sky by a line of pale blue light. Breakdown was occurring over the entire surface of these insulators at an average voltage gradient of not over 400 volts per inch, crest value.

Figs. 10 and 11. Observation station at Muir Beach

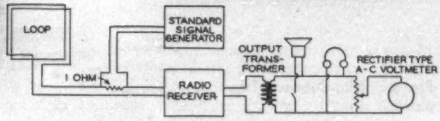


Fig. 12 (above). Arrangement of equipment used in the Muir Beach field tests

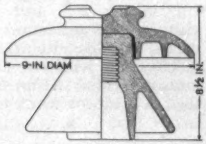


Fig. 13. Insulator used on the Muir Beach tap, 1933

Muir Beach Tap of the Alto-Bolinas Line

Location of the line and of the section used for test and observation at Muir Beach are shown in Figs. 8 and 9; Fig. 10 shows construction typical of the line. Important data are:

Voltage	11 kv, single phase, 60 cycles
Length of isolated section	3,400 ft
Number of poles	22
Pin type insulators (Fig. 13)	95
Transformer cut-outs	8
Suspension insulators in dead-end position	48
Transformers	4
High voltage transformer bushings	8

As indicated on the map, the line is near the sea coast, at a distance from it varying from 300 yards to $^1/_2$ mile. As shown in Fig. 9, the test section was a single-phase line and electrically isolated from the rest of the circuit by 2 transformers stepping the voltage down from 11,000 to 220 and back again. The purpose of this transformation was to exclude, if possible, the disturbances that otherwise might have been carried into this section by conduction from other parts of the circuit. Their efficacy in this respect was not determined.

Test Methods and Equipment Used in the Muir Beach Observations

The observation station was directly under the 11-kv line and about 20 ft west of the base of the transformer pole (see Fig. 9). The 2 11-kv wires were about 20 ft overhead. Figures 10 and 11 show the observation station.

The pick-up was a loop antenna which fed directly into a Radiola model 25 receiving set which had been completely shielded. The loop was tuned with a variable air condenser in the radio set. In series with one side of the loop was a 1-ohm resistance across which the output voltage of a standard signal generator could be impressed. The output of the receiving set fed into a speaker transformer. Across the output side of the speaker transformer was a speaker, a head-set, and a rectifier type of alternating current voltmeter. A switch in the speaker circuit was included for shutting off the speaker in making measurements of low interference levels. A potentiometer was used across the output transformer to vary the sensitivity of the output meter. A schematic diagram showing the arrangement of the equipment is shown in Fig. 12.

The Radiola model 25 is a 6-tube superheterodyne, using dry cell batteries which were incorporated within the shielded box. It has 2 tuning dials, one for tuning the loop, the other for tuning the oscillator. In addition, it has a volume control and a filament voltage control.

The standard signal generator consists essentially of 3 parts: an oscillator, an output meter, and a calibrated attenuator. The oscillator is tuned by a variable air condenser and modulated 30 per cent at 400 cycles per second. The output of the oscillator is measured by a thermal microammeter; the measured output then was attenuated by a calibrated attenuator.

The following procedure was used in making a measurement of the radio influence level: The radio set was tuned to the disturbance and the volume control adjusted to give a convenient deflection on the output voltmeter, the loop antenna being turned for maximum pick-up. The loop antenna then was rotated about 90 deg to zero pick-up. The signal

generator then was turned on and tuned to the frequency of the radio set. The output of the signal generator was adjusted to give the same deflection of the output meter as was caused by the radio disturbance, and the output and attenuation factor of the signal generator was recorded.

When the foregoing procedure had been completed, the microvolts induced in the loop antenna by the radio disturbance were equal to the microvolts inserted in the loop circuit by the signal generator, modulated 30 per cent at 400 cycles per second. The 1-ohm resistance in the loop circuit, across which the output voltage of the signal generator was applied, gave an additional attenuation factor of 10 for the signal generator output which was duly considered in the computations.

Fig. 14. Oscillogram of power line radio disturbance at Muir Beach as recorded at the output of the radio receiver

Fig. 15. 60-cycle timing wave for Figs. 14, 16, and 17

Figs. 16 and 17. Oscillograms of output of radio receiver obtained in the laboratory with coated glass surface and rounded inner electrode; 2,500 volts applied

Lower oscillogram (Fig. 17) taken with half-wave rectified voltage; inner electrode positive

When the oscillograms were made in the field, the output transformer of the radio set was replaced by a different output transformer which matched the impedance of the output of the radio set to the input impedance of the oscillograph. The oscillograph used was an "Osiso." Panchromatic motion picture film was used in the camera, which was driven by a synchronous motor through a belt.

Analysis of Substances Found on Surfaces of Muir Beach Insulators

Selected insulators carefully were removed from the pole top by a lineman who handled the insulators with a clean cloth in order to avoid contamination from handling. An insulator was placed in a large thoroughly clean, enameled pan, and washed with distilled water, using a clean test tube brush for scrubbing the surface. The water used in washing the insulator had been tested previously for chloride. Two insulators were washed for each sample. Three samples collected on October 24, 1933 were tested first.

A large amount of insoluble material was found on the insulator surfaces. Each wash water sample was filtered carefully through weighed filter papers. The total amount of insoluble material per sample was determined by weighing the dried filter paper and its contents. The filter paper then was ignited and the combustible material, which was essentially organic matter, was burned out of the sample. The residue, consisting of inorganic or uncombustible material, was weighed.

The filtered wash water was analyzed quantitatively for chloride and magnesium. The chloride content was determined volumetrically using silver nitrate of known concentration and dichlorofluorescein indicator. A second method, used as a check,

Fig. 18. Oscillogram of output of radio receiver obtained in the laboratory with clean glass surface and sharp-edge inner electrode; 7,000 volts applied

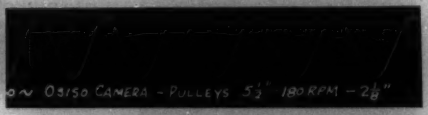


Fig. 19. 60-cycle timing wave for Figs. 18 and 20

Fig. 20. Oscillogram of power line radio disturbance (output of radio receiver) at a point 10 miles from Muir Beach

consisted of adding excess silver nitrate and back-titrating with potassium thiocyanate using ferric alum as an indicator. The magnesium content was determined volumetrically using the 8-hydroxquinoline method.

The total insoluble material per insulator was found to be 0.41 g of which 0.07 g was organic matter and 0.34 g was inorganic. The chloride content per insulator was about 0.011 g and the magnesium content was found to be about 0.0024 g per insulator.

A second set of samples, collected March 17, 1934, was found to contain 0.0107 g of chloride per insulator and 0.0022 g of magnesium. The amount of insoluble material was not determined.

Discussion of Results

Laboratory and field tests seem to demonstrate conclusively that because of the heavy leakage current a coating of hygroscopic material on the surface of an insulator promotes, such a coating can cause an electrical breakdown at overstressed terminal electrodes at a voltage very much lower than that at which it would occur if this coating were not present.

On the Muir Beach insulators the hygroscopic material was magnesium chloride. Analysis of the deposit showed a ratio of magnesium to chloride ion of 4 times that found in sea water, indicating a preferential tendency for the magnesium chloride to stick to the insulator surface. The most plausible explanation is that other salts, like sodium chloride, can dry out and blow away, whereas magnesium chloride, which never completely dries out, will remain adherent. It is possible also that the electric field and space charges play an important part in causing the magnesium chloride to stick.

Oscillograms were taken at all 5 frequencies at which radio influence was observed at Muir Beach; they are so nearly alike that only one, Fig. 14, is presented. Direction of time in Fig. 14 is opposite to that in all of the other oscillograms. The 60-cycle

Fig. 21. Oscillograms obtained in the laboratory for clean glass surface and sharp-edge inner electrode; 5,800 volts applied

oscillograms establish time intervals. In only the oscillograms of Figs. 21 and 22 were 60-cycle wave forms taken simultaneously with those of the audio-requency output of the radio set.

That the radio effect established in the laboratory and that measured in the field were ascribable to the same cause would seem to be established by the humidity-intensity relationship and by the marked similarity of the oscillograms shown in Figs. 14, 16, and 17.

Breakdown, when it occurs, takes place with equal suddenness, whether the insulator surface be coated or not; the only effect of the coating is to make it occur at a lower voltage. This is indicated by the similarity of the audio-frequency output in the oscillograms of Figs. 18 and 22. Figure 18 is for sharp-edged inner electrode on clean glass with 7,000 volts applied; Fig. 22 for rounded inner electrode on coated glass with 2,500 volts applied. The polarity effect is marked. Tests with a kenotron and half wave rectification indicate that the pronounced breakdown shown in Fig. 22 occurs when the inner electrode is positive.

Leakage current with coated plate is shown in Fig. 22, while Fig. 21 shows the charging current with a clean plate. In both cases the current rush at breakdown is so small as generally not to be recorded; this means that it must occur with extreme suddenness. The current recorded in Fig. 21 was of the order of one milliampere and required an element of maximum sensitivity, as did Fig. 22.

The oscillogram of Fig. 20 was taken under the Alto-Bolinas line about 10 miles from Muir Beach, on

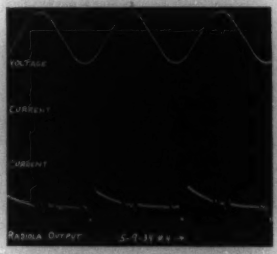


Fig. 22. Oscillograms obtained in the laboratory or coated glass surface and rounded inner electrode; 2,500 volts applied

May 10, 1934. It is quite different from the Muir Beach oscillograms of which No. 7 is typical, but similar to what the radio set output of Fig. 21 would have been if amplified. Since Fig. 21 gives the breakdown over a clean surface, the inference is that the disturbance recorded in Fig. 20 was caused by a cracked insulator. The Muir Beach insulators were all new, whereas only a short span length from where the oscillogram of Fig. 20 was taken were suspension insulators known to be more than 20 years old.

Testimony of operating men and a survey of power line radio effects covering half the state of California and circuits at all voltages from 11 to 220 kv, indicate that dirt, soluble salts, and humidity are among the principal factors causing power line radio influence in this territory.

Corona into the air seems to cause little disturbance. The breakdown is gradual, the rate of energy transfer slow, and there is no sudden charge or discharge as of a capacitor.

As to remedy, one, long known and expensive, is to keep insulators clean. Some of the protected or low capacity types of insulators recently brought on the market may be of value.

The Insulator String

A series of tests on suspension insulators for power transmission lines is described in this paper, and results are given which should be of interest to design engineers. The tests made included long-time fatigue tests, the distribution of voltage over the insulator string, and the flashover voltage when some of the units are electrically defective.

By
R. W. SORENSEN
FELLOW A.I.E.E.
Calif. Institute of Technology, Pasadena

THE insulator string as used on power transmission lines has been chosen for discussion because any progress made in standardizing the insulator unit itself, the number of units per string for any given voltage, and the supplementary appurtenances used in connection with them on transmission lines will be of value to engineers responsible for the design of such lines.

As an example of the need for some agreement on these points, consider a 230-kv transmission line, several of which have been built and operated for a number of years. Apparently agreement is found on one point only; namely, suspension insulators will be used. Also, it is found that the 10-in. insulator with a distance spacing along the string of $5^3/_4$ in. is the popular unit.

With this discussion limited to the insulator string and the units which comprise it, the features which determine the selection of the unit will first be considered. A.I.E.E. Standards No. 41 prescribe certain tests which enable the determination of the relative ability of insulators to render service. The tests prescribed, however, cannot tell the whole story, because such factors as the relation between short time mechanical loading tests and long time mechanical loading service, the number of units per string and the desirable distance spacing per unit along the string do not come within the scope of these rules.

This paper presents the results of some long-time fatigue tests on 10-in. insulators, and tests showing the voltage distribution and the flashover voltage for insulator strings made up of these units when there are electrically defective units in the string.

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. Pacific Coast convention Salt Lake City, Utah, Sept. 3–7, 1934. Manuscript submitted June 11, 1934; released for publication June 25, 1934. *Not published in pamphlet form.*

Inconsistencies Shown in Practice

An examination of the design data for various 230-kv transmission lines which have been built discloses the fact that insulator strings varying from 11 units per string to 18 units per string with conductor spacing varying from 17 ft 6 in. between conductors to 28 ft between conductors, are used. With full allowance made for all the variations in operating conditions, if 11 and 12 insulator units per string and 17 ft 6 in. spacing are satisfactory, as seems to be the case, on the original Big Creek lines, one naturally is somewhat puzzled to understand why other lines need 18 units per string with the consequent large spacing between conductors and the heavier towers required for strings of such length.

Apparatus for Long-Time Fatigue Tests

The long-time fatigue tests were made with the apparatus shown in Fig. 1. (For a description of the apparatus, see "Insulator Research," by R. J. C. Wood, N.E.L.A. *Proc.*, v. 83, 1926, p. 963–8.)

The apparatus is so constructed that one set of weights loads 2 strings, thus making the loading of one string of a pair dependent upon that of the other. The design is such that the 2 strings have different loading; hence, when the string with the greater pull is adjusted to give a certain rate of failure on the units, the rate of failure on the units of the other string will be lower. This is a good arrangement in that it furnishes a check regarding the tension to be used to get a satisfactory rate of failure.

Four strings of 20 units each can be set up in the apparatus at one time and each of the strings, for the tests being described, comprises 5 groups of insulators, each group consisting of 4 identical units. At the start of the test 16 units were selected at random from samples submitted by each manufacturer, these 16 units being divided into 4 groups of 4 units each, one of the groups being placed in each of the test strings. The weights at the end of the lever arms were then adjusted to give the tensions shown in the load-time test graphs of Figs. 2–5. These figures show the load in pounds on the string and number of days the load was applied to the particular string which the figure represents, and the time of failure for each of the units. It is intended to continue the test until all the insulators, 16 of each make, are tested to failure, either electrical or mechanical.

Definitions of Failure

The term electrical failure as applied to these tests is used to designate the fact that the insulator will no longer stand a flashover test, but breaks down by puncture when voltage is applied. A flashover voltage test was applied to every unit at the start of the test and whenever any change was made in the

string. Also the electrical integrity of every unit on the test was determined at such intervals as seemed desirable by the application of sufficient voltage to cause flashover. Thus, while the voltage was not applied continuously, it was applied at least once each day and at times when the rate of failures was high, the flashover test was applied several times per day.

The term mechanical failure means a failure of the insulator such as would drop the line conductor. All the mechanical failures did not involve electrical failure because in some cases the cap pulled off the porcelain or the pin pulled out without causing a fracture through the body of the insulator.

Replacement of Insulators on Test

Whenever an insulator failed electrically or mechanically it was replaced by a new unit and the test continued. This plan, of course, made it necessary to unload and reload again the remaining units of the string at each failure, a condition which may have shortened the life of some of the units of the string as compared to the life these same units would have had under a steady load. This feature, however, should not lessen the value of the

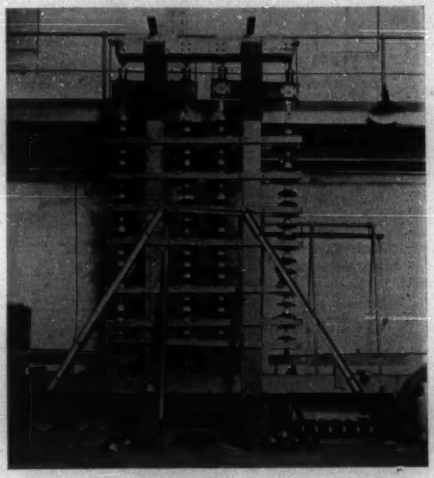


Fig. 1. Apparatus used in the long-time fatigue tests on suspension insulators

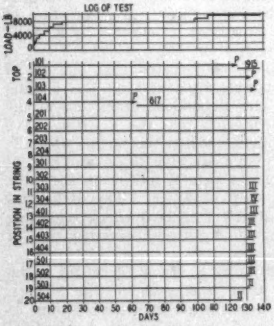


Fig. 2. Results of tests on string I

Numbers on horizontal lines identify the insulator unit

Arrows at end of lines show time of insulator failure

Dots show immediate failure when load was applied

P—Pin pulled
C—Cap pulled
S—Porcelain shear

Roman numerals show string to and from which insulator was transferred

Figs. 2–5. Long-time fatigue tests on insulators, showing load-time curves and time of failure of each unit of the insulator string

Length of line shows life of unit; *e. g.*, unit 101on at beginning failed on 125th day; unit 915 on at 125th day, still good at end of record

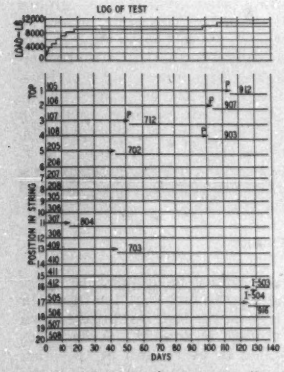


Fig. 3. Results of tests on string II

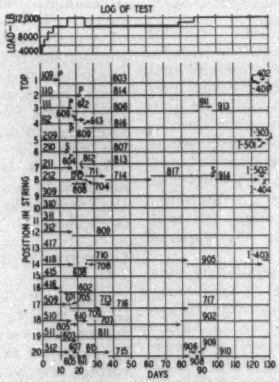


Fig. 4. Results of tests on string III

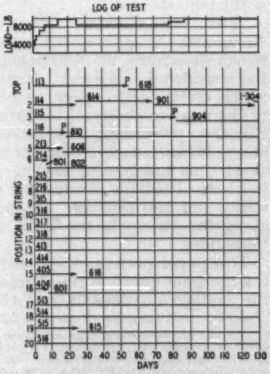


Fig. 5. Results of tests on string IV

tests because all units were subject so far as possible to identical conditions and in actual use on the line insulators are certainly subject to changes in load, though the changes are, of course, of lesser range. At all times the loading and unloading was done

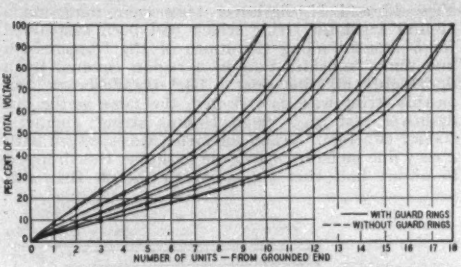


Fig. 6. Curves of voltage distribution on suspension insulator strings made up entirely of good units

slowly and great care was taken to avoid sudden shock to the units.

The apparatus is provided with dash pots to avoid shock when a unit in a string breaks.

Results of Fatigue Tests

In starting the tests, as shown by Figs. 2 to 5, small loads were applied to detect any weak units or damaged units and to provide opportunity for

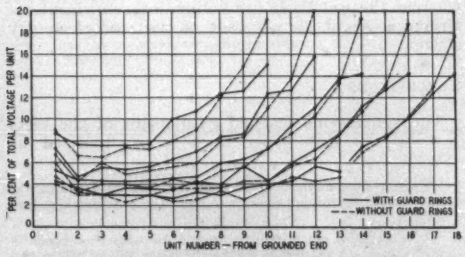


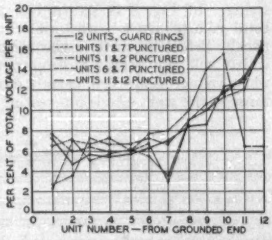
Fig. 7. Curves of voltage distribution on suspension insulator strings, using same data as in Fig. 6, but indicating the percentage of total voltage across each unit

perfecting the technique of testing before any failures could occur. It will be noted that the lowest tension at which any mechanical failure occurred was 8,000 lb and that there were several such failures as time went on at from 8,000 to 10,000 lb load, a condition of considerable concern to engineers responsible for lines located in places where sleet and wind loads approach these values.

There were also a few electrical failures on insulators at the lower mechanical load values, but these showed a greater division among the several lots tested and therefore may properly be charged to the inherent difficulty of obtaining a uniformity of product rather than to methods of assembly, the particular kind of material used in the insulator, or to the insulator design. (See "Testing Insulators to Assure Continuous Service" by R. W. Sorensen, *Elec. Wld.*, v. 70, 1917, p. 426–8.) Thus it may be said that while great progress has been made in the manufacture of porcelain, the material used most for insulators both as to maximum quality and uniformity, there still seems room for the development of technique in manufacture or perhaps change to materials yet to be found which will enable one to make a more uniform insulator.

There was only one mechanical failure of any porcelain insulator with caps and pins attached by

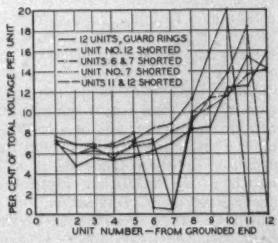
Fig. 8. Curves of voltage distribution across suspension insulator strings when there are electrically defective units in the string, drawn on the same basis as Fig. 7



cement. In this instance the cap pulled off the porcelain, a type of failure which must have been due to poor workmanship in applying the cement.

All the insulators used for these tests were specified as insulators capable of standing a pull of 15,000 lb or more on the short-time mechanical-electrical test. It is interesting to note that the life of those units which were rated for loads somewhat higher than 15,000 lb for the mechanical-electrical test did not show on the long-time test any great ad-

Fig. 9. Curves of voltage distribution across suspension insulator strings similar to those of Fig. 8, except each defective unit is shorted out



vantage over the others. The units tested which had the caps and pins attached to the insulating material by means of metal alloy rather than Portland cement did not give as good performance on the long time test as did the cemented units, and there

is some indication that on the long-time tests this metal tends to flow beyond the desired point of evening up the stress and thus causes a weakening of the insulator.

Distribution of Voltage Over the String

In addition to the mechanical tests on the insulator units, the study forming the basis of this paper includes an analysis of the distribution of voltage over the various units of the insulator string, particularly for strings in which there are damaged units.

Results of a few of the typical arrangements tested, are shown in Figs. 6 to 9. In Fig. 6 are shown distribution curves with and without guard rings for insulator strings made up entirely of good units. In Fig. 7 are shown curves using the same data but drawn in such a way as to show the percentage of total voltage across each unit of the string. In Fig. 8 is shown the percentage of the total voltage across each unit when there are electrically defective units in the string; that is, units which will not stand flashover voltage but will, when voltage is applied, permit current to discharge through the unit. It is interesting to note that the

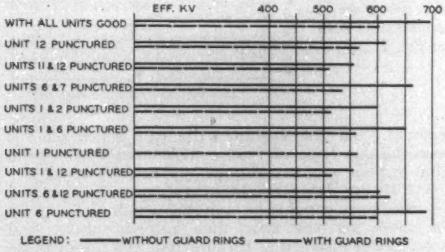


Fig. 10. Flashover voltages of 12-unit suspension insulator strings containing punctured units

voltage distribution is not badly disturbed by this condition. In Fig. 9 are shown curves similar to those of Fig. 8 for units shorted out by connecting the cap and pin of each defective unit together by a wire.

These tests were made on the hypothesis that from time to time during the operation of any transmission line there will be defective units in some of the insulator strings, thus making it highly desirable—in the consideration of lines which will not have the maximum factors of safety which one can purchase, but rather the minimum factor which will serve the purpose of the line—to know quite definitely the effect of defective units in different positions in the string. Not more than 2 defective units in each string were considered, because good practice in operation should permit the detection and replacement of defective units before more than 2 units per string have become defective.

Flashover Voltages

Flashover voltages under conditions noted for insulator strings in which some of the units are defective are shown in Figs. 10 and 11.

In addition to the flashover voltages shown by Figs. 10 and 11, flashover tests were made on a 15-unit insulator string which had been suspended for 5 months along the route of the transmission line under consideration in a region covered by a dry highly alkaline dust. The dry flashover test on this string was, as expected, the same as the dry flashover test of a clean 15-unit string; namely, 800 kv effective. When the string was sprayed with a very fine moisture spray the flashover test dropped to about half this value, which means that this

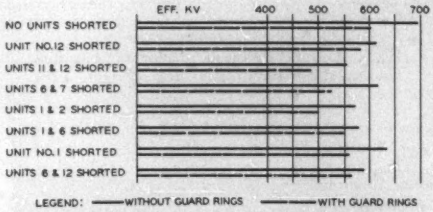


Fig. 11. Flashover voltages of 12-unit suspension insulator strings with certain units short-circuited

alkali dust wet with a fine spray to simulate a fog reduces the flashover voltage to 50 per cent of the dry flashover voltage for clean insulator strings; whereas the wet flashover voltage of clean insulator strings is about 70 per cent of that for clean dry strings.

Conclusions

The conclusions reached as a result of the tests described in this paper may be summarized as follows:

1. The short-time mechanical-electrical test does not determine the ability of the suspension insulators to maintain long-time high load stresses.

2. There has been much improvement in the suspension insulator during the past 15 years, but during the latter half of this period of improvement there has been little change except the addition of one make of glass insulator which ranks with the better ones of the group tested.

3. On the whole these tests indicate an apparent superiority of cement over metal as a means of attaching the hardware to the insulator.

4. Long-time mechanical tests, while somewhat troublesome, appear to have value and are recommended in making insulator selections.

5. One or 2 defective insulators in a 12-unit string do not change the voltage distribution along the string enough to overstress seriously any unit in the string.

6. Flashover tests show that defective units in an insulator string have little effect on flashover values unless the defective units are at the end of the string, in which case there is, of course, the expected reduction in equivalent string length.

News
Of Institute and Related Activities

50th Annual Summer Convention Held at Hot Springs, Va.

COMPLETING its first half century of technical and professional service, the American Institute of Electrical Engineers held its 50th annual summer convention during the week of June 25 at the Homestead Hotel, Hot Springs, Va. With but minor deviations, the program as previously published in ELECTRICAL ENGINEERING was followed out. In addition to the annual conference, the various technical sessions, and the regular meeting of the board of directors, numerous technical and other committee and subcommittee groups took advantage of the opportunity to hold informal meetings.

A feature of the convention, incident to the official recognition of the 50th anniversary, was the attendance of 9 past presidents of the Institute in addition to the president and president-elect, Charles F. Scott, 1902–03; Bion J. Arnold, 1903–04; Lewis B. Stillwell, 1909–10; Dugald C. Jackson, 1910–11; Paul M. Lincoln, 1914–15; Comfort A. Adams, 1918–19; Arthur W. Berresford, 1920–21; William McClellan, 1921–22; and H. P. Charlesworth, 1932–33. This is the fourth time in 14 years that the summer convention has been held in the South (District No. 4).

Annual Business Meeting

The opening session of the Institute's 50th annual summer convention was held Monday morning, and consisted of the annual business meeting, followed immediately by a 50th anniversary meeting. The annual business meeting was called to order by President J. B. Whitehead, who first introduced Prof. W. S. Rodman, chairman of the summer convention committee, who welcomed the members and guests at the convention.

The first item of business was the presentation by National Secretary H. H. Henline of a brief outline of the annual report of the board of directors, which indicates in general, improved conditions over those existent a year ago. The good work of the president and several of the more important committees was referred to, and the fact that the reserve capital fund upon which the Institute has depended for emergency has increased in value since a year ago was pointed out. (This report of the board of directors was published in full in ELECTRICAL ENGINEERING for July 1934, p. 1095–1107.)

REPORT OF THE COMMITTEE OF TELLERS

The report of the committee of tellers on the election of officers of the Institute was presented, and in accordance therewith President Whitehead declared the election of the following members, taking office August 1, 1934:

President: J. Allen Johnson, chief electrical engineer, Buffalo, Niagara & Eastern Power Corp., Buffalo, N. Y.

Vice Presidents:

W. H. Timbie, professor of electrical engineering and industrial practice, Massachusetts Institute of Technology, Cambridge, Mass.

R. H. Tapscott, vice president, New York Edison Company, New York, N. Y.

G. G. Post, vice president in charge of power, Milwaukee Electric Railway & Light Company, Milwaukee, Wis.

F. J. Meyer, vice president in charge of operation, Oklahoma Gas & Power Company, Oklahoma City, Okla.

F. O. McMillan, research professor of electrical engineering, Oregon State College, Corvallis, Ore.

Directors:

F. Malcolm Farmer, vice president and chief engineer, Electrical Testing Laboratories, New York, N. Y.

N. E. Funk, vice president in charge of engineering, Philadelphia Electric Company, Philadelphia, Pa.

H. B. Gear, assistant to vice president, Commonwealth Edison Company, Chicago, Ill.

National Treasurer:

W. I. Slichter, professor of electrical engineering, Columbia University, New York, N. Y.

The board of directors for the next administrative year, beginning August 1, 1934, will consist of these newly elected officers, together with the following holdover officers: J. B. Whitehead (retiring president), Baltimore, Md.; H. P. Charlesworth, New York, N. Y.; R. B. Bonney, Denver, Colo.; F. M. Craft, Atlanta, Ga.; A. H. Hull, Toronto, Ont.; R. W. Sorensen, Pasadena, Calif.; A. M. Wilson, Cincinnati, Ohio; L. W. Chubb, East Pittsburgh, Pa.; B. D. Hull, Dallas, Tex.; P. B.

1934 Pacific Coast Convention Headquarters

TECHNICAL sessions and many of the entertainment features which will be a part of the Institute's 1934 Pacific Coast Convention, Sept. 3–7, will be held in the Hotel Utah, at Salt Lake City. Details of the technical sessions and an outline of some of the entertainment features were given in ELECTRICAL ENGINEERING for July 1934, p. 1128–9. A brief summary is given in an accompanying item in the present issue.

Among those prominent at the Institute's recent 50th annual summer convention, held at Hot Springs, Va., June 25–29, 1934, were those shown here. From left to right: W. S. Rodman, chairman of the general convention committee and dean of engineering at the University of Virginia, University; G. A. Kositzky, Cleveland, Ohio, and H. W. Eales, Chicago, Ill., who were respectively winner and runner-up in the Mershon golf trophy play; F. M. Craft, Atlanta, Ga., winner of the Lee golf trophy; R. B. Stewart, Washington, D. C., and E. F. Lopez, Mexico City, respectively runner-up and winner (second time) of the Mershon tennis trophy

Juhnke, Chicago, Ill.; G. A. Kositzky, Cleveland, Ohio; Everett S. Lee, Schenectady, N. Y.; A. H. Lovell, Ann Arbor, Mich.; L. W. W. Morrow, New York, N. Y.; A. C. Stevens, Schenectady, N. Y.; H. R. Woodrow, Brooklyn, N. Y.

Introduction of the President-Elect

President Whitehead then presented the president's badge to President-Elect J. Allen Johnson. In his brief address of response, the incoming president stated in part ". . . perhaps you would like to know how it feels to be elected president of the American Institute. I think the first feeling is one of surprise that your fellow engineers have considered your accomplishments or services of sufficient value to be recognized, and then I would say there comes a feeling of pride and pleasure and warmth of spirit, and then that feeling is followed by a feeling of humility, wondering if you have the ability to meet the requirements of the job, and then that is followed by a spirit of resolution to do the best you can.

"Then I got to thinking, well, a resolution for what? Now of course, a resolution to carry on the spirit and the traditions of the Institute, but is that enough? And thinking it over, it seemed to me a little bit more than that was required, because we make progress as we prove all things and hold fast to that which is good, or as James Russell Lowell put it in his poem, 'The Crisis':

'New occasions teach new duties,
Time makes ancient good uncouth;
He must onward still, and upward
Who would keep abreast of truth.'

So I feel that in addition to keeping abreast or keeping up with the old traditions, we must have the courage in this changing world in which we find ourselves to try new things and find new goods and hold fast to those as well as to the old goods. And so it is my hope that I and we all of us in the coming year may find the courage or may not be lacking in the courage to try new things and hold fast to those which may prove to be new goods."

Institute Prizes Awarded

The report of the committee on award of Institute prizes, as published in Electrical Engineering for June 1934, p. 1026, and in the present issue, p. 1234 was read by R. N. Conwell, chairman of the committee on award of Institute prizes, after which President Whitehead presented the certificates of award to those winners who were present.

Presidential Address

Another feature of the annual meeting was the presentation of the annual presidential address delivered by President Whitehead, wherein he outlined his most striking impressions of Institute activities which he had gained during his term as president. Essentially the full text of President Whitehead's address appears in this issue, p. 1143–5.

Lamme Medal for 1933

An impressive event on program of the annual business meeting was the formal presentation of the Institute's Lamme Gold Medal to Dr. L. B. Stillwell (A'93, M'92, F'12, member for life, and past president) consulting engineer of New York, N. Y. This medal was awarded him "for his distinguished career in connection with the design, installation, and operation of electrical machinery and equipment." Brief biographical sketches of Doctor Stillwell are given in Electrical Engineering for March 1934, p. 503–4, and May 1934, p. 798.

Other Awards of the Lamme Medal

Previous awards of the A.I.E.E. Lamme Medal have been made to A. B. Field (A'03, F'13) consulting engineer, Manchester, England, 1928; R. E. Hellmund (A'05, F'13) chief engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., 1929; W. J. Foster (A'07, F'16) consulting engineer, retired, General Electric Company, Schenectady, N. Y., 1930; Guiseppe Faccioli (A'04, F'12) deceased, January 13, 1934, formerly associate manager of the Pittsfield (Mass.) Works of the General Electric Company, 1931; and Edward Weston (A'84, M'84, HM'33, member for life, and past president) chairman of the board, Weston Electrical Instrument Corporation, Newark, N. J.

The Institute's Lamme Medal was established by provision of the will of Benjamin Garver Lamme (deceased July 8, 1924)

Future AIEE Meetings

Pacific Coast Convention,
Salt Lake City, Utah, Sept. 3–7, 1934

Winter Convention,
New York, N. Y., Jan. 22–25, 1935

South West District Meeting,
Oklahoma City, Okla., Apr. 24–26, 1935

Summer Convention
Ithaca, N. Y., June 24–28, 1935

Pacific Coast Convention
Los Angeles vicinity, Fall 1935

Great Lakes District Meeting
Indianapolis-Lafayette Section territory (Date to be determined)

for the encouragement and recognition of "meritorious achievement in the development of electrical apparatus or machinery." By Mr. Lamme's will, 2 other similar bequests were made, one to Ohio State University, and one to the Society for the Promotion of Engineering Education. The Lamme Medal of Ohio State University, to be awarded a graduate of one of the technical departments for meritorious achievement in engineering of the technical arts was presented for 1934 to L. W. Chubb (A'09, F'21, and director) director of research laboratories, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. The 7th Lamme Medal of the S.P.E.E. was awarded to Prof. E. R. Maurer, professor of mechanics at the University of Wisconsin, during the annual meeting of the society in June 1934.

Medal Presented by D. C. Jackson

At the annual meeting at Hot Springs, Prof. P. M. Lincoln told of Mr. Lamme's interest in the education of engineers and mentioned some of his efforts to further the development of electrical engineering. In this connection, he spoke of the work in which Mr. Lamme and Doctor Stillwell coöperated when the power plant at Niagara Falls was designed in 1893. He pointed out that the adoption for that plant of alternating current, which was sponsored by both Mr. Lamme and Doctor Stillwell, has had a tremendous influence on the subsequent development of the electrical industry.

Prof. D. C. Jackson then outlined the career and the distinguished achievements of the medalist, Dr. L. B. Stillwell. In addition to describing many of the actual accomplishments of Doctor Stillwell, Doctor Jackson spoke of many of the mental qualities possessed by the medalist which made possible his contribution to electrical engineering design, to social welfare, and to education, saying, in part "Imagination coupled with optimism arouses visions which are pictured as capable of actual embodiment, but the pessimism produced by a restraining influence of historical hindsight prevents an over-optimism which might lead to a crash. Curiosity, interest, the intellectual joy of achievement, associate equally with all imaginative productions; and imagination, held definitely to face realities as a plane of origin, is a major tool of engineers. It seemed to me then (Editor's Note: in 1910, while both were officers of the Institute), and I continue of the conviction, that Stillwell held these qualities in high degree, and possessed this tool which he used well. His long-time successful practice as a consulting engineer proves the case."

Doctor Stillwell Responds

In his speech of response, Doctor Stillwell emphasized his deep appreciation of the action of the Institute in conferring the 1933 Lamme Medal upon him, pointing out that to the professional man, commendation of his work by the fellow members of his profession is perhaps his highest reward. He then spoke of "system engineering" referring to the development of electric power systems. It was in this work that his greatest activity was concerned, rather than in the detailed design of electrical machinery. Doctor Stillwell outlined one of the great periods of change in system engineering of a-c work in this country, pointing out that in the 10 years or so following the founding of the Institute in 1884, a tremendous number of new developments in electrical projects were brought about by energetic pioneers.

Doctor Stillwell closed his speech with a plea for the support of the magnificent work which has been carried out by members of the Institute during the last 50 years in the development of high voltage lines covering the entire country, and making available large economies and facilities for providing for emergency conditions. He pointed out that the general public's discontent with economic conditions accentuated by resentment toward some of the organizers of holding companies, has caused our state governments and even the federal government to open the door to the construction of municipal power plants. He pointed out that such a policy weakens the economic stability of the great public utility companies of today, and stated his opinion that the problem should be studied very carefully, but very promptly, and that the whole engineering profession should take a stand for the conclusions reached.

Celebration of 50th Anniversary

In commemoration of the founding of the Institute in 1884, a "50th anniversary meeting" was held on Monday morning, June 25, during the summer convention at Hot Springs, Va. At this meeting, which followed the Institute's annual business meeting, President Whitehead referred to the 50th anniversary issue of Electrical Engineering (May 1934) and of the various anniversary meetings which have been held throughout the country by the local Sections.

Prof. D. C. Jackson then spoke of the 2 senior living past presidents of the Institute, Dr. Edward Weston and Dr. Elihu Thomson, who were among the very great creators in the electrical industry that are left with us among the older pioneers. From Professor Thomson, with whom Doctor Jackson was recently in contact, a message was conveyed to this 50th anniversary meeting wherein Professor Thomson stated that he was exceedingly regretful that he could not attend as one of the past presidents who were gathered there but that he extended his salutations and wished to express his interest in the Institute and his wishes for its continued success through another jubilee.

Two addresses by prominent members of the Institute featured the anniversary meeting. The first of these, by Dr. W. E. Wickenden, president of Case School of Applied Science, Cleveland, Ohio, was on the subject of "Toward the Making of a Profession." Doctor Wickenden first outlined the many items which comprise the obligations of a profession and the reasons for the growth of professions, and discussed these points with particular reference to the Institute. Essentially full text of the address is given in this issue of Electrical Engineering p. 1143–5.

Doctor McClellan's Address

The other principal address on the 50th anniversary program was that of Dr. William McClellan, past president of the Institute (1921–22). Doctor McClellan, in his address, outlined briefly the principal developments in electrical engineering prior to the founding of the Institute in 1884, and then discussed the development of electrical engineering and some of the personalities involved during the next several years.

Doctor McClellan pointed out that for a "profession" to be successful, it was necessary not only that the members be motivated by ideals of service, but that they must have a unity of action. Using examples taken from the legal and medical profession, he pointed out the advantages of having all engineers, whether civil, mining, mechanical, or electrical, operate through one society, such as, for example, American Engineering Council. He stated his belief that the world will never recognize the engineering profession as on a par with other professions until such unity of thought and purpose is introduced and made apparent to all. In developing this idea, he suggested that graduates of engineering schools should all be given the degree of bachelor of engineering, without designating any particular branch of engineering at that

Results—

Total number of applications received for A.I.E.E. membership during:

May 1933—26	May 1934—42
June 1933—26	June 1934—50

The continued coördination of membership activities by the National and Section membership committees through the suggestion of names of those considered worthy to be asked to join the Institute will augment these results.

Chairman National Membership Committee

time. Doctor McClellan closed his address with a plea for the creation of a genuine engineering profession.

At the conclusion of this inspiring meeting, a radiogram conveying heartiest greetings and congratulations on the occasion of the Institute's 50th anniversary, transmitted by the South African Institute of Electrical Engineers, was read.

Other Features

Technical Sessions

All technical sessions at the convention were held during the mornings, and were very well attended. In all, 7 technical sessions had been aranged. At these sessions some 30 papers, most of them on technical subjects, were presented and discussed.

All of the papers presented at the convention appear in the June 1934 issue of Electrical Engineering, except 3 which had been previously published in Electrical Engineering. Discussions of the papers are scheduled for publication in subsequent issues.

Attendance

Although the official registration of 351 was only a little more than a third of the registrations prevailing in 1933 and in 1932, the level was just about equal to the average of previous conventions held in the South. An analysis of the attendance at Hot Springs is given in Table I accompanying, and a comparison of summer convention attendances over a period of 15 years is given in Table II.

Entertainment

In view of the fact that a rather complete range of facilities was available at the Homestead Hotel, and its subsidiary, The Cascades Inn, practically all entertainment activities centered there. A motor trip to the Greenbrier Hotel at White Sulphur Springs, W. Va., some 47 miles over the mountains from Hot Springs, was the only formally scheduled trip. Quite a large group enjoyed the trip and the refreshments served at the Greenbrier's casino. Monday evening was featured by the president's reception; Tuesday evening by an informal get-together banquet punctuated by impromptu entertainment; and Wednesday evening was the occasion of the annual convention banquet and its generous program of entertainment.

In the women's putting contest, played Tuesday morning by a large number of entrants including several non-golfers, Mrs. John W. Latham, Charlestown, W. Va., won on a play-off with a net score of 37; runner-up was Mrs. R. W. Harris, of New York, whose net score was 40. Other prize winners included Mrs. A. H. Lovell, Ann Arbor, Mich.; Mrs. R. E. Hellmund, Pittsburgh, Pa.; and Mrs. G. L. Weller, Washington, D. C. At the women's bridge-luncheon held Tuesday, the list of prize winners included Mrs. E. B. Meyer, South Orange, N. J.; Mrs. H. A. Holmes, Fairmont, W. Va.; Mrs. L. F. Hickernell, Hastings-on-Hudson, N. Y.; Mrs. W. W. Ballew, Birmingham, Ala.; Mrs. C. L. Dawes, Cambridge, Mass.; Mrs. E. J. Rommel, Toledo, Ohio; Mrs. L. G. Smith, Baltimore, Md.; and Mrs. W. H. Timbie, Cambridge, Mass.

Table II—Summer Convention Attendance During Recent Years

1934	Hot Springs, Va.	* (4)	351
1933	Chicago, Ill.	(5)	968
1932	Cleveland, Ohio	(2)	1,022
1931	Asheville, N. C.	(4)	525
1930	Toronto, Ont., Canada	(10)	1,110
1929	Swampscott, Mass.	(1)	1,000
1928	Denver, Colo.	(6)	500
1927	Detroit, Mich.	(5)	1,200
1926	White Sulphur Spgs., W. Va.	(4)	350
1925	Saratoga Spgs., N. Y.	(1)	900
1924	Chicago, Ill.	(5)	750
1923	Swampscott, Mass.	(1)	1,616
1922	Niagara Falls, N. Y.	(1)	950
1921	Salt Lake City, Utah	(9)	426
1920	White Sulphur Spgs., W. Va.	(4)	314

* District Numbers in parentheses.

Skeet

Skeet, a new and intriguing form of trap-shooting, proved attractive to several who were handy with their shot guns, and others who thought they should be. In the officially recognized tournament, E. P. Coles of Charlotte, N. C., won first honors, with C. O. Bickelhaupt, New York, N. Y., finishing as runner-up, closely followed by L. P. Ferris, New York, N. Y.

Table I—Analysis of Attendance at A.I.E.E. Summer Convention

Classification	Dist. 1	Dist. 2	Dist. 3	Dist. 4	Dist. 5	Dist. 6	Dist. 7	Dist. 8	Dist. 9	Dist. 10	Foreign	Totals
Members	47	79	51	22	26	3	9	5	5	4	1	252
Men Guests	1	8	3	2	1	0	0	0	0	0	0	15
Women Guests	12	31	21	7	10	0	2	0	1	0	0	84
TOTALS	60	118	75	31	37	3	11	5	6	4	1	351

Golf

The annual tournament and other officially recognized golfing events were played on the Cascades course, with competition spurred by the many beautiful prizes offered in addition to the Lee and the Mershon trophies. Competition also was intensified by the fact that several were playing with the hope of getting their names on one or the other of the trophies the second time.

The present Mershon trophy is the second cup donated by Past President Mershon, the first having been won permanently in 1931 by L. F. Deming of Philadelphia, Pa., as a result of his having won the right to have his name engraved upon it in 1916 and again in 1931. The trophy had withstood competition since 1912. The new trophy is competed for by match play on a handicap basis, the same as the first trophy and also is subject to permanent possession by virtue of 2 winnings by an Institute member. The 16 men having the lowest net scores in a preliminary qualifying round are privileged to play through 4 successive elimination rounds to determine the ultimate winner. The results of the Hot Springs competition were:

Winner—G. A. Kositzky, Cleveland, Ohio; score 7-5.
Runner-up—H. W. Eales, Chicago, Ill.

Mr. Kositzky, by winning the right to have his name engraved on the Mershon trophy, prevented Mr. Eales from taking permanent possession. The names now appearing on the cup are: L. R. Kieffer, Cleveland, Ohio, 1932; H. W. Eales, 1933; G. A. Kositzky, 1934.

The Lee trophy, presented by Past President Lee in 1932, is competed for annually on the basis of lowest net score for 36 holes; it, too, must be won twice by the same player for permanent possession. The results for the 36-hole medal play at Hot Springs:

Winner—F. M. Craft, Altanta, Ga. (gross score 178, handicap 36, net 142).
Runner-up—T. O. Rudd, New York, N. Y. (gross score 152, handicap 9, net 143).

Names now appearing on the Lee trophy are: C. H. Teskey, Cleveland, Ohio, 1932; G. R. Canning, Cleveland, Ohio, 1933; F. M. Craft, 1934.

Winners of prizes in special events arranged by the local sports committee were:

First low net—E. S. Atkinson, Battle Creek, Mich.; score 67.
Second low net—T. O. Rudd, New York, N. Y., 68.
Blind bogey: winner—G. A. Zehr, Niagara Falls, N. Y.; low gross—T. O. Rudd, New York, N. Y.; low net—W. A. Buchanan, Welch, W. Va.

The "tombstone" tournament aroused considerable interest. The event was opened to members and guests. Each player was assigned the number of strokes represented by the par of the course (71) plus his regularly assigned handicap; the idea being to make the greatest possible distance in the assigned number of strokes, planting his "tombstone insignia" at the point where his ball rested at the end of his final stroke. Prizes were awarded to the several players covering the greatest yardage in the number of strokes assigned as follows:

Winner—W. A. Buchanan, 95 strokes, ball finished on 19th green.
Second place, F. M. Craft, 89 strokes, ball 2.5 ft from 18th hole.
Third, T. O. Rudd, 74 strokes, ball 5 ft from 18th hole.
Low gross, J. H. Irwin, Chicago, Ill., 78.
Low net, James Nichols, Wauwatosa, Wis., score 73.

District team competition, on the basis of 36-hole medal play, was won by a team representing District No. 2 as follows:

C. G. Teskey, C. A. Kositzky, G. R. Canning, and F. Quigley, all of Cleveland, Ohio.

Tennis

With fewer entrants for the tennis tournament than for the golf tournament, the competition was not so widespread. How-

ever, a large gallery very much enjoyed the several lively sets and close scores. The Mershon trophy for tennis was presented by Past President Mershon and has been up for competition since 1927. The trophy is available to Institute members, the winner each year being recognized by having his name engraved on the cup, and receiving a photograph of it, unless it be his second winning, in which event the cup passes permanently into the winner's possession. At Hot Springs, Delegate E. F. Lopez of Mexico City, Mex., won the cup for the second time, and took it back to Mexico with him. Mr. Lopez won from R. B. Stewart of Chevey Chase, Md.; score, 6–3, 6–0, 3–6, 6–2. The winners, as the names were finally engraved upon the cup, were as follows:

1927 G. A. Swain, East Pittsburgh, Pa.
1928 P. H. Hatch, Stamford, Conn.
1929 A. J. Gowan, St. Petersburg, Fla.
1930 E. F. Lopez, Mexico City, Mex.
1931 J. K. Peek, New York, N. Y.
1932 R. A. Monroe, Pittsburgh, Pa.
1933 A. J. Krupy, Chicago, Ill.
1934 E. F. Lopez, Mexico City, Mex.

Committees

Credit for the successful arranging of the number of events comprising the 50th annual summer convention must go to the committees who were responsible for carrying out the work.

The general convention committee consisted of the following members: W. S. Rodman, *chairman;* C. A. Robinson, *vice chairman;* R. C. Bailey, *secretary;* and E. P. Coles, R. N. Conwell, F. M. Craft, S. A. Flemister, J. T. Graff, E. L. Lockwood, W. R. McCann, and I. M. Stein. The chairmen of the various subcommittees working with the general convention committee were as follows:

Hotels and Registration—E. L. Lockwood, *chairman;* H. C. Bailey, R. M. Bush, E. S. Fitz, and J. M. Wilson.
Entertainment—C. A. Robinson, *chairman;* H. A. Holmes, J. W. Latham, A. M. Rosenblatt, J. C. Smith, and C. H. Weber.
Sports—J. T. Graff, *chairman;* Cecil Gray, J. L. Harrington, J. W. Latham, and G. L. Weller.
Technical Sessions—R. N. Conwell, *chairman;* C. S. Rich, *secretary;* F. M. Craft, L. A. Doggett, S. L. Henderson, H. W. Leitch, E. J. Rutan, D. M. Simmons, and D. W. Taylor.
Finance—E. P. Coles, *chairman;* W. E. Mitchell, *vice chairman;* J. S. Miller, Jr., *treasurer;* C. I. Burkholder, N. H. Colt, F. M. Craft, Mark Eldredge, E. S. Fitz, Thomas Fuller, E. H. Ginn, J. W. Hancock, W. S. Lee, Jr., Berrier Moore, J. H. Pagent, and J. E. S. Thorpe.

1934 Lamme Medal Nominations Due Nov. 1

In fulfilment of by-law requirements, a second posting is hereby given to the necessity of all nominations for the Lamme Medal for 1934 being submitted not later than November 1, 1934. (See Electrical Engineering, June 1934, p. 1022–3.) Presentation of the 1933 Lamme Medal was made to Lewis B. Stillwell (A'92, M'92, F'12, member for life and past president), consulting engineer, New York, N. Y., at the opening session of the Institute's recent summer convention at Hot Springs, Va.

A.I.E.E. Directors Meet During Summer Convention

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at The Homestead, Hot Springs, Va., June 27, 1934, during the annual summer convention of the Institute.

Present: *President*—John B. Whitehead, Baltimore, Md. *Past President*—H. P. Charlesworth, New York, N. Y. *Vice Presidents*—R. B. Bonney, Denver, Colo.; F. M. Craft, Atlanta, Ga.; J. Allen Johnson, Buffalo, N. Y.; E. B. Meyer, Newark, N. J.; and R. W. Sorensen, Pasadena, Calif. *Directors*—L. W. Chubb, East Pittsburgh, Pa.; B. D. Hull, Dallas, Tex.; P. B. Juhnke, Chicago, Ill.; A. E. Knowlton, New York, N. Y.; G. A. Kositzky, Cleveland, Ohio; A. H. Lovell, Ann Arbor, Mich.; L. W. W. Morrow, New York, N. Y.; A. C. Stevens, Schenectady, N. Y.; R. H. Tapscott, New York, N. Y.; and H. R. Woodrow, Brooklyn, N. Y. *National treasurer*—W. I. Slichter, New York, N. Y. *National secretary*—H. H. Henline, New York, N. Y. By invitation: *Past Presidents*—Bion J. Arnold, Chicago, Ill.; A. W. Berresford, New York, N. Y.; Dugald C. Jackson, Cambridge, Mass.; Paul M. Lincoln, Ithaca, N. Y.; William McClellan, Washington, D. C.; Charles F. Scott, New Haven, Conn.; Lewis B. Stillwell, Princeton, N. J.; also *officers-elect*—F. M. Farmer, New York, N. Y.; N. E. Funk, Philadelphia, Pa.; H. B. Gear, Chicago, Ill.; F. J. Meyer, Oklahoma City, Okla.; and W. H. Timbie, Cambridge, Mass; and C. O. Bickelhaupt, New York, N. Y., an Institute representative on Coördination Committee of Engineering Societies.

Minutes of the meeting of the board of directors held May 25, 1934, were approved.

A report of a meeting of the board of examiners held June 20, 1934, was presented and approved. Upon the recommendation of the board of examiners, the following actions were taken: 2 applicants were elected and 8 were transferred to the grade of Fellow; 4 applicants were elected and 32 were transferred to the grade of Member; 102 applicants were elected to the grade of Associate; 121 Students were enrolled.

The finance committee reported disbursements for the month of June amounting to $17,939.27. Report approved.

Report was made of appointments, upon nomination of the standards committee, of representatives on committees of the American Standards Association, as follows: Edward E. Ashley, representative, M. Freund, alternate, on sectional committee on ventilation code; J. B. Russell, a representative on sectional committee on standardization of vacuum tubes for industrial purposes; W. H. Lesser, representative on the mining standardization correlating committee.

Recommendations to the board of directors adopted at the Conference of Officers, Delegates, and Members, held on June 25 and 26, at Hot Springs, Va., were presented and referred to appropriate committees for recommendation.

President-elect J. Allen Johnson was appointed a representative of the Institute on the Assembly of American Engineering Council, effective August 1, 1934, succeeding the retiring president, Dr. J. B. Whitehead.

The board adopted resolutions of appreciation of the effective services of the 1934 summer convention committee and subcommittees and of the ladies' entertainment committee in arranging for the comfort and entertainment of the members and guests in attendance at the annual summer convention, Hot Springs, Va., June 25–29, 1934.

Other matters were considered, reference to which may be found in this or future issues of Electrical Engineering.

Last Call for the Pacific Coast Convention

All is in readiness for the Pacific Coast convention, which will be held in Salt Lake City, Utah, September 3–7, 1934, with headquarters in the Hotel Utah. The general convention committee, under the chairmanship of B. C. J. Wheatlake, has arranged an excellent series of events—5 technical sessions, 2 Student sessions, with sports and ample opportunity for recreation in this scenic vacation land. With Yellowstone National Park but a night's ride from Salt Lake City, and such scenic wonders as the Grand Canyon, Zion and Bryce Canyons within the boundaries of Utah and Northern Arizona, members are offered unusual possibilities to combine a few vacation days with the convention trip. There is also a possibility of combining a trip to Boulder Dam, now at its most interesting construction stage, with the convention trip to the Utah Parks.

Technical Program

A technical program of 5 sessions—communication, management and protective devices, lightning, transmission, and selected subjects—has been scheduled with one session a day during the interval of the convention. In addition Student sessions will be held on the afternoons of Tuesday and Wednesday, September 4 and 5, respectively. The program is of broad scope, containing a number of papers by well-known western engineers, which deal with recent developments in their localities, and these have been combined with papers from the east on new developments and operating practice, which should be of particular interest to western engineers. For a more complete account of the convention and the technical program see the July issue of Electrical Engineering, p. 1128–29 and 1127. For the papers which have been previously published reference to the issue

Table I—Hotel Rates

Hotels	Rooms With Bath: Single	Rooms With Bath: Double
Hotel Utah	$2.50	$3.00–4.00
Hotel Newhouse	$2.50, 3.00, 3.50	$3.00, 3.50, 4.00
Hotel Temple Square	$2.00	$2.50

and page is given after each title on the program. The remaining papers on the program which are not so indicated are published in this issue.

HOTEL RATES AND ACCOMMODATIONS

Very reasonable rates at the headquarters hotel, the Hotel Utah, and several other recommended hotels are shown in Table I. Members should make their reservations directly by writing to the hotel of their preference.

Keep abreast of your profession and enjoy a few vacation days in this region of scenic splendor by attending the Pacific Coast convention at Salt Lake City, September 3–7.

Officers, Delegates, and Members Hold Annual Conference at Hot Springs, Va.

HELD jointly under the auspices of the Sections committee and the committee on Student Branches, the regular conference of officers, delegates, and members of the Institute, was held at Hot Springs, Va., Monday and Tuesday afternoons, June 25–26, 1934, as a part of the summer convention activities. Present at these sessions were delegates from 55 Institute sections, and counselor-delegates from 6 of the 9 districts in which committees on student activities have been organized. In addition to these formally constituted delegates, there were other officers, officers-elect, and Institute members, bringing the recorded attendance total up to 101. The principal topics under discussion at the conference were as outlined in a program previously mailed to the delegates and others:

Monday, June 25, 2:00 p.m.

1. Opening of conference; Announcements by I. Melville Stein, chairman of the sections committee.
2. Remarks by President J. B. Whitehead.
3. Remarks by President-Elect J. Allen Johnson.
4. Remarks by National Secretary H. H. Henline.
   a. Report on action on recommendations made last year.
   b. General Institute affairs.
5. Institute finances—E. B. Meyer, chairman, finance committee.
6. Division into parallel sessions.

Session A—Sections Committee Meeting—I. Melville Stein, Chairman, presiding

7. Communication from membership committee—Everett S. Lee, chairman, membership committee.
8. Section and District technical committee activities—Prof. N. S. Hibshman, Chairman Lehigh Valley Section.
9. Institute dues—J. Allen Johnson, chairman, special committee to consider dues of associates and related matters.
10. The Electrical Engineer and the Codes—J. B. Whitehead, president.
11. General discussion on improving Institute activities.

Session B—Student Branch Committee Meeting—Prof. L. A. Doggett, Chairman, presiding

12. Reading of Annual Report.
13. Student and associate member statistics.
14. Qualifications for student membership. Shall students, taking certificate courses, extension courses, or other work not equivalent to the work of a technical school of recognized standing, be admitted to the privilege of student membership? Cases of (*a*) University of Cincinnati, (*b*) Franklin Union, (*c*) University of Minnesota.

Tuesday, June 26, 2:00 p.m.

Session C—General

15. Report on Student Branch committee meeting—Prof. L. A. Doggett, chairman, student branch committee.
16. Résumé of Monday's sections committee meeting discussion—I. Melville Stein, chairman, sections committee.
17. "Engineering: A Career—A Culture"—Prof. L. A. Doggett. (A communication from the Engineers' Council for Professional Development.)
18. Continuation of discussion on improving Institute activities.
19. The coming year—President-Elect J. Allen Johnson.

Inasmuch as the Annual Report on Sections and Branch Activities was published in full in the June 1934 issue of ELECTRICAL ENGINEERING (p. 1037–9), no pamphlet copies of the report were prepared for use at the meeting, and nothing further remains to be reported here.

Opening Session

President Whitehead in his brief introductory remarks expressed pleasure at being able to attend the conference, stating that in his opinion a conference provided an excellent opportunity for better mutual acquaintance and understanding among the leaders in Institute activities and "as a most important and interesting occasion for those who are entrusted with the administrative and executive functions of the Institute to learn what the members are thinking about."

J. Allen Johnson, responding briefly to his introduction as president-elect of the Institute, mentioned the fact that inasmuch as $^2/_3$ of the Institute membership resided in Section territory, "certainly the desires and influence of the Sections must bulk large in Institute policy. At the same time we must always keep in mind the minority who do not have the opportunity to take part in Section activities." He urged active and thoughtful coöperation in the promotion of Institute affairs, and indicated that in the administration of his office as president his own large store of experience in Institute activities (Branch chairman, Section chairman, chairman of membership and other important committees, District vice president) would be drawn upon liberally.

NATIONAL SECRETARY AND FINANCE CHAIRMAN REPORT

National Secretary Henline reported in some detail the present status of the various recommendations made at the 1933 conference in Chicago. (See ELECTRICAL ENGINEERING: August 1933, p. 576–7; Sept. 1933, p. 640; Nov. 1933, p. 794; and other issues.) Concerning general Institute activities, Secretary Henline had the following comments to offer:

"As has been mentioned several times, one of the most important items in Institute work and one to which we must always be giving consideration, is the need for bringing into the activities more of the members who are qualified to carry them on effectively, and a good many things have been done in recent years in that direction. . . . I think this (conference) is the greatest opportunity we have for improving Institute affairs. . . . Of course, we haven't solved all our problems and we never shall. . . . Certainly as we expand Institute activity to bring in more individuals, there will be more subjects requiring discussion and consideration instead of fewer. These activities offer wonderful opportunities alike for the student, the young graduate, and the more experienced engineer; thus the Institute is doing everything possible within its means to provide something of interest and attractiveness for all members from the youngest to the oldest.

"One of the principal purposes of such conference as this is to seek out these new ways in which the Institute may make itself helpful to its members and to its prospective members . . . a large number of the Institute policies and procedures have resulted directly from these conferences. . . . . This annual meeting . . . a few years ago was called a Section delegate conference and Sections committee conference . . . (but has been) broadened so that now it is called a conference of officers, delegates, and members, so that anyone in these various groups is at liberty to come to listen and take part in the discussion. As these conferences have served effectively in the past, so do they hold still greater possibilities for the future."

E. B. Meyer, finance committee chairman, presented facts and figures representing a résumé of his illuminating article "The Story of the Institute Budget" that was published in the March 1934 issue of ELECTRICAL ENGINEERING. Supplementing this, Mr. Meyer reported that for the first 9 months of the current appropriation year, October 1 to June 30, the Institute's income had slightly exceeded the expenditures for the same period, an improvement over last year's condition, which in turn was an improvement over that of the preceding year. Mr. Meyer reported also that the outlook for the remainder of the appropriation year was such that an originally contemplated withdrawal from the Institute's reserve fund probably would not be required; further, that the market value of the securities held by the reserve fund had appreciated in market value.

Sections Session

Before launching into the business program of the session, Chairman I. M. Stein

recognized and expressed appreciation for the work done by the program committee: F. L. Christenbury of the Memphis Section, Raymond Foulkrod of the Detroit Section, and R. L. Kirk (chairman) of the Pittsburgh section.

Membership Committee Reports

A report on the activities of the Institute's membership committee prepared by E. S. Lee, chairman of that committee, was read by E. P. Coles in Mr. Lee's absence. The report, essentially in full, follows:

"When we speak of the work and activities of the membership committee of the Institute, we are really speaking of the work and activities of some 600 members coordinated with the 15,000 members of the Institute. Such an organization and such a conception is bound to succeed and we feel that we are succeeding. We have an admirable Institute to which to invite those who, we feel, should become members with us.

"During the year we have appealed on 2 occasions to the entire membership to send in the name of a person considered worthy to be asked to join the Institute. While we have made an effort to ascertain how many names were so sent in, it has been somewhat difficult to obtain totally reliable figures, but from data presented it seems that one application is obtained for about 7 names submitted. Assuming that $^1/_8$ of the 500 applications from other than students received last year resulted from such contribution of names, it would mean that about 1,500 members aided in this work. I do not think this number is large enough and therefore feel that the membership committee is right in continuing its present policy of trying to interest the present membership in seeking out worthy persons to become associated with us.

"From the larger membership the activities of the membership committee center in the Section membership committees who through the chairman deal with a District vice chairman who with 4 members-at-large provide a smaller group with whom the chairman can consult. I must admit this year that being new to the work I suggested a policy at the beginning of the year which was generally approved by the vice chairmen and this I have tried to carry out without further consultation but I am sure that anyone has felt free at any time to send in suggestions and several suggestions have been received which we have tried to act upon with advantage.

"Each month a report of membership statistics has been sent to the chairman of each Section membership committee together with copies to the chairmen and secretaries of each Section, copies to the District vice chairmen, and copies to the members of the board of directors. This has given opportunity to keep everybody informed of the progress of the work and I believe that if the Section activities can be coördinated around these reports, we have a strong and forceful means whereby the activities of the membership as a whole may be carried on efficiently and to the satisfaction of all."

Major Objectives

"The membership committee sought the following 3 major objectives:

1. To contact for new members.
2. To contact Students eligible to become Associate members.
3. To contact member for reinstatements.

"In regard to the first objective, the final report of the membership committee for the year shows that applications for membership were received from every Section of the Institute and this, I believe, is cause for gratification on your part. With the continuance of your interest in membership activities this record should be maintained and the total number increased month by month. It seems to me that this might well be our bogey that the number of applications received each month should be more than received in the same month of the preceding year. For the first month of this year, May 1934, we have made that bogey in that total applications received for May 1934, were 42 while during May 1933, they were 26. With your help this bogey will be made.

"In regard to the second objective, while it is the responsibility of the committee on Student Branches to provide for our Students, it is the responsibility of the membership committee to see that Students are brought into Associate membership as they become eligible. The number of Students brought into Associate membership this year was not as large as last year. Undoubtedly there are reasons for this but I feel that the Section membership committees should give increasing time, thought, and attention to this phase of our activity and with the help of the Section officers I am sure that we can bring about the same attainment as regards bogey results as with those who are not Students. So far this year we have not made this bogey for in May 1934, no applications were received from Students for Associate membership while in May 1933, 7 such applications were received. It is interesting to note, however, that during the past year applications from Students to enter Associate membership were received from every Section of the Institute except 3.

"Our third objective to contact members for reinstatement has been a part of our work which has been particularly happy for those who have participated in it and the record shows that since August 1, 1933, there have been 637 reinstatements. As chairman of the membership committee and as a member of the board of directors I feel that our board of directors not only this year but in the past years has been very thoughtful in dealing with those who have not been able to pay their dues regularly and I believe that if you could know intimately of all the cases that have had to be handled, you would be inspired, enthused, and

One of the Scenic Features Near Salt Lake City

ALTHOUGH the majority of those members of the Institute who will attend the 1934 Pacific Coast convention at Salt Lake City, Utah, Sept. 3–7, will be attracted primarily by the technical papers outlining recent advances in a number of fields of electrical engineering, the many scenic features offered by that section of the country provide an additional incentive for attendance at the convention. Many members are making plans to attend with their families, and will combine the opportunities of acquiring technical information with the pleasure of a vacation trip. The view shown here was taken from the Alpine Highway in north central Utah, and shows Mount Timpanogas in the background. Mount Timpanogas, highest of the Wasatch Mountains, rises to 11,957 feet above sea level.

pleased both with the resolutions emanating from the board of directors in these respects and from the thoroughness with which our headquarters' staff has handled the enormous correspondence in this regard. Since August 1, 1933, there have been reinstatements in every Section of the Institute except 3, which again speaks for the universality of this work."

The report mentioned the fact that no statistics are included, but that complete statistics covering the entire phase of the work included were given in the report of the board of directors for the fiscal year ending April 30, 1934, published in ELECTRICAL ENGINEERING for July 1934, p. 1095–107. The report concluded with an appeal for sustained endeavor by the chairmen of the various Section membership committees. It also requested of the entire membership "your individual and official interest in this work that there may be brought into our Institute for association with ourselves all of those who are interested in our aims and ideals and who should rightfully be associated with us."

SECTION TECHNICAL COMMITTEES PROPOSED

The proposal (see p. 631, April 1934 issue ELECTRICAL ENGINEERING) to broaden the opportunity for individual participation in Section activities, and for Section participation in national activities, through the establishment of provision for Section and District technical committees, was extensively discussed at both afternoon sessions of the conference. Several points of apparent confusion were cleared up in the discussion. It was clearly established that the basic idea of the proposal was principally to establish a definitely recognized basis for uniformity so far as possible Section technical activities were concerned, and to establish definite relationship between such activities and the Institute national organization in so far as its 18 technical committees are concerned. Also, it was emphasized that the whole idea is permissive rather than mandatory. At the close of discussion on the subject, the following resolution was adopted:

RESOLVED: That this conference recommends to the board of directors of the American Institute of Electrical Engineers that such changes be made in the by-laws of the Institute as will provide for an expansion in function and membership of the national technical committees and for the creation of District and Section technical committee activities. It is suggested that these results may be accomplished in the following manner:

1. Let each Section be authorized at its own discretion, and on its own initiative, to organize within its membership, technical committees corresponding in name and scope to any or all of the recognized Institute technical committees.

2. Membership in a Section technical committee shall be open to any Fellow, Member, and/or Associate of the Institute who is a member of that Section and who shall signify his wish to participate in the activities of that Section technical committee.

3. Each Section technical committee shall consist of a suitable number of Fellows, Members, or Associates of the Institute; shall have a chairman selected in a manner determined by the Section; and this Section technical committee chairman shall be a member of the District technical committee.

4. The vice president of each District shall appoint, with the advice of the committee, annually one member of each District technical committee to serve as a member of that national technical committee and to be chairman of his District technical committee.

5. The president of the Institute will appoint annually members-at-large to each national technical committee, and will designate its chairman as is the present practice.

This resolution was considered by the board of directors at its Hot Springs meeting, June 27, at which time the board voted to refer the recommendations to the technical program committee, the chairmen of the technical committees, and the Institute policy committee for study, and report to the board of directors at its next meeting, scheduled for August 14, 1934.

JOHNSON DISCUSSES INSTITUTE DUES

The question of Institute dues was discussed by President-Elect J. Allen Johnson,

Presidential Group at the 1934 Summer Convention, Hot Springs, Va., June 25–29

The largest group of Institute presidents assembled during recent years was present at Hot Springs for the celebration of the Institute's 50th anniversary. From left to right: J. Allen Johnson, 1934–35; D. C. Jackson, 1910–11; H. P. Charlesworth, 1932–33; Louis B. Stillwell, 1909–10; Comfort A. Adams, 1918–19; Bion J. Arnold, 1903–04; Charles F. Scott, 1902–03; A. W. Berresford, 1920–21; William McClellan, 1921–22; P. M. Lincoln, 1914–15; and J. B. Whitehead, 1933–34

chairman of the special committee on Associate dues, who stated that the only bases on which dues are likely to be criticized are that the average dues are too high, that they are not properly distributed over the different grades of membership, or that the right uses are not made of the dues after they are collected.

Mr. Johnson cited evidence for concluding that the average dues are not too high, and that there appears to be no good reason to question the uses to which dues are put after collection. In regard to the second basis, namely, the distribution of dues over the different grades of membership, he pointed out the logical reasons for the present arrangement, and also some of the difficulties, largely psychological in origin, which have resulted from it. He indicated that some of the other societies had avoided these difficulties by establishing separate grades of membership for certain classifications now included by the Institute in the one grade of Associate. This suggested the desirability of establishing in the Institute a "Junior" grade to meet the needs of the younger members and to take the place of the present anomalous 6-year period of $10 Associate membership. At the session held the following day a resolution was adopted endorsing this suggestion.

Student Branches Session

As a result of an afternoon's deliberation on the part of student counselors and other interested persons in attendance at the session, the student Branches group adopted unanimously the following resolution:

RESOLVED, that the student Branches committee requests that:

(a) An assistant editor in charge of student matters be appointed. His duties shall be to prepare 2 pages per issue for ELECTRICAL ENGINEERING under the supervision of Mr. Henline and Mr. Henninger. These pages shall be made attractive to our student members incorporating such items as Branch news, editorial comments of current technical and other material similar to students' page in the "London Electrician."

(b) He shall as rapidly as possible qualify to take on the duties formerly performed by Mr. Henline when he was assistant national secretary.

In brief, we recommend that steps be taken to initiate the reestablishment of the office of assistant national secretary with student activities as its chief responsibility.

Closing General Session

In presenting the foregoing resolution before the reconvened joint session, L. A. Doggett, chairman of the student Branches committee, spoke of the high proportion of new members that now are coming from the ranks of former Enrolled Students, and emphasized the necessity of continuing to promote student participation in A.I.E.E. affairs. He characterized as "a very serious loss" the discontinuance of the services of an assistant national secretary.

The proffered resolution was endorsed unanimously by the joint session and forwarded at once to the board of directors for consideration. When the resolution came before the board June 27 it was the consensus of opinion of that body that the resolution could not be acted upon by them as worded; therefore the resolution was referred to the chairman of the finance committee and the national secretary for advice and recommendation.

E.C.P.D. REQUEST

Chairman Stein, speaking as chairman of the A.I.E.E. Sections committee concerning a request for coöperation received R. L. Sackett, dean of engineering at Pennsylvania State College and chairman of the committee on student selection and guidance of the Engineers' Council for Professional Development, requested L. A. Doggett, chairman of the A.I.E.E. committee on education and student Branches, to read the following letter from Dean Sackett:

"The following statement will, I hope, give you an idea of what the committee proposed and also serve as a text for discussion of the subject at the A.I.E.E. meeting.

"The instructions by the E.C.P.D. to the committee on selection and guidance stated that it was: " 'To develop further means for the educational and vocational orientation of young men with respect to the responsibilities and opportunities of engineers. . . .'

"First, the committee carefully considered all the guidance literature available and after due deliberation a subcommittee consisting of Dean O. J. Ferguson and Prof. W. B. Plank reported that 'Engineering: A Career—A Culture' was the most suitable for the present purpose of the committee.

"Second, the committee considered methods by which guidance agencies could be provided in the more important centers.

"It was also deemed important that some measure of the effectiveness of the pamphlet 'Engineering: A Career—A Culture' should be provided and tried out. This was done by preparing 2 sets of questions for use by a small group of engineering colleges who were asked to invite local high school juniors and seniors to a meeting. A set of questions was given each student at the beginning of the program to test his knowledge of engineering. He was then given a series of short talks and a copy of the pamphlet to read carefully. He then answered a second set of questions. One conclusion was clear. It is expressed by the comment, 'I did not know the field of engineering was so broad'; therefore the pamphlet is helpful.

"A second set of objective tests is now being revised by a specialist in New York with the aid of funds provided for this purpose by The Engineering Foundation. When this set of questions is completed it will be tried out in a few engineering institutions in order to test the validity of the tests; second, in order to bring the institution in contact with prominent local counselors of engineering education; and third, to test the value of the pamphlet, 'Engineering: A Career—A Culture' as a guide to high school students. The procedure should also serve as a guide in selecting the best students or those who would profit most from pursuing an engineering curriculum. One set of questions is to be given to the interested students before they have read the pamphlet and the second set afterward.

"If the foregoing procedure gives promising results, an appeal then will be made to local Sections of the coöperating societies to set up a guidance committee, council, or bureau to make contact with the high schools in that territory and to pursue such guidance methods as may be considered most effective considering all of the local circumstances. The pamphlet on 'Engineering: A Career—A Culture' should be an important informative agency which may be supplemented by talks to interested groups or by individual conferences of prospective students with local counselors. The best technique to pursue will depend on the tact and interest of local Section officers in presenting the subject to high school principals and superintendents and in getting interested high school students together for the purpose.

"Since certain preliminary tests have been given which showed the desirability of guidance and the need for reliable information such as is contained in the pamphlet on 'Engineering' the preliminary period necessary to test out the new objective tests should be short, and Sections may expect a general appeal in October or November for assistance in carrying out the above suggested program.

"Further information will be given you concerning the method of handling the tests and sending the results in to me for tabulation and report to the E.C.P.D."

The consensus of the opinions of delegates present, arrived at through subsequent discussion, was that when Dean Sackett and the E.C.P.D. committee had carried its work far enough to make specific suggestions to or requests of local Sections, the Sections would "agree to coöperate within the bounds of their ability."

INSTITUTE ACTIVITIES DISCUSSED

A brief résumé of some of the principal topics presented during the "Discussion on Improving Institute Activities" is given in the following paragraphs.

J. M. Todd, delegate from the New Orleans Section (the Institute's newest), cited the rapid growth of interest in New Orleans and spoke with great emphasis concerning the necessity for greater local Section activity. R. L. Kirk of Pittsburgh, Pa., urged a general improvement in Institute activities, a strengthening of barriers that would prevent non-members from profiting so generally by Institute activities, and a strengthening of requirements for Institute membership. E. J. Rommel, Toledo, Ohio, Section delegate, reported that Section's success in having members make short informal talks preceding the regular programs at Section meetings, and in conducting forum groups meeting every 2 weeks "to discuss matters other than technical, to take in economic, world wide problems, and things of that kind." He also urged that Sections report successful activities so that they could be reflected and an exchange of ideas effected through ELECTRICAL ENGINEERING.

P.L. Alger of Schenectady, N. Y., pointed to the recent outstanding success of the annual convention of the Society for the Promotion of Engineering Education held at Cornell University, Ithaca, N. Y., the week before the A.I.E.E. Hot Springs convention, emphasizing the fact that some 65 technical sessions and conferences were held, and urging that future A.I.E.E. conventions should have many more sessions with fewer papers per session and more opportunity for group discussion by those really interested in the various topics.

President-Elect J. Allen Johnson, in speaking on his assigned topic "The Coming Year," stated that he hoped that the "Institute in the coming year and in all coming years will not lack the courage to make experiments and changes to keep abreast of the changing conditions." He urged Section delegates to find ways and means of better acquainting members of the various Sections with the national activities of the Institute, "referring particularly to the joint activities of the national society which are being carried on for the benefit of the whole profession of engineering," such as the Engineers' Council for Professional Development, and the American Engineering Council. He called attention also to the fact that next year's summer convention is slated to be held at Cornell University, Ithaca, N. Y., urging full coöperation throughout the year in order that all possible opportunities might be developed for the enlargement of summer convention activities.

Doctor Whitehead Explains Proposed Code for Engineering Division of Construction Industry

SPEAKING on the assigned topic "The Electrical Engineer and the Codes" at the Sections session of the annual conference of officers, delegates, and members, held Monday afternoon, June 25, 1934, at Hot Springs, Va., Dr. J. B. Whitehead, retiring president of the A.I.E.E., presented the results of his investigation into the question of the code for the construction industry and its effect on electrical engineers. The full text of Doctor Whitehead's address on this subject follows:

The NRA and the Position of the A.I.E.E.

In the spring of 1933, along with all other organizations, the Institute was asked through the mail to subscribe to the principles of the NRA and to follow this up with the submitting of a code for the regulation of its activities. The Institute subscribed to the principles aimed at in the NRA, but on information from American Engineering Council that counsel of the NRA had advised that the proposed regulations were not intended to apply to scientific and professional societies, and on similar advice from its own counsel, the board of directors determined that no further action in the matter was indicated for the Institute.

During succeeding months several inquiries and resolutions were received at Institute Headquarters from Sections of the Institute asking for information as to a proposed code for engineers, and urging the Institute to combat the adoption of a code that was being proposed by the construction industry, and which included a chapter or division for engineers engaged in that industry. The grounds for the proposed action were that the code being prepared for these engineers was so general in its terms as to make it appear possible at least that electrical and other engineers might be considered as subject to its provisions.

As a consequence of these communications, the board of directors has considered this matter at several of its meetings. It has taken no action, principally because no evidence was presented that any considerable number of electrical engineers could possibly be considered as subject to the code, and because there was no proposal nor suggestion of other grounds upon which possible action might be based. As time has advanced it also has been evident that those who were interested in the formulation of a suitable code for the engineering division of the construction industry, were giving it the most careful consideration with a view to limiting its application, and were well informed as to contemporary discussion and criticism. As a consequence several successive drafts have been prepared, and in its final form now under consideration by the NRA the code appears to contain no features which need give members of the Institute any concern.

A copy of the final draft of the code is printed in *Civil Engineering* for June 1934, together with an interpretation (by Carlton S. Proctor, chairman of the Code Committee of the American Society of Civil Engineers) of how it will operate. I have read these documents with some care and with special thought for the interests of electrical engineers, and I invite your attention to the following:

Code Limited to Construction Industry

In the first place, the code is for the construction industry and is limited to services "for the construction or anticipated construction of any private or public buildings, structures or works, or construction accessory thereto, where such services involve a knowledge of engineering laws, formulas, and practice, and a knowledge of the physical properties of the materials of construction and methods of installation."

All codes are written to insure fair practice among employers, and so are strictly employers' codes. The description in the foregoing paragraph indicates clearly that this code is meant to apply to employers engaged in "construction of buildings, structures or works, and construction accessory thereto."

However the construction industry is defined as including the designing as well as the construction of buildings and fixed structures. For this reason, the code itself contains a division described as the Engineering Division of the Construction Industry. Accordingly, the application of the code is extended to those who are engaged *competitively* in the business of proffering or rendering architectural or engineering service in the form of design for new or anticipated new construction.

This at once eliminates from the application of this code the Federal Government, states, cities, and all other political subdivisions, railroads, utilities, constructors, manufacturers, institutions, and all others, until they shall engage in *competition* on the basis of design for projected construction. The term "engineering service" includes the offer to provide or the providing of engineering service such as investigation, studies, surveying, planning, designing, supervision, inspection, testing or laboratory analyses for *construction only* as defined in the foregoing. It does not include engineering services necessarily adjunctive to the manufacture, sale, installation, or construction of patented devices or specialized processes or engineering design adjunctive to particular processes or particular equipment or combinations of the same. As an example, I suggest that in the erection of a hydroelectric power plant, the application of the engineering division of the construction industry would be limited to the contractors on the buildings, dams, foundations of turbines, generators, etc., but not beyond these foundations, and only when on a competitive basis.

Does Not Affect Electrical Engineers

Furthermore, it is clearly stated that in the case of an architect, landscape architect, consulting or other type of engineer who might be qualified and called upon to furnish engineering services for construction features, such engineers are subject to this code only when in competition and only to the extent as related to such construction, and are free of its conditions in their other activities.

It is difficult to see where in the provisions of this code the interests of electrical engineers are seriously affected. I have been able to think of only one case in which it might apply directly to electrical engineers, namely, in the electric welding of welded steel buildings and structures. It is conceivable that a company engaged in such work might wish to retain the services of electrical engineers expert in this field and these, accordingly, would become subject to the provisions of the code. Obviously, engineering employees of such a firm would also be so subject, but in this latter case, it is difficult to see how their position would be any different from that of engineers employed in any other types of industry, all of which are themselves subject to codes solely when in competition and for the insuring of fair practices among *employers*. In these cases no code for engineers is involved, but only a code for employers.

It is possible that other cases might be cited, but I think it impossible that any considerable number of our members will be found to be subject to the conditions of this code. Incidentally, there is no reference in the code to electrical engineers, nor do the words "electric" or "electrical" appear in it anywhere.

Prominent Consulting Engineer Dies

Carl Ewald Grunsky, consulting engineer of San Francisco, Calif., and past president of the American Society of Civil Engineers and of the American Engineering Council, died June 9, 1934. He was a native of California, having been born near Stockton in 1855. He received his technical education at Stuttgart, Germany, after which he entered public works in California. He was city engineer of San Francisco 1900–04 and on the Panama Canal Commission in 1904. He has been engaged as a consultant on many important works.

Mr. Grunsky received the Norman medal of the American Society of Civil Engineers in 1910, and was president of that society in 1924. He served as president of the American Engineering Council in 1930, and was president of the California Academy of Sciences. Several books on engineering subjects were written by him. His sons, C. E. Grunsky, Jr., and E. L. Grunsky, are consulting engineers in Oakland and San Francisco, Calif.

Additional Awards for 1933 Institute Papers

In addition to the national and District prizes for papers presented before the Institute during the calendar year 1933, as

announced in ELECTRICAL ENGINEERING for June 1934, p. 1026, announcement now has been made of the award of prizes for Districts No. 6 and No. 8. These awards are:

DISTRICT No. 6

Prize for branch paper awarded to Albert E. Logan and Stewart W. Hannah for their paper "The Measurement and Control of the Synchronous Machine Torque Angle," presented at a joint meeting of the Denver Section and University of Colorado Branch, April 28, 1933.

DISTRICT No. 8

Prize for initial paper awarded to A. H. Albrecht (A'14, M'29) for his paper "Variable Voltage Oil-Well Drilling Equipment," presented at the winter convention, New York, N. Y., January 23–27, 1933.

Prize for branch paper awarded to John H. Genzenhuber for his paper "An Experimental Study of Series Modulation," presented at joint meeting held at California Institute of Technology, April 4, 1933.

Date for International Commission on Illumination Selected. The next session of the International Commission on Illumination, as announced in ELECTRICAL ENGINEERING for October 1933, p. 722, and February 1934, p. 360, is to be held in Berlin, Germany, in 1935. Information has recently been received through the central office of the commission in London that the German National Committee affiliated with the commission has chosen the latter half of June, and probably the last week, as the time for the session. Although there will be no general illumination congress like those held in America in 1928 and in Great Britain in 1931, the meetings will afford a comprehensive review of the developments in illuminants and illumination practice taking place in Europe. Information may be obtained from G. H. Stickney, secretary-treasurer of the U.S. National Committee, I. C. I., Nela Park, Cleveland, Ohio.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Theory of Probability

To the Editor:

The most interesting article by Professor Bennett on "Theory of Probability" published in the November 1933 issue of ELECTRICAL ENGINEERING, p. 752–7, called forth a "Letter to the Editor" by Mr. S. A. Smith, Jr., published in the January issue of ELECTRICAL ENGINEERING, p. 229–30. In this letter Mr. Smith raised a very important question about application of theory of probability to the problem of determining the proper number of spare units in the electric system.

In this connection I should like to call your and Mr. Smith's attention to the fact that I had made an attempt to solve for some time the above mentioned problem in some more definite way also by application of theory of probability and had published an article on the subject in the No. 20, 1932 issue of *Electricity* (U.S.S.R.) under the title "The Method of Economic Valuation of the Spare Capacity of Electrical System."

Very truly yours,
R. A. FERMAN
(Electrical Engineer,
Moscow, U.S.S.R.)

Electrical Characteristics of Impregnated Cable Papers

To the Editor:

I have just received the following letter (which I have translated from the German) concerning the paper "Electrical Characteristics of Impregnated Cable Papers" by Professor Humphries and myself. It occurred to me that the suggestions contained therein might interest others who are working on dielectrics. The letter follows:

Diplomingeniör A. Basberg
Torp Brugs A/S
Fredrikstad
Norwegen

An den Associate Professor of Electrical Engineering
C. L. Dawes
The Harvard Engineering School
Cambridge, Mass.
America

Permit me to refer to the paper "The Electrical Characteristics of Impregnated Cable Papers," in the A.I.E.E. TRANS., v. 52, 1933, p. 711–20. In this connection, I should like to have your attention called to a paper which I presented in the fall of 1932 at a meeting of the Norway paper engineers and manufacturers in Oslo, and which was published in the professional journal *Papir-Journalen*, Nos. 11 to 14, 1933, under the title "Die Einwirkung der Feuchtigkeit und Temperatur auf Festigkeits- und Elastizitätsverhaltnisse im Papier." (The Influence of Moisture and Temperature on Strength and Elasticity Relations in Paper.)

Based upon an extensive amount of research material in this work, laws for the strength and elasticity variations of unimpregnated cable papers for various moisture contents and temperatures have been drawn up. From the curves one readily deduces that an unimpregnated cable paper under variable temperature shows a strength curve which has a maximum at about 50 deg C.

It now seems probable to assume that in the judgment of the variations of the electrical characteristics for impregnated cable paper these can be traced back to the above-mentioned relationships for unimpregnated paper.

From the results of the aforesaid researches with unimpregnated cable paper, a theory for the cause of the strength characteristics has been deduced in which the opinion is presented that the fibers and cells possess surface potentials which are variable with the temperature and possibly also with the moisture. These electrical potentials determine the strength of the paper due to their attraction on the water film present between adjacent fibres and cells.

If I may be permitted to draw certain comparisons between your work and my work, it is remarkable how close your curves approach mine, to such a degree that I feel it admissible to assume that variations in your electrical curves can in part be traced back to the changes in the surface potentials of the fibers and cells.

I would be greatly obliged to you for an exchange of opinions over these questions and am of course glad to give you any further information on the subject.

Most respectfully,
A. BASBERG

I have attempted to find a copy of this paper in this country but have not been able to do so. I have answered the letter requesting a copy of the paper but have suggested that the sudden changes in the electrical characteristics of impregnated cable papers which occur around 50 deg C appear to be more a property of the impregnating compound rather than the paper itself.

I have also stated that the minimum point of the V- or U-curve which frequently occurs when the power is plotted as a function of temperature is due to the fact that the power loss in the paper may decrease with temperature and that in the compound may increase with temperature. These characteristics are shown in the paper "Fundamental Properties of Impregnated Paper" by J. B. Whitehead and W. B. Kouwenhoven, TRANS. A.I.E.E., v. 50, 1931, p. 699–704. An analysis of this type of characteristic together with the explanation by Hochstädter appears on p. 705 in my discussion of the foregoing paper.

Also the separate effects of oil and paper appear in Fig. 21 of the paper "Predetermination of the A-C Characteristics of Dielectrics" by J. B. Whitehead and Alfredo Banos, Jr., TRANS. A.I.E.E., v. 51, 1932, p. 402. From the data which I have available, I am therefore inclined to attribute such variations to the combined effects of the paper and compound, although I believe that any new theory, such as the one presented should be carefully considered.

Very truly yours,
C. L. DAWES (A'12, M'15)
(Harvard University,
Cambridge, Mass.)

Excitation and Ionization in Gases

To the Editor:

A pictorial representation of what is supposed to take place during excitation and ionization in gases may be useful in conveying to the reader an explanation of these actions. Further, the use of pictures is of assistance in impressing these ideas on the memory. Such a pictorial representation is given in the sketches of Figs. 1 to 19. The first figure in the group gives the notation which is followed throughout. The nucleus (shown as a circle with a plus sign in it) represents the proton and all the internal electrons which do not take part in the action being illustrated.

Information on the subject of excitation and ionization in gases was given in "Electric Discharges in Gases" by Dr. Lewi Tonks in ELECTRICAL ENGINEERING for February 1934, p. 239–43. Although this paper is much more scientific and informative, I believe that young engineers may get something out of such "primer pictures" as given in this letter, when becoming acquainted with the subject for the first time.

Electricity passing through a gas does not obey the same laws that it does in the case of passing through metallic conductors. The process seems to be a very complicated one and there are certain phenomena which are observed such as the emission of light, and effects of external agents such as sources of light on the conductivity of the gas, that make it essential that special study be given the subject. The group of figures shown in Figs. 3 to 19 is intended to illustrate some of the possible atomic processes. This group of figures is by no means complete, ionization by chemical processes, and by temperature, etc., having been omitted. The action in some of the pictures is supposed to take place in 2 or more steps; these steps are described in the picture title, and the reader is asked to let his imagination fill in the essential gaps in the story.

It must not be inferred from the figures that we claim the electron to be spherical or of any particular shape, or that a metastable atom has an electron moving along a zigzag path; these diagrams simply illustrate processes making them more tangible to the student. "Structure of Atoms and Molecules" by M. L. Huggins in ELECTRICAL ENGINEERING for June 1934, p. 851–6, and "A Chart of Consecutive Sets of Electronic Orbits within Atoms of Chemical Elements" by V. Karapetoff in the *Journal* of the Franklin Institute, v. 210, 1930, p. 609 may be referred to for information on the shape of the atoms and molecules.

Some sources of ionization in gases may be found, conveniently arranged in a table, on p. 128 of "Nature of a Gas" by L. B. Loeb (John Wiley & Sons).

At Professor V. Karapetoff's suggestion I prepared a similar set of figures to be used in connection with a course given at Cornell University.

It is suggested that in the remaining articles of the science series for engineers, which is appearing month-by-month in ELECTRICAL ENGINEERING, authors do not hesitate to use such "picture" stories in conveying ideas which they wish to impress upon the memory.

Very truly yours,

HARRY SOHON (A'28)
(Instructor in Elec. Engg., Cornell Univ., Ithaca, N. Y.)

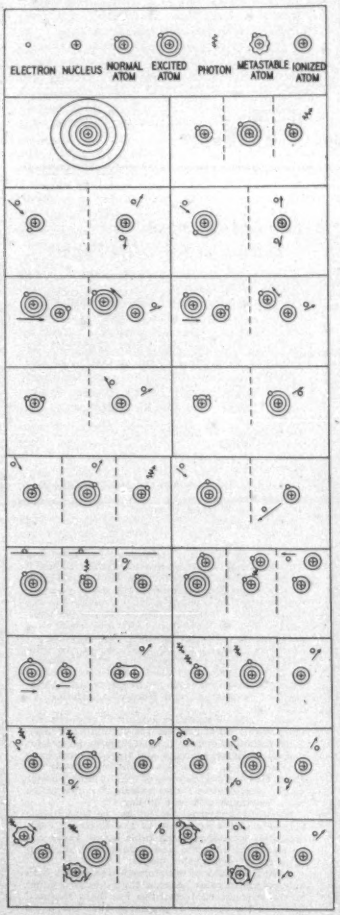


Fig. 1. Nomenclature

Fig. 2. Excitation potentials or energy levels

Fig. 3. Atom becomes excited, emits photon and returns to normal

Fig. 4. Electron strikes normal atom and ionizes it

Fig. 5. Electron strikes excited atom and ionizes it

Fig. 6. Excited atom strikes normal atom and ionizes it

Fig. 7. Excited atom strikes normal atom ionizing it, and returns to normal

Fig. 8. A normal atom may lose two electrons

Fig. 9. A normal atom may lose one electron and have another move to an upper level

Fig. 10. Electron strikes normal atom and excites it. The atom emits photon and returns to normal

Fig. 11. Collision of the second kind. Electron strikes excited atom and rebounds at increased velocity as atom returns to normal

Fig. 12. Excited atom returns to normal emitting photon which knocks an electron from solid surface

Fig. 13. Excited atom returns to normal emitting photon which ionizes another atom

Fig. 14. Excited atom collides with normal atom forming ionized molecule

Fig. 15. Ionization in two steps. One photon excites atom, and second photon ionizes it

Fig. 16. Ionization in two steps. Electron excites atom, and photon ionizes it

Fig. 17. Ionization in two steps. One electron excites atom and second electron ionizes it

Fig. 18. Ionization in two steps. Metastable atom excites normal atom and photon ionizes the latter

Fig. 19. Ionization in two steps. Metastable atom excites normal atom and electron ionizes the latter

Personal Items

JOSEPH SLEPIAN (A'17, F'27) consulting research engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and his co-author L. R. LUDWIG (A'28) have been awarded the 1933 A.I.E.E. national prize for best paper in theory and research for their contribution "A New Method for Initiating the Cathode of an Arc." Doctor Slepian was born at Boston in 1891, and received the degrees of A.B., A.M., and Ph.D. from Harvard, the last in 1913. After a year of study in Germany and Paris he was an instructor in mathematics at Cornell University until he entered the student course of the Westinghouse company in 1916. He joined the research department in 1917, shortly thereafter being given charge of the development of electrolytic condensers. In 1921 he devised the autovalve lightning arrester, and as a result of his researches on arcs he later produced the deion circuit breaker. Doctor Slepian holds numerous patents and has written many Institute papers. He is at the present time serving on 3 Institute committees, being chairman of the electrophysics committee.

L. R. LUDWIG (A'28) an electrical engineer for the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and his co-author JOSEPH SLEPIAN (A'17, F'27) have been awarded the 1933 A.I.E.E. national prize for best paper in theory and research for their contribution "A New Method for Initiating the Cathode of an Arc." Mr. Ludwig was born at Kansas City, Mo., in 1904 and received the degree of B.S. from the University of Illinois in 1925. Following graduation he entered the electrical design school of the Westinghouse company and later became assistant to the chief electrical engineer. In 1928 he entered the railway motor engineering department, and in 1929 he received the Lamme memorial scholarship; during 1929–30 he was a graduate student at the University of Berlin. Since 1931 Mr. Ludwig has been associated with Doctor Slepian in the research department. He has prepared several Institute papers.

T. B. WAGNER (Enrolled Student) Portland, Ore., has been awarded the 1933 A.I.E.E. national prize for Branch paper for his paper "A Universal Measuring Instrument for Communication Circuits." Mr. Wagner received the degree of B.S. in electrical engineering from Oregon State College in 1933, and the degree of M.S. in electrical engineering in 1934. He was active in communication work while at college, being radio operator during 1932–34 at station KOAC, which is a one-kilowatt broadcast transmitter. He also built, repaired, and installed radio and other communication equipment at the college, and during 1933–34 he was assistant to A. L. ALBERT (A'27), associate professor of electrical engineering. He is a member of Sigma Pi Sigma and of Eta Kappa Nu, and joined the student branch of the Institute in 1930.

C. H. WILLIS (A'22, M'28) associate professor of electrical engineering, Princeton University, Princeton, N. J., has received honorable mention in the 1933 A.I.E.E. national prize award for best paper in theory and research for his paper "Amplifications of Harmonic Commutation for Thyratron Inverters and Rectifiers." Doctor Willis was born in Culpeper County, Va., in 1893. He received the degrees of B.A. from the University of Richmond in 1914 and B.S. in Engineering from Johns Hopkins University in 1916. He entered the cadet course of the New York Edison Company, but served in the Signal Corps during the war, being commissioned second lieutenant in 1918, and remaining with the army of occupation until 1919. From then until 1925 he was in the physics department of the University of Richmond, with a year of graduate study, 1922–23, at Johns Hopkins University, from which he received the degree of Ph.D. after an additional year of study there in 1926. He then became assistant professor of electrical engineering at Princeton University, and has been associate professor since 1929. During this time he has spent 2 leaves of absence in the research laboratory of the General Electric Company in Schenectady, N. Y. He is at present on 2 Institute committees.

B. W. KENDALL (M'18, F'29) toll transmission engineer, Bell Telephone Laboratories, Inc., New York, N. Y., with his co-author A. B. CLARK (M'19, F'30) has received honorable mention in the award of the 1933 A.I.E.E. national prize for best paper in theory and research for the paper "Carrier in Cable." Mr. Kendall was born in Gardner, Mass., in 1883, and graduated from Massachusetts Institute of Technology in 1906 with the degree of B.S. Following graduate study in physics at Columbia University, New York, N. Y., he became an instructor there, and entered the research laboratory of the Western Electric Company in 1913. At this time his work was principally on telephone repeaters, but in 1915 he devoted a year to radio apparatus. In 1919 he was a member of a group sent to France to study a project for a telephone cable to connect Paris with Alsace and Lorraine. Upon his return he was given charge of toll development in the Western Electric Company and later in the Bell Telephone Laboratories. The work described in several Institute papers has been done in his department. Mr. Kendall is a member of the American Physical Society, the New York Electrical Society, and the Telephone Pioneers of America.

G. B. SCHLEICHER (A'20) technical assistant, meter division, Philadelphia Electric Company, Philadelphia, Pa., has received honorable mention in the 1933 A.I.E.E. national prize awards for initial paper for his contribution "Compensating Metering in Theory and Practice." Mr. Schleicher was born at Hamburg, Germany, and came to the United States in 1909. He graduated from the electrical construction course of the Philadelphia Trades School in 1915 and from Drexel Institute, Philadelphia, in 1919. From 1915 to 1917 he was employed by Leeds and Northrup Company, Philadelphia, for experimental work on electric resistance furnaces, and since 1917 he has been in the testing section and meter division of the Philadelphia Electric Company. Mr. Schleicher has prepared 2 papers for technical publications, and is the inventor of a compensating meter. He is secretary of the Philadelphia Society of Metermen and a member of the Pennsylvania Electric Association, and was awarded the silver medal for distinguished service rendered as a member of the International Jury of Awards, Sesqui-Centennial Exposition, Philadelphia, 1926.

A. B. CLARK (M'19, F'30) toll transmission engineer, American Telephone and Telegraph Company, New York, N. Y., with his co-author B. W. KENDALL (M'18, F'29) has received honorable mention in the award of the 1933 A.I.E.E. national prize for best paper in theory and research, for the paper "Carrier in Cable." Mr. Clark was born in Clay Centre, Ohio, in 1890. In 1911 he graduated from the University of Michigan with the degree of B.E.E. In that year he entered the engineering department of the company, and in 1919 took charge of a section of the department of development and research. He has been in this department since that

L. R. LUDWIG

T. B. WAGNER

JOSEPH SLEPIAN

W. J. MOULTON-REDWOOD

C. L. DAWES

P. H. HUMPHRIES

R. F. EDGAR

time, and is the inventor of a number of devices and systems, for the most part pertaining to long distance telephone transmission. He has written several papers on various developments. Mr. Clark is also a fellow of the Acoustical Society of America and a member of the American Association for the Advancement of Science.

C. L. Dawes (A'12, M'15) associate professor of electrical engineering, Harvard University, Cambridge, Mass., has been awarded the 1933 A.I.E.E. North Eastern District prize for best paper jointly with his co-author P. H. Humphries (A'26) for their paper "The Electrical Characteristics of Impregnated Cable Papers." Professor Dawes was born at Somerville, Mass., in 1886 and received the degree of B.S. in electrical engineering from the Massachusetts Institute of Technology in 1909, where he remained as an assistant until 1911, when he became an instructor at Harvard. During the summers of these 2 years he worked for the Edison Electric Illuminating Company of Boston, Mass. In 1913–14–15 he was professor of electrical engineering at the United States Naval Academy on leaves of absence, and assisted in establishing the post graduate school for naval officers. The schools of Harvard and Massachusetts Institute of Technology were combined from 1915 to 1919, and during the war Professor Dawes was an instructor in electrical engineering and radiotelegraphy at the Naval Aviation Ground School at M.I.T. He was appointed assistant professor of electrical engineering at Harvard in 1919, and became associate professor in 1931. He has been connected with a number of electrical industries for some years in a consulting capacity, and has contributed several papers on engineering and educational subjects.

P. H. Humphries (A'26) assistant professor of electrical engineering, Tulane University, New Orleans, La., shares with his co-author C. L. Dawes (A'12, M'15) the award of the Institute's North Eastern District 1933 prize for best paper, their contribution being "The Electrical Characteristics of Impregnated Cable Papers." Professor Humphries was born at Inlet, Va., in 1903. In 1917 he moved to Boston, Mass., and graduated from Boston Latin School in 1921, in which year he entered the electrical engineering course of Harvard University. He graduated with honors in 1925, after which he spent 1 year as an assistant and 2 years as an instructor in the electrical engineering department. He received the degree of M.S. in electrical engineering in 1928, and was a research associate until 1930, when he was appointed assistant professor of electrical engineering at Tulane University. In addition to teaching he is engaged in research upon the electrical characteristics of ionized gas films and related problems in high voltage engineering. He has been co-author with Professor Dawes of several previous papers. Professor Humphries is a member of the Society for the Promotion of Engineering Education, American Association of University Professors, Sigma Xi, Harvard Engineering Society, and American Academy of Political and Social Sciences.

R. F. Edgar (A'29) General Electric Company, Schenectady, N. Y., has received the 1933 A.I.E.E. North Eastern District prize for initial paper for his paper "Loss Characteristics of Silicon Steel at 60 Cycles With D-C Excitation." Mr. Edgar is a native of the Middle West, having been born on a farm near Detroit, Mich., in 1905. His family subsequently moved to a wheat ranch in North Dakota, and he attended school and college in Minneapolis, Minn., receiving the degree of B.S. in electrical engineering from the University of Minnesota in 1927. He remained 2 years longer, engaging in teaching and graduate work, and received the degree of M.S. in electrical engineering in 1929. In the summer of that year he came to Schenectady to enter the test course of the General Electric Company, and in the fall of 1930 was transferred to the magnetic division of the general engineering laboratory. Mr. Edgar is a member of Eta Kappa Nu, Tau Beta Pi, and Sigma Xi.

E. L. Angell (A'34) meter department, Narragansett Electric Company, Providence, R. I., has been awarded jointly with his co-author H. L. Anderson (A'34) the 1933 A.I.E.E. North Eastern District prize for Branch paper for their paper "A Study of Mercury Switches." Mr. Angell was born at Woonsocket, R. I., in 1912 and received the degree of B.S. in engineering from Brown University in 1933. While in college he specialized in the field of electrical engineering and was a student member at the time the paper was written.

H. L. Anderson (A'34) meter department, Narragansett Electric Company, Providence, R. I., shares with E. L. Angell (A'34) the 1933 A.I.E.E. North Eastern District prize for Branch paper for their paper "A Study of Mercury Switches." Mr. Anderson was born at Cranston, R. I., in 1911. He received the degree of B.S. in engineering from Brown University, Providence, in 1933, having specialized in electrical engineering. He was an Enrolled Student at the time the paper was written.

W. J. Moulton-Redwood (A'20) consulting and appraisal engineer, Toronto, Ont., Canada, has been awarded the 1933 A.I.E.E. Canada District prize for best paper for his paper "Valuation and Depreciation." Mr. Moulton-Redwood was born at London, England, in 1893 and received his education there. After some experience in an electrical laboratory and as a draftsman in a foundry he came to the United States in 1914 and worked on construction. With the outbreak of the war he was commissioned in the Canadian Expeditionary Force, and was seriously wounded at Cambrai in 1918. He returned to Canada in 1920 and was employed by the Canadian National Carbon Company and the Prest-O-Lite Company. He has also been employed by General Motors Corporation in New Zealand, and on the valuation staff of the Canadian National Railways. His most recent work of note has been the appraisal of the physical assets of the General Steel Works for the whole of Canada. He is now a registered professional engineer of the Providence of Ontario.

C. F. Himes (A'34) electrical department, Stanolind Pipe Line Company, Haven, Kan., has been awarded the 1933 A.I.E.E. North Eastern District prize for Branch paper for his paper "Aviation Radio." Mr. Himes was born at Edmond, Okla., in 1909. On completion of high school he entered the State Teachers' College in Edmond, from which he received a life certificate in 1928. After another year of study of courses which would apply in engineering he entered Oklahoma Agricultural and Me-

chanical College at Stillwater, Okla., from which he received the degree of B.S. in electrical engineering in 1933, having returned to the State Teachers' College in 1931 to receive the degree of B.S. in education. He was interested in aviation and during college was co-organizer of a glider club in 1930, engaging also in other campus activities. Before his present employment he was a teacher in the Mound Valley Public School at Hominy, Okla.

C. M. Davis (A'08) formerly assistant engineer of the transportation department, General Electric Company, Erie, Pa., has been appointed engineer in charge of that department. Mr. Davis is a native of Chicago, Ill., and was graduated from the University of Michigan in 1908. He received his master's degree at Union College in 1909, and entered the test department of the General Electric Company at Schenectady, N. Y., in that year. Following some time in the consulting engineering department under Dr. C. P. Steinmetz he entered the railway engineering department in 1913, and became assistant engineer in 1930, the department meanwhile having been moved to Erie. In 1924 he was sent to Australia in connection with the South Wales Government Railway electrification.

A. L. Powell (A'13, F'26) supervising engineer, incandescent lamp department, General Electric Company, New York, N. Y., has been elected president of the Illuminating Engineering Society for the year 1934–35. Mr. Powell is an internationally known authority on illumination design and application, and as lighting consultant for the Rockefeller Center development originated many of the ingenious effects in the Radio City Music Hall and other buildings. He has been with the General Electric Company since 1910, and is a member of the U.S. National Committee of the International Commission on Illumination. He is at present serving the Institute on the board of examiners and on the committee on the production and application of light.

L. W. Chubb (A'09, F'21) director of the research laboratories of the Westinghouse Electric and Manufacturing Company, has been awarded the Lamme medal of Ohio State University, the presentation taking place on June 11, 1934. Except for a short period with the Radio-Victor Corporation of America, he has served the same company continuously since his graduation from Ohio State. Mr. Chubb has been active in standardization work and has twice served as a delegate of the International Electrotechnical Commission. He has served on numerous committees of the Institute since 1914. His development work has resulted in his being awarded some 200 patents in the electrical, mechanical, chemical, electrochemical, and welding fields.

T. W. Carraway (A'21, M'32) former manager of the Unit Cooler Division of the Grinnell Company, resigned that position on January 1, 1934, to head the Carraway Engineering Company, although he retains identity with the former company in a different capacity. Mr. Carraway has designed and supervised the installation of about 100 plants of various sizes during the past 10 years, and has designed a number of automatic controls. While in the Army he installed the 2 largest plants of their kind on the American continent, at Camp Holabird, Baltimore, and Camp Normoyle, San Antonio.

J. L. Holton (A'30) division engineer, New York and Queens Electric Light and Power Company, New York, N. Y., has been awarded a James H. McGraw prize by the Edison Electric Institute for his paper "Engineering Necessary in the Development of an Extensive Low Voltage Network," which was judged one of the 3 most meritorious papers on any engineering or technical subjects relating to the light and power industry.

C. E. Tullar (A'22, M'31) manager of the patent department of the General Electric Company, Schenectady, N. Y., has been elected a vice president in charge of that department. Mr. Tullar has been with the company since 1919, having previously been in the U.S. Patent Office. He is a member of the bar of the Supreme Court and the Court of Appeals of the District of Columbia, and of the bar of the Supreme Court of the United States.

H. L. Andrews (A'16, M'26) former engineer in the transportation department of the General Electric Company, Erie, Pa., has been elected a vice president in charge of the activities connected with the electrification of steam railroads, and such other duties as may be assigned to him by the president. Mr. Andrews entered the testing department in 1910 and has been engineer of the transportation department since 1929.

E. B. Meyer (A'05, F'27, and vice president) vice president, United Engineers and Constructors, Inc., Newark, N. J., has been elected first vice president of the New York Electrical Society. Mr. Meyer has been active for many years in Institute affairs and has served the Institute in many important capacities, including the vice presidency for District No. 3 from which he retired Aug. 1, 1934.

D. D. Smalley (A'20, M'33) distribution superintendent of the Midland Counties Public Service Corp., Santa Maria, Calif., has been appointed general superintendent of the San Joaquin Light and Power Corporation, to succeed E. A. Quinn (M'15). Mr. Smalley has been with the San Joaquin and Midland Counties organizations since 1911. He will continue to supervise the operations of the Midland subsidiary.

A. W. Berresford (A'94, F'14, member for life, and past president) has resigned as managing director of the National Electrical Manufacturers Association whose activities he has guided for 5 years. Mr. Berresford was president of the Institute 1920–21, having served previously as a manager and

A. L. POWELL

as a vice president. A biographical sketch of Mr. Berresford is given on p. 804 of Electrical Engineering, May 1934.

S. O. Schamberger (A'21) hydraulic engineer, New York Power and Light Company, Albany, N. Y., has been awarded a James H. McGraw prize by the Edison Electric Institute for his paper "Hydro Station Operation With Minimum Loss," which was judged one of the 3 most meritorious papers on any engineering or technical subjects relating to the light and power industry.

I. E. Moultrop (A'10, F'29) chief engineer and superintendent of construction bureau, Edison Electric Illuminating Company of Boston, Mass., is a member of the executive committee of the Engineering Societies of New England. He has served on numerous Institute committees and is now a member of the committees on power generation and automatic stations.

H. H. Spencer (A'25) formerly assistant engineer of the New England Power Construction Co., Boston, Mass., has joined the Raytheon Manufacturing Corporation, Newton, Mass., where he will specialize in problems of product development. Mr. Spencer is a member of the committee on power transmission and distribution, having served since 1931.

William Fondiller (M'15, F'26) assistant director of apparatus development, Bell Telephone Laboratories, New York, N. Y., has accepted the invitation of the Columbia University school of engineering to act as research associate in the department of industrial engineering. Mr. Fondiller served on the electrophysics committee of the Institute, 1922–24.

H. S. Vassar (A'06, M'18) laboratory engineer, Public Service Electric and Gas Company, Irvington, N. J., has been elected a vice president of the American Society for Testing Materials. Mr. Vassar served the Institute on the electrophysics committee, 1920–21, and on the instruments and measurements committee, 1920 and 1922–25.

R. C. Muir (A'08, M'19) manager of the engineering department of the General Electric Company, Schenectady, N. Y., has been elected a vice president in charge of

the engineering department. Mr. Muir has been with the General Electric Company since he entered the student course in 1905, most of the time in the industrial engineering department.

L. V. Sutton (A'11) president and general manager of the Carolina Power and Light Company, Raleigh, N. C., has been elected second vice president of the Southeastern Electric Exchange, which is the successor to the Southeastern geographic division of the former National Electric Light Association.

C. C. Driscoll (A'28) formerly in the frequency change department of the Consumers Power Company, Grand Rapids, Mich., left recently to return to his home in Australia, where he will be associated with K. H. Milne (A'26) as an engineer with the Adelaide Electric Supply Company, Adelaide, Australia.

E. O. Shreve (A'08) former assistant vice president, has been elected vice president in association with Vice President J. G. Barry (A'03) in the commercial activities of the apparatus and supply business of the General Electric Company, Schenectady, N. Y. He has been associated with the company since 1904.

Bancroft Gherardi (A'95, M'04, F'12, past president, and member for life) vice president and chief engineer, American Telephone and Telegraph Company, New York, N. Y., has been appointed a representative of the Institute on the John Fritz Medal board of award, to succeed the late W. S. Lee.

E. A. Quinn (M'15) general superintendent of the San Joaquin Light and Power Corporation, Fresno, Calif., has resigned on account of ill health. Mr. Quinn has been a member of the San Joaquin organization since 1914, during most of that time occupying the post from which he resigned.

R. D. Lillibridge (A'02, M'19) former president of Ray D. Lillibridge, Inc., has recently established an advertising business under the name of Lillibridge, Adamson, and Kitchen. Mr. Lillibridge has been engaged in the advertising of electrical and other products for 25 years.

W. O. Batchelder (A'08) central district manager of the General Electric Company, Chicago, Ill., has been elected a commercial vice president in charge of the commercial activities of that district. Mr. Batchelder has served previously in the Minneapolis, Butte, and Detroit offices.

L. A. S. Wood (M'24) manager, exterior lighting section, Westinghouse Electric and Manufacturing Company, Cleveland, Ohio, has been elected a vice president of the Illuminating Engineering Society.

R. H. Hughes (A'20, M'30) assistant vice president, New York Telephone Company, New York, N. Y., has been elected second vice president of the New York Electrical Society.

Obituary

Harris Joseph Ryan (A'87, M'95, F'23, past president, and member for life), emeritus professor of electrical engineering, Leland Stanford, Jr., University, Palo Alto, Calif., died on July 3, 1934, from a heart attack. He was born at Powells Valley, Pa., January 8, 1866, and received his early education at Baltimore City College and Lebanon Valley College. In 1883 he entered Cornell University, Ithaca, N. Y., as a member of the first class in the newly organized course in electrical engineering, for which the equipment consisted of that of the physics laboratory with the addition of a d-c generator made by W. A. Anthony, president of the Institute, 1890–91. Following his graduation in 1887, Professor Ryan spent 2 years with the Western Engineering Company, Lincoln, Neb., and then returned to Cornell to become an instructor in the physics department. During 1889 he and Ernest Merritt, who later became a president of the American Physical Society, prepared a paper on transformers which was presented before a meeting of the Institute in December of that year and published in the Proceedings the following month. It was this paper which first brought him to prominence. He was appointed assistant professor of electrical engineering in 1890, associate professor in 1892, and professor and head of the department in 1895 at the age of only 29. One of his important works while at Cornell was the development of the pole face winding and the principle of the interpole which counterbalanced the effects of armature reaction in d-c machines. He also became interested in high voltage transmission, and succeeded in disproving the then common belief that 40,000 volts was the maximum economical transmission voltage. In the course of this work he constructed an air insulated transformer for 90,000 volts which was in use in the laboratory for many years afterward. The results were presented in a paper in 1904. About 1900 he started a series of studies of the cathode ray tube, which he applied to the measurement of voltage and current. When the Ithaca Section of the Institute was authorized in 1902, Professor Ryan became its first chairman, a position which he held until 1905, when he went to Stanford University to become professor of electrical engineering in charge of the department there. In addition to his other work he was consulting engineer for the Los Angeles Aqueduct Power Bureau from 1909 to 1923. He continued his researches in power transmission, and in recognition of his work the university built a high voltage laboratory in 1913 in which the principal item of equipment was a 350,000-volt transformer. Here Professor Ryan constructed a 60,000-cycle oscillator for use in the study of insulator flashover, and in 1916 devised a potentiometer for measuring the potential across each unit in a suspension string. For the year 1918–19 he was director of the supersonics laboratory of the National Research Council, Pasadena, Calif. As voltages continued going higher, he was frequently called on as a consultant, and devoted much time to the study of corona formation on conductors. He was elected president of the Institute for the year 1923–24, and in 1925 was awarded the degree of doctor of laws by the University of California, during which year he was also awarded the Edison Medal of the Institute. The following year the Harris J. Ryan high voltage laboratory at Stanford University was opened. The building and equipment were gifts from manufacturing and power companies, while the university provided the land, including a strip suitable for a 7-mile experimental transmission line. He became emeritus professor in 1931. He was a manager of the Institute, 1893–96, and a vice president, 1896–98, as well as president. Among the 11 committees on which he served were the Edison Medal, the John Fritz Medal board of award, and the Coffin fellowship and research fund; he also served on the United States national committee of the International Electrotechnical Commission. He was judge, board of awards, at the World's Fair, Chicago, 1893; United States delegate to the International Electrical Congress, St. Louis, 1904; and member of the jury, Panama Pacific International Exposition, San Francisco, 1915. He was a member of The American Society of Mechanical Engineers, the American Physical Society, the American Association for the Advancement of Science, the National Academy of Sciences, the Institute of Radio Engineers, Phi Kappa Psi, and Sigma Xi.

Edward Marriott Hewlett (A'91, F'17, and member for life) consulting engineer, Schenectady, N. Y., died May 24, 1934, after an illness of a few days. He was born at Cold Spring Harbor, N. Y., Sept. 14, 1866, and was educated in private schools and by private study in civil and mechanical engineering and physics. From 1884 to 1890 he was general manager and civil engineer of the Cascade Town Improvement Company of Cascade, Col. In 1888 he surveyed and laid out the road to the top of Pike's Peak. He began his electrical career in 1890 with the Thomson-Houston Electric Company in Lynn, Mass., which later became the General Electric Company. He was appointed head of the switchgear department when it was organized in 1898, and from 1907 until 1927 he was engineer of this department. At this time he became consulting engineer, and retired from active service in 1931. Mr. Hewlett was responsible for many important developments and held about 160 patents. Among the projects on which he worked were the illumination of the Statue of Liberty, the design of switchboards for several railway electrifications, notably the Interborough Rapid Transit system and the New York Central Railroad terminal electrification, both in New York. He assisted in the development of the oil switch and the suspension insulator, and designed the control apparatus for operating the locks on the Panama Canal. He also proposed and designed the modern fire control system of the United States Navy, and during the World War was chief engineer of the Navy Experimental Station at New London, Conn. Mr. Hewlett served the Institute on the protective devices committee from 1916 until 1922.

Frederick George Proutt (A'03, M'04) consulting engineer and chairman of the City Board of Water Commissioners of Memphis, Tenn., died May 27, 1934, after an illness of 6 months. Mr. Proutt was born at Bowmanville, Ont., Canada, on November 27, 1870. He was employed by the Canadian Bell Telephone Company for miscellaneous work in 1877, but he left in 1890 to become superintendent of the Bowmanville Electric Light Company and 2 years later entered the student course of the General Electric Company at Lynn, Mass. Upon completion of the course in 1894 he became chief electrician of the Malden Electric Company, Malden, Mass., and in 1897 joined the Memphis Light and Power Company, Memphis, Tenn., in the same capacity, where he was responsible for rebuilding the plant. For 2 years following 1906 he was general manager of the street railway and electric and gas plant at Jackson, Miss., after which he returned to Memphis and opened his office as a consulting engineer. He worked as consultant for many utilities, and during the war was an engineer and appraiser for the War Finance Corporation. Since 1920 he had been chairman of the board of water commissioners. Mr. Proutt was a charter member of the Engineers' Club of Memphis, of which he was its first president, and a charter member of the Memphis Section of the Institute. He was also a member of The American Institute of Mechanical Engineers.

Roy William Gray (A'03, F'28) formerly principal telephone and telegraph engineer of the Interstate Commerce Commission, Washington, D. C., died at Washington, April 28, 1934. He was born at Bradford, Iowa, in 1875. Following 3 years of study at what is now the California Institute of Technology, Pasadena, he became engaged with Wybre and Lawrence Company, Los Angeles, Calif., contracting electrical engineers, in 1896, as draftsman. Between 1898 and 1910 he was with the Bell Telephone system, being employed at different times in the states of California, Oregon, Washington, Nevada, and Arizona, acquiring a wide experience in telephone plant construction and operation. In 1910 he joined the organization of the Western Union Telegraph Company, becoming division plant superintendent of the Pacific division in charge of design, construction, and operation. In 1914 he became senior telephone and telegraph engineer for the Pacific district of the Bureau of Valuation of the Interstate Commerce Commission. In 1921 he became telephone and telegraph engineer of the Interstate Commerce Commission at Washington, D. C., in charge of the telephone and telegraph branch of the Bureau of Valuation. During 1913 and 1914 Mr. Gray served as a member of the joint committee on inductive interference of the Railroad Commission of California, and a member of its subcommittees on tests and on program.

Edward Dubois Mathey (A'07, F'19), New York, N. Y., died May 13, 1934, after a prolonged illness. He was born at Cranford, N. J., August 22, 1873, and graduated from Stevens Institute of Technology in 1894 with the degree of M.E. His first work was as draftsman for street railway companies, designing the west side substations for the Manhattan Elevated Railway Company, New York, N. Y., in 1901. In 1902 he joined Westinghouse Church Kerr and Company, New York, where he remained until 1917. During this time he was in charge of electrical design of the Pennsylvania Railroad power station in Long Island City, N. Y., and of substations of the Long Island Railroad. He was also engineer of electrical work for several power installations. In 1917 he became electrical engineer in charge of the electrical division of Air Nitrates Corporation, agents for the United States government for the design, construction, and operation of plants for nitrate production. His work included plants at Muscle Shoals, Ala., Toledo, Ohio, and Cincinnati, Ohio. The last 2 were not completed because of the signing of the armistice. He continued the same type of work after the war, joining the American Cyanamid Company, New York, as electrical engineer, which involved oven, electric furnace, power, and other electrical and electrochemical operations.

Harry Allen Currie (A'03, F'29) electrical engineer, New York Central Railroad Company, New York, N. Y., died suddenly on June 9, 1934, of angina pectoris. He was born at Maitland, Nova Scotia, on August 25, 1872. He attended high school at Halifax, Nova Scotia, and followed this with a course at Cooper Union, New York, N. Y., having also spent some time at sea. From 1894 to 1903 he was employed by the Brooklyn Heights Railway, Brooklyn, N. Y., in power house operation, electrification of elevated lines, and general maintenance of rolling stock. In 1903 he entered the service of the New York Central Railroad, where his first work was at Schenectady, N. Y., in connection with development for the electrification of that railroad. He was transferred to New York in 1906 to take charge of third rail installation, and the following year was appointed assistant electrical engineer, becoming electrical engineer in 1928. He was in charge of the electrical work for the improvements now nearing completion on the West Side, New York City, and was a consulting engineer for the electrification of the Cleveland (Ohio) Union Terminal. Mr. Currie was a member of the board of examiners 1930–34, and of the committee on transportation 1931–34.

Leonard P. Dickinson (A'07, M'28) professor of electrical engineering, University of Vermont, Burlington, Vt., died in the early part of June 1934. He was born at Hill, N. H., May 3, 1874. After receiving his degree in the electrical engineering course at Massachusetts Institute of Technology, Cambridge, Mass., in 1896, he worked for short periods for the American Telephone and Telegraph Company and the General Electric Company, and then began teaching in 1898. During the next few years he was an instructor at the University of Maine, Orono, Me.; Manual Training School, New Haven, Conn.; Armour Institute of Technology, Chicago, Ill; and Lafayette College, Easton, Pa. He became professor of physics and electrical engineering at Rhode Island State College, Kingston, R. I., in 1909, and remained there until 1919 when he went to Constantinople, now Istanbul, Turkey, as professor of electrical engineering at Robert College. He returned 2 years later to become professor of electrical engineering at the University of Vermont. In each of these last 3 he was head of the department. Professor Dickinson was a member of the Society for the Promotion of Engineering Education.

James Milne (M'33) electrical and mechanical engineer, City of Toronto, Ont., died suddenly on May 21, 1934. He was born in Scotland, January 29, 1865, and received his technical education at Gordons College, Aberdeen. From 1881 to 1886 he served an apprenticeship as a mechanical engineer, and in 1887 came to Canada, where he was employed by the Edison General Electric Company in Montreal. For 6 years following 1890 he was general superintendent of the Toronto Electric Light Company, after which he taught for 2 years in the Toronto Technical School. He then became general manager and chief engineer of The Underfeed Stoker Company, Toronto, and also engaged in consulting engineering. In 1906 he accepted the position of general superintendent of the British Columbia Electric Railway Company, Vancouver, B. C., which he left in 1910 to engage in consulting engineering in Vancouver, Windsor, Ont., and Toronto. He assumed his duties as engineer for the City of Toronto in 1914 and was so engaged until his death. Mr. Milne was a member of The American Society of Mechanical Engineers and of the Professional Engineers of Ontario.

Floyd Elliott Dellinger (A'26, M'33) overhead electrical engineer of the Los Angeles Gas and Electric Corporation, Los Angeles, Calif., died suddenly of a heart attack on June 8, 1934. He was born at Java Village, Wyoming County, N. Y. Starting with the Olean Electric Light and Power Company, Olean, N. Y., in 1898, he was afterward engaged in wiring with the Pan-American Exposition Company, Buffalo, N. Y., in 1901, and as a foreman of wiring and line construction with the General Machinery Company, Suffolk, Va., in 1902. He returned to Olean in that year as electrician with the Vacuum Oil Company and in 1905 joined the Nevada California Power Company for 4 years at Goldfield, Tonopah, and Manhattan, Nev., as wireman, foreman, and superintendent. In 1909 he entered the Los Angeles Gas and Electric Corporation as a meter tester, later becoming inspector, foreman, and overhead electrical engineer. Mr. Dellinger was a member of the Los Angeles Electric Club and the Pacific Coast Electrical Association. He served on the Institute's membership committee 1928–29 and was chairman of the Los Angeles Section 1932–33.

William Morton Scott (M'22) division superintendent, Utah Power and Light Company, Salt Lake City, Utah, died May 20, 1934, from heart trouble. His death occurred in Reno, Nev., while he was on a vacation trip to California. Mr. Scott was born at New Point, Ind., July 5, 1864. He studied a course in lighting and railways through the International Correspondence School, and went to Utah as a young man, entering the Union Power and Light Company in 1897. He became construction superintendent of lines 6 years later, and, absorbing additional responsibilities in the fast growing industry, was made superintendent of the Salt Lake division of the Utah Power and Light Company about 1914, in which position he was in charge of substations, electrical service, and line construction. During this time he handled many problems incident to the growth of the electrical industry in that territory. He was active in many organizations and was vice president of the Salt Lake Council of the Boy Scouts of America. At the time of his death Mr. Scott was secretary of the Utah Section of the Institute.

Hermann C. Henrici (M'23) president, Henrici, Lowry Engineering Company, Kansas City, Mo., died May 30, 1934, following an illness of several months' duration. He was born at Kansas City, Mo., in 1884, graduating from Massachusetts Institute of Technology in 1906. Upon graduation he entered the engineering department of the Missouri and Kansas Telephone Company, Kansas City. The following year he became a manager, holding this position until he left the company in 1909 for work in the W. T. Osborn Electric Company, contractors and engineers. In 1913 he joined the company of which he became president. In this firm he designed and supervised the installation of power plants and water works, and prepared appraisals and presented them before public utilities commissions in several midwestern states. Much of the work was for municipalities. He was a member of the American Society of Heating and Ventilating Engineers, the American Society of Refrigerating Engineers, and of the Engineers' Club.

Paul W. Ripple (A'04, M'13), The Connecticut Company, New Haven, Conn., died May 15, 1934. He was born at Orbisonia, Pa., May 8, 1877, and after completing high school studied electrical engineering through the International Correspondence Schools. He then was employed by the Westinghouse Electric and Manufacturing Company for 7 years, leaving in 1904 to accept a position as electrical engineer with the Lehigh Valley Railroad Company. Three years later he was employed by the Worcester Consolidated Street Railway Company, Worcester, Mass., where he remained until 1912, when he joined the Connecticut Company as chief engineer, having supervision of power equipment and rolling stock, including that of several subsidiary New England street railway companies.

Ralph Roberts Laxton (A'04, M'13) sales engineer, Westinghouse Electric and Manufacturing Company, Charlotte, N. C., died April 15, 1934. He was born at Morgantown, N. C., April 21, 1870, and attended high school there. He received private instruction in engineering and law. Following varied experience in railroad and power plant work he became assistant to the local manager of the General Electric Company in Atlanta, Ga., in 1903, and after a short period of supervisory work joined the Westinghouse organization in 1906, working in Atlanta and Charlotte offices.

George Martin McCarty (A'22, M'30) telephone engineer, American Telephone and Telegraph Company, New York, N. Y., died March 30, 1934. He was born at Norwich, N. Y., Sept. 2, 1881. He graduated from Brooklyn Polytechnic Institute in 1906, and entered the New York Telephone Company, where he was engaged in general design work. In 1912 he joined the A. T. and T. Co., where he was concerned with the design and layout of equipment of manual and dial apparatus. Lately he has supervised the investigation of new magnetic, insulating, contacting, and structural materials.

Membership

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before Aug. 31, 1934, or Oct. 31, 1934, if the applicant resides outside of the United States or Canada.

Aunen, H. J., Stone & Webster Engg. Corp., Lake Charles, La.
Barstow, J. MacD., Bell Tel. Lab., N. Y. City.
Beckwith, S., Metropolitan Water Dist. of Southern California, Los Angeles.
Boyce, H. A., Jr., Amer. Tel. & Tel. Co., Cleveland, Ohio.
Breen, F. J., Jr., Cincinnati Bell Tel. Co., Cincinnati, Ohio.
Clayton, W. R., City of Thomasville, Thomasville, Ga.
Day, I. F., U.S. Lighthouse Service, Portland, Ore.
Dunseath, H., Jr., Menlo Hotel, Oakland, Calif.
Healis, G. A., I-T-E Circuit Breaker Co., Philadelphia, Pa.
Kawecki, H. C., 1912 N. Damen Ave., Chicago, Ill.
Kettig, T. H., Southern Bell Tel. Co., Louisville, Ky.
Johnson, C. O. (Member), Bd. of Public Utilities, Jamestown, N. Y.
Johnston, E. F., N. Y. Hospital, N. Y. City.
LaBarr, W. W., Allis-Chalmers Mfg. Co., Los Angeles, Calif.
Langley, R. H. (Member), 165 Broadway, N. Y. City.
Leonard, M. G., Westinghouse Elec. & Mfg. Co., Sharon, Pa.
Love, W. S., Niagara Lockport & Ontario Power Co., Olean, N. Y.
Morrill, W., Virginia Elec. & Power Co., Williamsburg, Va.
Murray, C. S., Jr., N. Y. Edison Co., N. Y. City.
Myrick, E. B., Gen. Elec. Co., Louisville, Ky.
Noble, C., Mountain Park Collieries, Ltd., Alberta, Can.
Peck, C. E., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Philips, E. D., Chesapeake & Potomac Tel. Co., Washington, D. C.
Schuler, G. J., N. Y. Steam Corp., N. Y. City.
Van Vechten, G. E., Bklyn. Edison Co., Inc., Brooklyn, N. Y.

25 Domestic

Foreign

Claricia, P. M., Western Equip. & Supply Co., Manila, Philippines.
Harrap, G. V., North-Eastern Elec. Supply Co., Ltd., Dunston, Gateshead, Eng.
Jamora, L. L., Iloilo, Philippines.
Matto, R. N. (Member), Supply Centre, Srinagar Kashmir, India.
Ramakrishna, R., Tata Power Co., Ltd., Kalyan, India.

5 Foreign

Recommended for Transfer

The board of examiners, at its meeting of July 25, 1934, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Dorsey, Herbert G., principal E.R., U.S. Coast & Geodetic Survey, Washington, D. C.

1 to Grade of Fellow

To Grade of Member

Bellaschi, Peter L., devpmt. and res. engr., Westinghouse Elec. & Mfg. Co., Sharon, Pa.
Brosnan, Thomas J., E.E., Buffalo, Niagara & Eastern Power Corp., Buffalo, N. Y.
Carlson, Edward, Jr., E.E., Blackstone Valley Gas & Elec. Co., Pawtucket, R. I.
Ewart, J. Norton, asst. elec. supt., C. R. Huntley Steam Stations of Buffalo Gen. Elec. Co., Buffalo, N. Y.
Faus, Harold T., devpmt. eng., Gen. Elec. Co., West Lynn, Mass.
Ferguson, Edward F., chief engr., Gustav Hirsch Organization, Columbus, Ohio.
Ferguson, Whitworth, vice president and E.E., Robertson Elec. Constr. Co., Buffalo, N. Y.
Foadick, Ellery R., asst. engr., Public Service Commission, Olympia, Wash.
Grasser, Arthur P., E.E., Cleveland Elec. Illum. Co., Cleveland, Ohio.
MacDonald, Cecil J., asst. E.E., Susquehanna Collieries Co., Nanticoke, Pa.
McKinley, Victor L., asst. network engr., Louisville Gas & Elec. Co., Louisville, Ky.
Scanlon, J. Leo, elec. sales engr., J. Leo Scanlon Co., Buffalo, N. Y.
Scott, John Alexander, E.E., Gen. Elec. Co., Schenectady, N. Y.
Terman, Frederick E., assoc. prof. of E.E., Stanford University, Calif.
Wilde, Oscar A., asst. E.E., Sun Shipbuilding & Dry Dock Co., Chester, Pa.

15 to Grade of Member

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Clark, Merrill C., 161 Madison Ave., New York, N. Y.
Handley, Wilbur H., 4416 Loren Ave., Los Angeles, Calif.
McNitt, Donald P., 1009 First Natl. Life Bldg., St. Louis, Mo.
Mexal, J. Rene, 86-03 Britton Ave., Elmhurst, L. I., N. Y.
Miller, Frank D., Box 34, Yatesboro, Pa.
Moellendick, K. P., L. A. Automotive Works, 1010 Towne Ave., Los Angeles, Calif.
O'Handley, Joseph A. E., 679—61st St., Bklyn., N. Y.
Patton, Edgar P., Standish Arms, 169 Columbia Heights, Bklyn., N. Y.
Schultz, Carl H., 15 Cook St., Jersey City, N. J.
Stuntz, Hans, 106 Peck Ave., Newark, N. J.
Tamburello, G., 307 West 20th St., N. Y. City.
Thompson, B. F., Minas de Matahambre, Matahambre, Pinar Del Rio, Cuba.
Villegas, Lucio P., Tacoma General Hospital, Tacoma, Wash.
Wagoner, K. S., 320 Wisconsin, Oak Park, Ill.

14 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

KEMPE'S ENGINEER'S YEARBOOK of Formulae, Rules, Tables, Data & Memoranda for 1933–34. A compendium of Civil, Mech., Elec., Marine, Gas, Aero, Mine & Metallurgical Engg. Rev. by L. St. L. Pendred. 40th ed. Lond., Morgan Bros. (Publishers) Ltd., 1933. 2623 p., illus., 7x5 in., lea., 31s 6d. The current edition has undergone a very thorough revision, which undoubtedly will greatly increase its usefulness. All tables and general data have been revised, many illustrations replaced, obsolete material deleted and several entirely new articles added.

METALLURGY of IRON and STEEL. By B. Stoughton. 4 ed. N. Y. & Lond., McGraw-Hill Book Co., 1934. 559 p., illus., 9x6 in., cloth, $4.00. The new edition of this standard textbook and work of reference is practically a new book, having been entirely rewritten and rearranged. The subject is now presented largely from the historical point of view.

MUNICIPAL ELECTRIC PLANT MANAGERS, Their Selection, Training, Salaries, and Tenure, with a list of Municipally Owned Plants in the U.S. Pub. Administration Serv. Pub. 38. By E. C. Macmahon. Chicago, Pub. Administration Serv., 1934. 40 p., tables, 11x8 in., paper, $.60. This monograph is a study of the mode of selection, background, training and experience, salary, and tenure of managers of municipal electric plants. The study is based upon the practice of 690 American municipalities, about 36 per cent of the active municipal plants of the country.

NACHTRAG VI zum WERKSTOFFHANDBUCH "NICHTEISENMETALLE." Ed. by the Deutsche Gesellschaft für Metallkunde im Verein deutscher Ingenieure. DIN A 5, 33 p. Berlin, Beuth-Verlag, 1934. illus., 2.20 rm. This supplement completes the series, as originally contemplated. It includes papers on measuring instruments for mechanical testing, aluminum in the food industry, welding aluminum and its alloys, and methods of heat treating.

NATIONAL ELECTRICAL CODE HANDBOOK, based on the 1933 edition of the National Electrical Code. By A. L. Abbott. N. Y. & London, McGraw-Hill Book Co., 1934. 523 p., illus., 8x5 in., lea. In this handbook the provisions of the Code are grouped in a way that enables the user to ascertain quickly all the rules applying to any piece of work. Explanations, comments, and diagrams that clarify the rules have been added, with the aim of providing a helpful reference book for the engineer and contractor, and a systematic text for students. This edition is based on the 1933 Code.

PHYSICAL CONSTANTS. By W. H. Childs. Lond., Methuen & Co.; N. Y., E. P. Dutton & Co., 1934. 77 p., illus., 7x4 in., cloth, $1.20. Presents, in a volume which will go easily into the pocket, the constants which are in everyday use. Contains a large amount of information upon heat, light, electricity, magnetism, sound, and general physics, together with tables of logarithms and trigonometric functions.

PHYSICAL OPTICS. By R. W. Wood. 3 ed. New York, Macmillan Co., 1934. 846 p., illus., 9x6 in., cloth, $5.25. A clear, scholarly, and thoroughly modern treatment is afforded by this volume. As in preceding editions, the use of intricate mathematics has been avoided and physical pictures of the processes have been given. Special attention is given to describing experimental technique.

SIGNALS and SPEECH in ELECTRICAL COMMUNICATION. By J. Mills. N. Y., Harcourt, Brace & Co., 1934. 281 p., 8x5 in., cloth, $2.00. An attempt to give the general reader a few general principles, some illustrations, and as far as practicable a physical and philosophical background for the appraisal of present, and the imagination of future, systems or means of communication. This, as it is an unusual achievement, a clear, readable and accurate account of electrical systems of communication.

SPANNUNGSVERTEILUNG in KONSTRUKTIONSELEMENTEN. By E. Lehr. Berlin, VDI-Verlag, 1934. 64 p., illus., 12x8 in., paper, 7.50 rm. Special methods of investigation of the distribution of stresses in machinery by means of models, optical measurements, etc., have been developed, and numerous reports have been published which clarify the problem. These reports, however, are widely scattered and often understandable only to specialists. The present publication summarizes the results of these investigations in form for practical use.

TECHNIK GESCHICHTE. (Beiträge zur Geschichte der Technik und Industrie, Bd. 22, 1933). Berlin, VDI-Verlag, 1933. 156 p., illus., 12x8 in., cloth, 12 rm. The new volume of this annual contains papers on many branches of industry. Early Alpine roads, transportation in the Middle Ages, pre-Christian foundry practice, the oldest use of iron, the earliest electric telegraph, the history of the windmill, and other topics are discussed by authorities.

Die TECHNISCHE ELEKTROLYSE WÄSSERIGER LÖSUNGEN, A.-Die technische Elektrometallurgie wässeriger Lösungen, Die GALVANOTECHNIK, by G. Elsner. (Handbuch der technischen Elektrochemie, v. 1, pt. 3, ed. by V. Engelhardt.) Leipzig, Akademische Verlagsgesellschaft, 1933. 448 p., illus., 10x7 in., cloth, 41 rm.; paper, 38 rm. A handbook of practical information on electroplating, electrotyping, and electroforming, intended for the electrochemist or engineer who wishes a concise, yet comprehensive review of these subjects.

THEORY of ELASTICITY. (Engineering Societies Monographs.) By S. Timoshenko. N. Y. & Lond., McGraw-Hill Book Co., 1934. 416 p., illus., 9x6 in., cloth, $5.00. Presents the fundamentals of the theory of elasticity with special reference to the needs of the engineer. The presentation considers both 2-dimensional and 3-dimensional problems. The photo-elastic, soap-film, and other experimental methods are included. The book is the third of the series of Engineering Societies Monographs.

THERMODYNAMICS of ELECTRICAL PHENOMENA in METALS. By P. W. Bridgman. N. Y., Macmillan Co., 1934. 200 p., diagrs., 9x6 in., cloth, $3.75. During the past 10 years Professor Bridgman has published a number of papers upon interrelations of a thermodynamic character between various electrical properties of metals. The substance of these papers, with some extensions and added relations, is now presented in this volume, which attempts a more or less systematic application of classical thermodynamics to those electrical phenomena amenable to thermodynamic treatment.

WAVE MECHANICS: Advanced General Theory. By J. Frenkel. Oxford (Eng.), Clarendon Press; N. Y., Oxford Univ. Press, 1934. 524 p., tables, 10x6 in., cloth, $12.00. Continues the comprehensive treatise begun with the publication in 1932, of the author's "Wave mechanics: elementary theory." This volume is devoted to the mathematical development of the ideas underlying the new mechanics, to connecting it with classical mechanics and constituting it a complete self-supporting theory.

ELECTRONS at WORK, a Simple and General Treatise on Electronic Devices, Their Circuits and Industrial Uses. By C. R. Underhill. N. Y. and Lond., McGraw-Hill Book Co., 1933. 354 p., illus., 9x6 in., cloth, $3.00. A comprehensive survey of electronics, written without mathematics or undue use of technical language. The fundamental principles and the ways in which the various tubes and cells function are clearly explained; and the applications of electronic devices in industry and beauty are indicated in detail. Useful to those who wish to understand these devices or are interested in their industrial uses.

AIR CONDITIONING. 2 vol. By S. R. Lewis. Scranton, Pa., Intl. Textbook Co., 1933. Illus., 8x5 in., lea., v. 1, $1.65; v. 2, $2.00. The subject of air conditioning is presented without complicated mathematics, practical methods being emphasized. The physics of air conditioning, equipment, refrigeration, heat transmission through buildings, piping and duct design, and temperature control are discussed, and a final section deals with design.

AMERICAN INVENTORS. By C. J. Hylander. N. Y., Macmillan Co., 1934. 216 p., illus., 8x5 in., cloth, $3.00. The stories of 19 well-known inventors, from Franklin and Fitch to Jenkins and De Forest, are briefly related in this book, which is intended for boys of a mechanical turn of mind. In spite of their brevity, the sketches are pleasant reading.

BOOK of SCIENTIFIC DISCOVERY, How Science Has Aided Human Welfare. By D. M. Turner. Lond., Bombay & Sidney, G. G. Harrap & Co., 1933. 255 p., illus., 9x6 in., cloth, 7s 6d. This is a readable history of science, intended for popular reading and for use as a textbook. The development of science since the Middle Ages is outlined, with emphasis upon its effect upon society and human welfare. The work is attractively illustrated.

ELEMENTS OF RADIO COMMUNICATION. By J. H. Morecroft. 2 ed. N. Y., John Wiley & Sons, 1934. 286 p., illus., 9x6 in., cloth, $3.00. Aims to provide a sound, thorough course in a-c theory and its applications to radio communications for those without the preparation or the time called for by the author's "Principles of Radio Communication." Thoroughly revised.

ENGLISH for ENGINEERS. By S. A. Harbarger. 3 ed. N. Y. and Lond., McGraw-Hill Book Co., 1934. 314 p., 8x5 in., cloth, $2.00. Designed to give the engineering student a good, practical command of the language for letter writing and for preparing reports and technical articles. At the same time cultural reading is not overlooked, and sensible suggestions are given to guide the beginner.

EXPLORING the UPPER ATMOSPHERE. By D. Fisk, with introduction by H. L. Brose. N. Y., Oxford Univ. Press, 1934. 166 p., illus., 8x5 in., cloth, $1.75. A popular description, for nontechnical readers, of recent developments in stratospheric physics. Describes the investigations of Professor Piccard and others by means of balloons and discusses sound as an explorer, ultraviolet rays and their discovery of the ozone layer, the paths of radio waves, polar lights, and cosmic rays.

LOUD SPEAKERS, Theory, Performance Testing and Design. By N. W. McLachlan. Oxford (Eng.), Clarendon Press; N. Y., Oxford Univ. Press, 1934. 399 p., illus., 10x6 in., cloth, $13.50. An advanced, fairly complete treatment of the theory and practice of loud speakers. The first part is devoted to an analysis of the theoretical problems of speaker design, and in the second part the theory is applied practically.

ROYAL TECHNICAL COLLEGE JOURNAL Vol. 3, Pt. 2, January, 1934, p. 205–334. Glasgow, Royal Technical College. Illus., diagrs., charts, tables, 10x7 in., paper, 10s 6d. Devoted to recording research work by the staff and senior students of the College. Papers in this number include: An example of magnetic aging, the determination of the moisture content of wood, 2 applications of the thin conical wall theory, parabolic weirs, viscous effects in dynamometer belts, electrode systems for dielectric loss measurements, and some notes on the ignition coil.

SHORT WAVE WIRELESS COMMUNICATION. By A. W. Ladner and C. R. Stoner. 2 ed N. Y., John Wiley & Sons, 1934. 384 p., illus., diagrs., charts, tables, 9x6 in., cloth, $3.75. A self-contained presentation, largely nonmathematical in character and designed to meet the needs of professional engineers and radio operators, as well as amateurs. Enlarged by the addition of new material.

Engineering Societies Library

29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

Summary of Real Property Inventory

THE vast potential market for electric, gas, and other lighting, cooking, and refrigeration equipment in the United States is reflected in the statistics recently made available for 55 of the 64 cities specially enumerated under the real property inventory recently taken by the U.S. Bureau of Foreign and Domestic Commerce, under the supervision of Daniel E. Casey. In the following table, compiled in the statistical division by Alanson D. Morehouse, chief statistician of the real property inventory unit of the U.S. Bureau of Foreign and Domestic Commerce, are shown the number of structures and dwelling units in these cities, with the number and percentage of dwelling units using or not using electricity for lighting and cooking, and the number and percentage of homes provided with mechanical refrigeration, distributed by geographical divisions and cities. (Preliminary figures, July 20, 1934.)

Geographic Divisions and Cities	No. of Structures	No. of Dwelling Units	Dwelling Units: Lighting Facilities: Using Electricity	Dwelling Units: Lighting Facilities: Not Using Gas or Electricity	Dwelling Units: Cooking Facilities: Using Electricity	Dwelling Units: Cooking Facilities: Not Using Gas or Electricity	No. With Mechanical Refrigeration
Totals for 55 Cities	1,114,033	1,421,096	1,253,700 (88.7%)	160,380 (11.3%)	49,955 (3.5%)	431,406 (30.3%)	238,242 (16.8%)
Geographic Divisions							
New England	50,435	85,417	82,498 (96.6%)	2,351 (2.8%)	1,293 (1.5%)	29,482 (34.5%)	11,188 (13.1%)
Middle Atlantic	117,731	176,871	170,608 (96.5%)	5,300 (3.0%)	619 (0.4%)	19,016 (10.8%)	26,243 (14.8%)
East North Central	99,677	117,858	111,590 (94.7%)	5,618 (4.8%)	1,654 (1.4%)	21,148 (17.9%)	18,788 (15.9%)
West North Central	144,407	174,087	163,670 (94.0%)	9,924 (5.7%)	1,149 (0.7%)	41,430 (23.8%)	35,140 (20.2%)
South Atlantic	127,615	166,291	128,482 (77.3%)	36,138 (21.7%)	4,174 (2.5%)	77,563 (46.6%)	30,998 (18.6%)
East South Central	129,220	154,447	103,185 (66.8%)	50,908 (33.0%)	1,588 (1.0%)	102,333 (66.3%)	16,458 (10.7%)
West South Central	181,256	215,827	175,555 (81.3%)	39,248 (18.2%)	575 (0.3%)	44,963 (20.8%)	37,147 (17.2%)
Mountain	89,309	114,828	108,668 (94.6%)	5,730 (13.8%)	5,796 (13.8%)	51,790 (45.1%)	21,870 (19.0%)
Pacific	174,383	215,470	209,444 (97.2%)	5,154 (2.4%)	23,107 (10.8%)	43,681 (20.3%)	40,410 (18.8%)
New England							
Burlington, Vt.	4,252	6,618	6,465 (97.6%)	123 (1.8%)	217 (3.3%)	1,370 (20.7%)	1,068 (16.1%)
Nashua, N. H.	4,646	7,969	7,595 (95.3%)	259 (3.2%)	23 (0.3%)	2,740 (34.3%)	1,156 (14.5%)
Portland, Me.	10,475	19,689	18,858 (95.7%)	533 (2.7%)	294 (1.4%)	5,868 (29.8%)	2,884 (14.6%)
Waterbury, Conn.[1]	16,060	30,304	29,409 (97.0%)	804 (2.6%)	181 (0.6%)	5,280 (17.4%)	3,977 (13.1%)
Worcester, Mass.[1]	15,002	20,837	20,171 (96.8%)	632 (3.0%)	578 (2.7%)	14,224 (68.2%)	2,103 (10.0%)
Middle Atlantic							
Binghamton, N. Y.[1]	21,757	32,409	31,660 (97.6%)	692 (2.1%)	329 (1.0%)	5,703 (17.6%)	4,417 (13.6%)
Erie, Pa.[1]	25,194	33,179	32,424 (97.7%)	638 (1.9%)	32 (0.1%)	2,062 (6.2%)	3,052 (9.2%)
Syracuse, N. Y.[1]	35,764	56,340	55,364 (98.2%)	751 (1.3%)	164 (0.03%)	2,105 (3.7%)	10,799 (19.1%)
Trenton, N. J.[1]	26,557	42,802	39,863 (93.1%)	2,535 (5.9%)	36 (0.1%)	6,284 (14.6%)	6,298 (14.7%)
Williamsport, Pa.	8,459	12,141	11,297 (93.0%)	684 (5.6%)	58 (0.5%)	2,862 (23.5%)	1,677 (13.8%)
East North Central							
Decatur, Ill.	14,662	16,407	15,164 (92.4%)	1,081 (6.5%)	28 (0.2%)	3,278 (19.9%)	2,330 (14.2%)
Kenosha, Wis.[1]	11,058	13,843	13,398 (96.7%)	411 (2.9%)	98 (0.7%)	2,036 (15.0%)	1,743 (12.6%)
Lansing, Mich.	18,144	20,815	20,458 (98.3%)	330 (1.6%)	1,055 (5.0%)	4,030 (19.7%)	2,987 (14.3%)
Peoria, Ill.[1]	31,206	35,862	33,619 (93.7%)	2,138 (5.9%)	150 (0.42%)	7,405 (20.6%)	7,363 (20.5%)
Racine, Wis.[1]	15,565	20,253	19,489 (96.2%)	700 (2.4%)	228 (1.1%)	2,818 (13.0%)	2,917 (14.4%)
Zanesville, Ohio	9,042	10,678	9,462 (88.6%)	958 (8.9%)	95 (0.9%)	1,481 (13.8%)	1,448 (13.6%)
West North Central							
Des Moines, Iowa[1]	37,341	44,858	42,594 (94.9%)	2,219 (4.9%)	233 (0.6%)	9,129 (20.3%)	7,780 (17.3%)
Fargo, N. Dak.	5,209	7,467	7,276 (97.4%)	129 (1.7%)	15 (0.2%)	1,202 (16.1%)	1,929 (25.8%)
Lincoln, Neb.	18,790	23,242	22,550 (97.0%)	554 (2.4%)	102 (4.3%)	4,403 (19.1%)	6,403 (27.5%)
Sioux Falls, S. Dak.	7,561	9,240	9,028 (97.7%)	192 (2.0%)	165 (1.7%)	1,618 (17.5%)	1,701 (18.4%)
Springfield, Mo.	14,801	16,200	13,880 (85.7%)	2,202 (13.6%)	100 (0.7%)	7,809 (48.2%)	2,783 (17.1%)
St. Joseph, Mo.	16,686	19,932	18,350 (92.0%)	1,540 (7.7%)	251 (1.2%)	7,348 (36.8%)	3,833 (19.2%)
Topeka, Kan.	16,300	19,092	18,079 (99.7%)	995 (5.2%)	61 (0.32%)	3,169 (16.6%)	3,216 (16.8%)
Wichita, Kan.[1]	27,729	34,056	31,913 (93.7%)	2,093 (6.1%)	213 (0.7%)	6,752 (19.8%)	7,495 (22.0%)
South Atlantic							
Asheville, N. C.	10,833	12,584	10,139 (80.5%)	2,434 (19.3%)	815 (6.4%)	9,498 (75.4%)	2,013 (15.9%)
Charleston, S. C.	10,759	17,911	8,926 (49.8%)	8,950 (49.9%)	182 (1.0%)	11,414 (63.7%)	1,637 (9.1%)
Columbia, S. C.	10,000	12,188	7,882 (64.6%)	4,102 (33.6%)	24 (0.2%)	7,168 (58.8%)	1,895 (15.5%)
Frederick, Md.	2,635	3,785	3,321 (87.7%)	437 (11.5%)	170 (4.5%)	1,896 (50.0%)	764 (20.1%)
Greensboro, N. C.	11,000	12,061	9,977 (82.7%)	2,050 (16.9%)	352 (2.9%)	7,731 (64.0%)	2,214 (18.4%)
Hagerstown, Md.	5,035	8,149	7,706 (94.6%)	394 (4.8%)	265 (3.2%)	3,504 (42.9%)	1,592 (19.5%)
Richmond, Va.[1]	41,201	54,957	43,697 (79.5%)	11,121 (10.2%)	1,924 (3.5%)	24,257 (44.1%)	14,102 (25.6%)
Wheeling, W. Va.[1]	36,152	44,656	36,834 (82.5%)	6,550 (14.9%)	442 (1.0%)	12,095 (27.0%)	6,781 (15.2%)
East South Central							
Birmingham, Ala.[1]	82,704	101,721	67,548 (66.4%)	34,105 (33.5%)	942 (1.0%)	64,749 (63.6%)	11,198 (11.0%)
Jackson, Miss.	9,563	11,422	7,307 (63.9%)	4,075 (35.7%)	3 (0%)	5,219 (45.7%)	1,155 (10.1%)
Knoxville, Tenn.[1]	29,188	32,275	22,161 (68.7%)	10,018 (31.0%)	629 (1.9%)	26,156 (81.0%)	3,524 (10.9%)
Paducah, Ky.	7,765	9,029	6,169 (68.3%)	2,710 (30.0%)	14 (0%)	6,209 (68.7%)	581 (6.4%)
West South Central							
Baton Rouge, La.	6,951	7,692	5,379 (69.9%)	2,142 (27.8%)	10 (0.1%)	3,232 (42.0%)	999 (12.9%)
Oklahoma City, Okla.[1]	40,093	49,714	43,135 (86.8%)	6,114 (12.3%)	103 (0.2%)	6,470 (13.0%)	11,795 (23.7%)
Dallas, Texas[1]	66,813	83,628	70,972 (84.8%)	12,507 (14.9%)	298 (0.4%)	17,187 (20.5%)	13,894 (16.6%)
Austin, Texas	12,849	14,407	11,321 (78.6%)	3,052 (21.2%)	41 (0.3%)	5,043 (35.0%)	2,166 (15.0%)
Little Rock, Ark.	25,161	27,792	20,089 (72.3%)	7,630 (27.4%)	50 (0.2%)	9,607 (34.6%)	4,667 (16.8%)
Wichita Falls, Tex.	9,667	10,722	8,968 (83.6%)	1,735 (16.2%)	67 (0.7%)	1,639 (15.3%)	1,418 (13.2%)
Shreveport, La.	19,722	21,872	15,691 (71.7%)	6,068 (27.7%)	6 (0%)	1,785 (8.1%)	2,208 (10.0%)
Mountain							
Albuquerque, N. Mex.	6,458	7,820	6,855 (87.8%)	928 (11.8%)	64 (0.9%)	2,996 (38.3%)	1,124 (14.4%)
Boise, Idaho	5,167	6,477	6,362 (98.2%)	210 (3.2%)	1,917 (29.6%)	3,169 (48.9%)	1,307 (20.1%)
Butte, Montana	7,358	10,727	10,540 (98.3%)	126 (1.1%)	1,098 (10.2%)	6,394 (59.6%)	991 (9.2%)
Casper, Wyoming	4,270	5,600	5,108 (91.2%)	477 (8.5%)	31 (0.6%)	673 (12.0%)	813 (14.5%)
Phoenix, Arizona	10,519	14,392	13,182 (91.4%)	1,137 (7.9%)	98 (0.7%)	3,285 (22.8%)	2,909 (20.2%)
Pueblo, Colo.	10,882	12,723	11,539 (90.7%)	1,033 (8.1%)	1,464 (11.5%)	6,465 (50.8%)	1,593 (12.5%)
Reno, Nev.	4,652	6,194	5,953 (96.1%)	121 (1.9%)	1,330 (21.4%)	2,973 (48.0%)	1,360 (21.9%)
Salt Lake City, Utah[1]	37,858	48,175	47,088 (97.7%)	1,027 (2.1%)	9,717 (20.1%)	24,078 (49.9%)	11,479 (23.8%)
Santa Fe, N. Mex.	2,145	2,720	2,031 (74.7%)	680 (25.0%)	77 (2.9%)	1,757 (64.6%)	294 (10.8%)
Pacific							
Portland, Oregon[1]	93,526	115,270	112,120 (96.3%)	2,648 (2.2%)	21,266 (18.4%)	34,383 (29.8%)	23,665 (20.5%)
Sacramento, Calif.[1]	28,292	36,505	35,144 (96.2%)	1,126 (3.0%)	1,406 (3.8%)	5,504 (15.0%)	6,408 (17.5%)
San Diego, Calif.[1]	52,565	63,695	62,180 (97.3%)	1,380 (2.1%)	435 (0.7%)	3,794 (5.9%)	10,337 (16.2%)

1. Metropolitan district, city proper and environs. 2. Environs only. 3. City proper only.

Published Monthly by

American Institute of Electrical Engineers

(Founded May 13, 1884)

Electrical Engineering

Registered U. S. Patent Office

September 1934
Volume 53
No. 9

The Official Monthly Journal and Transactions of the A.I.E.E.

J. Allen Johnson, President
H. H. Henline, National Secretary

Publication Committee

C. O. Bickelhaupt, Chairman
J. W. Barker
R. N. Conwell
L. A. Doggett
W. S. Gorsuch
H. H. Henline
L. F. Hickernell
E. B. Meyer
L. W. W. Morrow
I. M. Stein
H. R. Woodrow

Publication Staff

G. Ross Henninger, Editor
C. A. Graef, Advertising Manager

PUBLICATION OFFICE, 20th and Northampton Streets, Easton, Pa.

EDITORIAL AND ADVERTISING OFFICES, 33 West 39th Street, New York, N. Y.

ENTERED as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918.

SUBSCRIPTION RATES—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii and the Philippine Islands, Central America, South America, Haiti, Spain and Spanish Colonies; $13 to Canada; $14 to all other countries. Single copy $1.50.

CHANGE OF ADDRESS—requests must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered due to incorrect address cannot be replaced without charge. Be sure to specify both old and new addresses and any change in business affiliation.

ADVERTISING COPY—changes must be received by the fifteenth of the month to be effective for the issue of the month succeeding.

STATEMENTS and opinions given in articles appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters.

REPUBLICATION from "Electrical Engineering" of any Institute article or paper (unless otherwise specifically stated) is hereby authorized provided full credit be given.

COPYRIGHT 1934 by the American Institute of Electrical Engineers.

ELECTRICAL ENGINEERING is indexed in Industrial Arts Index and Engineering Index.

Printed in the United States of America. Number of copies this issue—

16,500

This Month—

Front Cover

The Rhaetian Railway viaduct at Filisur in the Grisons, Switzerland, is a triumph of engineering skill.

Photo by E. Meerkamper, Davos

Educational Series—No. 9

Recent Theories of Ferromagnetism . . 1246
By FRANCIS BITTER

Special Articles

A Study of Nitrogen in Metallic Arc Weld Metal 1250

Electrical Practices in USSR Steel . . . 1251
By GORDON FOX

A 100-Kw Vacuum Tube 1266

A.I.E.E. Papers

A New Laboratory for High Voltage Testing 1255
By J. T. LUSIGNAN, JR., and H. L. RORDEN

Output Wave Shape of Controlled Rectifiers 1259
By F. O. STEBBINS and C. W. FRICK

Machine Characteristics for Steady Welding 1268
By F. CREEDY, R. KOGGE, and A. O. DANELLO

Equivalent Circuits in Stability Studies . . 1272
By O. G. C. DAHL and A. E. FITZGERALD

Low Pressure Gaseous Discharge Lamps—Part II 1283
By SAUL DUSHMAN

Transient Voltages in Welding Generators 1296
By A. R. MILLER

Overvoltages on Transmission Lines . . 1301
By C. L. GILKESON and P. A. JEANNE

News of Institute and Related Activities 1326

Discussions of A.I.E.E. Papers

Communication

Stabilized Feed-Back Amplifiers—Black 1311
Iron Shielding for Telephone Cables—Moore . . . 1323
Iron Armored Aerial Communication Cable—Gilkeson & Hanks 1324
Recent Developments in Power Line Carrier—Johnson. 1325

Electrical Machinery

Induction Motor Locked Saturation Curves—Norman 1312
A Graphical Solution of Steady State Stability—Dwight 1316
Irregular Windings in Wound Rotor Induction Motors—Hellmund & Velnott. 1316
Stray Load Loss Test on Induction Machines—Morgan & Narbutovskih 1317
Transformer Reactance and Losses With Nonuniform Windings—Stephens. 1318

Electric Power Switching

Switching at State Line Station—White 1312

Electrical Measurements

Portable Schering Bridge for Field Tests—Hill, Watts & Burr 1311

Power Transmission and Distribution

Corona Losses From Conductors of 1.4-In. Diameter—Carroll, Cozzens & Blakeslee 1310
Shunt Resistors for Reactors—II—Kierstead & Bewley 1315
Theory of Primary Networks—Part II—Starr 1315

Protective Devices

Distance Relay Action During Oscillations—Bancker & Hunter 1320

Transportation

Pantograph Trolleys. I—Design Features—Schaake. 1313
Pantograph Trolleys. II—Operating Features—Pickens 1313
Trolley Wire Lubrication Improved—Lamson. . . . 1314

Recent Theories of Ferromagnetism

By FRANCIS BITTER
FELLOW A.M. PHYS. SOC.
Westinghouse Elec. & Mfg. Co.
E. Pittsburgh, Pa.

Recent advances in ferromagnetic theory, which are outlined briefly in this article, are concerned principally with the effect of elastic deformation on magnetic properties and the related magnetostriction. This is the ninth of a series of special articles reviewing contemporary advances in several of the more important and rapidly advancing fields of science that are of especial interest to electrical engineers, and prepared under sponsorship of the A.I.E.E. committee on education.

NOT so very long ago ferromagnetism was merely one of the many curious and mystifying properties possessed by certain types of solids, too complicated to be of particular interest to scientists and, until the spread of electricity, of little practical importance except in the mariner's compass. Today, the subject is of great interest not only to the engineer, who has found many ways of using ferromagnetic properties and has developed new alloys that are far more satisfactory than the more common ferromagnetic materials, but also to the physicist. It seems very probable that ferromagnetism soon will be an important tool in the study of the fundamental theory and structure of metals.

It is proposed to outline in this article the progress that has been made in the understanding of ferromagnetism during the past few years. Since the successes have been confined to a small part of the subject, it may be well before entering upon a more detailed exposition to point out the general character of the experimental facts, so that the reader may see the recent contributions, important as they are, in a reasonable perspective.

One of the important facts about ferromagnetic materials is that their magnetic properties change radically with temperature. However, discussion of those properties, especially that part of especial interest to engineers, may be limited to room temperatures. Suffice it to say that temperature dependence of those properties which are understood at normal temperatures may be explained qualitatively at least. The most important quantitative results in this regard are contained in the Weiss equation

$$\frac{I_s}{I_o} = \tanh \frac{aI_s}{T} \qquad (1)$$

relating the saturation value of the magnetization I_s at any temperature T to the saturation value at the absolute zero of temperature, I_o, and certain atomic theory constants represented by the symbol a. For a more complete discussion of eq 1 the reader is referred to any book on ferromagnetism, for instance, "Magnetism and Atomic Structure" by E. C. Stoner.

At normal temperatures, then, the behavior of ordinary soft ferromagnetic materials may be divided conveniently into 2 parts. In small fields, of the order of one oersted or less, there are usually hysteresis effects, i. e., the magnetization is not determined uniquely by the external field, but depends also on the previous magnetization. This is the magnetic range of interest primarily in the transmission of signals, as in telegraph or telephone lines, where the energy available for magnetizing fields is limited. The discussion in the following pages will be limited to phenomena not involving hysteresis, and therefore will omit a large part of that interesting and important phenomena. In larger fields hysteresis effects are usually negligible—magnetization approaches saturation reversibly. Recent developments in theory have been useful chiefly in this range, and have had practical applications in the development of materials for power machinery, where both large and small fields are involved. In addition to the soft ferromagnetic materials, there are magnetically hard materials, the permanent magnets, which at present will have to be left completely out of the discussion.

Further, of very great importance is the effect of elastic deformation on magnetic properties and the related magnetostriction, or deformation caused by magnetization. This phenomenon can be treated by the new theories within the previously mentioned limitations—in the absence of hysteresis effects. Other phenomena, such as the effect of magnetization on elastic constants, on electrical resistance, etc., can be treated by the methods to be outlined with the same order of accuracy as magnetostrictive effects, but will not be discussed further in this paper. For details and further references see a review by the author in *Metallwirtschaft*, v. 12, 1933, p. 720, 735.

Model of a Ferromagnetic Substance

Without going into detail, or justifying the procedure on the basis of atomic theory, an array of elementary permanent magnets of atomic dimensions having a marked tendency to be parallel to their neighbors will be used as a model of a ferromagnetic substance for purposes of this discussion. In the absence of other restraining forces these elementary units will point in the direction of any applied field, because by doing so they reduce their energy in the field to a minimum and at the same time satisfy their tendency of being parallel to their neighbors. In the absence of external fields they may break up into groups pointing in various directions, in which condition their resultant magnetization is

indeterminate. As already explained, in very small fields hysteresis effects usually are pronounced, and these effects will be left out of the discussion. Magnetization of the model will proceed as in the curve marked [100] in Fig. 2.

Magnetization curves for ordinary ferromagnetic materials do not resemble the curves assumed for this model; but it has been found that single ferromagnetic crystals, when magnetized in certain particular crystallographic directions, do behave very much like the model. For simplicity attention will be confined to iron, a cubic crystal. Similar results have been obtained for other substances and presumably hold equally well for solid solutions. The customary designation of the principal axes is shown in Fig. 1. In Fig. 2 are shown magnetization curves for polycrystalline iron as well as for a single crystal magnetized in the 3 principal crystallographic directions. It may be seen that only along a tetragonal

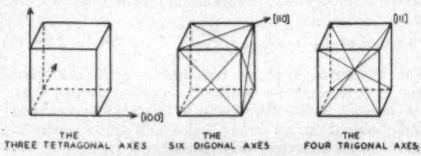


Fig. 1. The principal axes in cubic crystals

axis does the actual curve approach the theoretical curve of the model. A theoretical interpretation for all these curves has been worked out by N. S. Akulov (*Zeit. für Physik*, v. 67, 1931, p. 794, and many more articles in the same journal); his results are shown in solid lines in Fig. 2. Experimental ob-

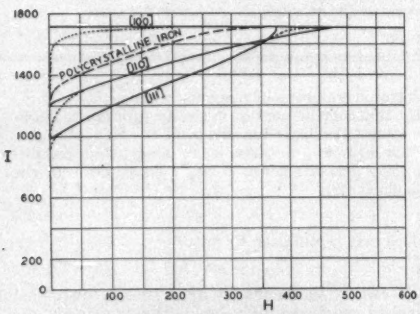


Fig. 2. Magnetization curves of iron

servations are in agreement with the theoretical curves except as shown by broken lines. The curve for polycrystalline material may be considered as the average of the curves obtained for all possible crystallographic orientations. The theoretical curve for polycrystalline material never has been calculated.

Magnetization of Perfect Crystals

Akulov's theory is based upon the proposed model, modified by the addition of crystallographic symmetry. Since magnetization proceeds practically to saturation in very small fields only if these are applied parallel to one of the 3 tetragonal axes, it may be assumed that the elementary magnets are constrained by some type of force to point along one of these axes, and that work must be done to rotate them into other directions. An easy check on this suggestion is the following: If a small field be applied parallel to a digonal or trigonal axis, the resultant magnetization in the direction of H must be given by

$$I_{[110]} = I_s \frac{1}{\sqrt{2}} = \frac{1{,}710}{1.414} = 1{,}210$$

$$I_{[111]} = I_s \frac{1}{\sqrt{3}} = \frac{1{,}710}{1.732} = 990$$

as may be seen readily from the diagram in Fig. 3. That these magnetizations are found experimentally may be seen in Fig. 2. The tetragonal axes are called the directions of easy magnetization. If a field be applied in any direction, magnetization will proceed to saturation in the direction of the nearest tetragonal axis. A further increase in the component of I parallel to H can take place only by a rotation of the direction of magnetization. Of the forces opposing such a rotation little can be said beyond the fact that their existence and order of magnitude falls quite within the limits predicted by the quantum theory of atomic phenomena.

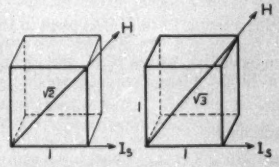
Instead of dealing with forces, it is more convenient to consider E_θ, the energy per unit volume of a crystal, as a function of the direction of magnetization. Supposing one could take hold of the saturated magnetization, how much work would have to be done to rotate it from some standard orientation, say [100], to any other given by the direction cosines α_i, α_j, α_k, measured with respect to the cubic axes of the crystal? Expanding E_θ in powers of α gives a general expression of the form

$$\begin{aligned} E_\theta = a &+ \\ & b_i\alpha_i + b_j\alpha_j + b_k\alpha_k + \\ & c_{ij}\alpha_i^2 + c_{ij}\alpha_i\alpha_j + \ldots\ldots + \\ & d_{iii}\alpha_i^3 + d_{iij}\alpha_i^2\alpha_j + \ldots\ldots + \\ & e_{iiii}\alpha_i^4 + \ldots\ldots + e_{iijj}\alpha_i^2\alpha_j^2 + \ldots\ldots \end{aligned}$$

where a, b, etc., are arbitrary constants.

Remembering that $\alpha_i^2 + \alpha_j^2 + \alpha_k^2 = 1$ and that E_θ must have cubic symmetry, or that it must have

Fig. 3. Shows that the component of I_s along digonal or trigonal axis is $I_s/\sqrt{2}$ and $I_s/\sqrt{3}$, respectively



the same value for crystallographically similar directions of magnetization, as for instance $\alpha_i = 1$, $\alpha_j = 0$, $\alpha_k = 0$, or $\alpha_i = 0$, $\alpha_j = 1$, $\alpha_k = 0$, or $\alpha_i = 0$,

Fig. 4 (left). Model of an iron crystal, and a plaster model representing E_θ, the energy required to magnetize this crystal in different directions, as described in the text

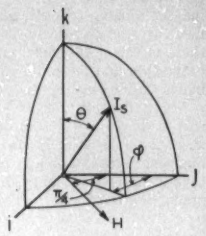


Fig. 5 (right). Diagram illustrating the transformation in eq 5

$\alpha_j = 0$, $\alpha_k = 1$, the most general expression involving powers of α not higher than the fourth is found to be

$$E_\theta = 2c(\alpha_i^2\alpha_j^2 + \alpha_j^2\alpha_k^2 + \alpha_k^2\alpha_i^2) + \text{constant}$$

$$= c\sum_{i,j,k}{}' \alpha_i^2\alpha_j^2 + \text{constant} \qquad (2)$$

c being an arbitrary constant. Figure 4 shows a plaster model of E_θ in which the length of the radius from the middle of the model to the surface in any direction represents the energy of the crystal when magnetized to saturation in that direction. In the model c is chosen positive. This makes the hollows of the figure (directions of easy magnetization) fall parallel to the tetragonal axes, as in iron, and humps (directions of most difficult magnetization) parallel to the trigonal axes. In the presence of a magnetic field a further term must be added to the energy, the total being

$$E_\theta = \text{constant} + c\sum{}' \alpha_i^2\alpha_j^2 - I_sH\cos\psi \qquad (3)$$

ψ being the angle between I_s and H. In order to find the actual direction of magnetization in any given field it is necessary to find for what direction (or what values of α_i, α_j, α_k) E_θ has its lowest or minimum value. This is the most stable direction of magnetization, and from it follows at once the component of I_s in the direction of H. For example, to compute the magnetization for any value of H applied along the [110] direction, it is convenient to rewrite eq 3 in polar coördinates

$$\alpha_i = \sin\theta\sin\varphi \qquad \alpha_j = \sin\theta\cos\varphi \qquad \alpha_k = \theta \qquad (4)$$

Magnetizing force H is applied in the direction $\theta = \pi/2$, $\varphi = \pi/4$ (see Fig. 5). It is apparent that for any positive values of H, the minimum of E_θ must lie in the plane $\theta = \pi/2$, so that eqs 4 reduce to

$$\alpha_i = \sin\varphi \qquad \alpha_j = \cos\varphi \qquad \alpha_k = 0$$

and finally

$$E_\theta = 2c\sin^2\varphi\cos^2\varphi - I_sH\cos(\pi/4 - \varphi) + \text{constant}$$

which has a minimum when φ satisfies the equation

$$\frac{\partial E_\theta}{\partial\varphi} = 0 = 4c\sin\varphi\cos\varphi(\cos^2\varphi - \sin^2\varphi) - I_sH\sin(\pi/4 - \varphi)$$

Putting $I = I_s\cos(\pi/4 - \varphi)$ this easily can be shown to reduce to

$$H = -4c\frac{I}{I_s^3} + 8c\frac{I^3}{I_s^4} \qquad (5)$$

The value of c chosen to give the close agreement between theory and experiment shown in Fig. 2 is

$$c = 2.15 \times 10^5 \text{ ergs per cubic centimeter}$$

The hysteresis loops of reasonably pure annealed iron have in general a width of considerably less than one oersted. The discrepancies between theoretical and observed curves in Fig. 2 in fields up to about 50 oersteds are therefore not caused by hysteresis effects, and will be discussed after the effect of elastic deformation on magnetization has been considered.

Magnetization of Homogeneously Distorted Crystals

The elastic distortion of a crystal may be represented by means of a tensor A_{ij}, which gives the coördinates of a point after the distortion (x', y', z') in terms of its coördinates before the distortion by means of the equations

$$x' = (1 + A_{ii})x + A_{ij}y + A_{ik}z$$
$$y' = A_{ji}x + (1 + A_{jj})y + A_{jk}z$$
$$z' = A_{ki}x + A_{kj}y + (1 + A_{kk})z$$

(A tensor is a group of numbers, such as A_{ii}, A_{ij}, . . . etc., that may be used as in the foregoing equations to express the distortion of a solid.)

For instance, if there is an elongation parallel to the x axis of amount e, and a contraction in the y-z plane $e/2$,

$$x' = (1 + e)x \qquad y' = (1 - e/2)y \qquad z' = (1 - e/2)z$$

which may be obtained by putting

$$A_{ii} = e \qquad A_{jj} = A_{kk} = -e/2 \qquad A_{ij} = A_{ji} = \ldots = 0$$

It can be shown readily that such a distortion involves no change of volume. For reference the

Table

Elongation parallel to [100]	$A_{ii} = e$, $A_{jj} = A_{kk} = -e/2$
Elongation parallel to [110]	$A_{ii} = A_{jj} = \frac{e}{4}$, $A_{kk} = -e/2$, $A_{ij} = A_{ji} = \frac{3e}{4}$
Elongation parallel to [111]	$A_{ij} = A_{ji} = A_{ik} = A_{ki} = A_{kj} = A_{kk} = e/2$

tensor components of a distortion of this type in a cubic crystal whose tetragonal axes are parallel to the x, y, and z axes of the coördinate system used are given in Table I.

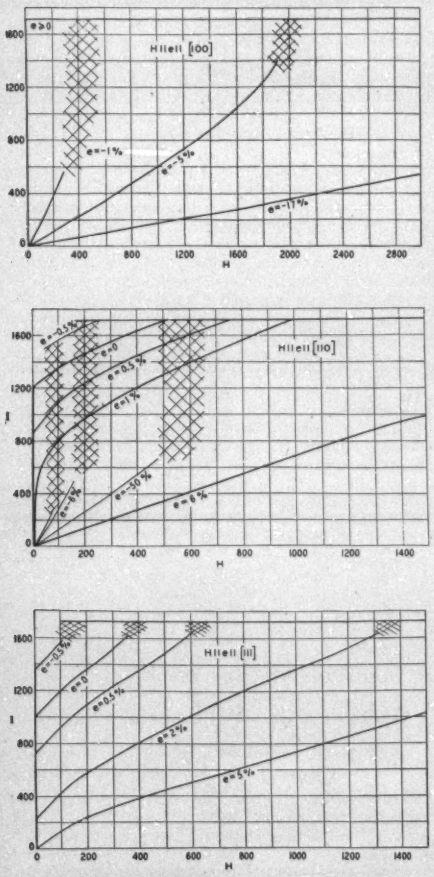
The procedure outlined for obtaining the energy of a crystal as a function of the direction of magnetization may be applied equally well to distorted crystals; it is necessary merely to add in the expansion terms involving products of A_{ij} and α_i, etc. Doing so, and limiting the operation to the simplest terms of the expansion, the most general expression for E_θ having the desired cubic symmetry is found to be

$$E_\theta = c\sum{}'\alpha_i^2\alpha_j^2 + K_1[A_{ii}\alpha_i^4 + A_{jj}\alpha_j^4 + A_{kk}\alpha_k^4] + K_2[(A_{ij}+A_{ji})\alpha_i\alpha_j + (A_{jk}+A_{kj})\alpha_j\alpha_k + (A_{ki}+A_{ik})\alpha_i\alpha_k] - I_sH\cos\psi$$
$$= c\sum{}'\alpha_i^2\alpha_j^2 + K_1\sum A_{ii}\alpha_i^4 + K_2\sum{}'A_{ij}\alpha_i\alpha_j - I_sH\cos\psi \quad (6)$$

The magnetization curve of a crystal elastically distorted in any manner describable by the tensor A_{ij} now can be calculated by the same processes, merely using the more complete expression for E_θ, provided the values of constants K_1 and K_2 suitable for iron are known. How these constants may be evaluated from data on magnetostriction will be shown in the next section. The result is

$K_1 = -3.06 \times 10^7$ ergs per cubic centimeter
$K_2 = 2.85 \times 10^7$ ergs per cubic centimeter

Magnetization curves for iron crystals elongated in each of the 3 principal directions are shown in Figs. 6 to 8. The values of A_{ij} used are those shown in Table I. Only very small elastic distortions can be given a single crystal and these, in general, would not have the simple form given in Table I. The curves are intended merely to indicate the type of result to be expected. For certain values of H and e the function E_θ has several minima of equal or almost equal energy. In such cases the procedure outlined becomes ambiguous, and this fact is indicated by the cross-hatched part of the curves. A comparison of these curves with experiment cannot be made as no experimental data are available. The theory of distorted crystals was advanced by R. Becker (*Zeit. für Physik*, v. 62, 1930 p. 253, and subsequent articles with collaborators in the same journal; also F. Bitter, *Physical Review* v. 43, 1933, p. 655). He and his collaborators have checked certain predictions with observations on polycrystalline material, especially nickel.



Figs. 6 to 8. Magnetization curves of iron crystals elastically distorted by tension in various crystallographic directions

Magnetostriction

When the magnetization of an iron crystal changes, its shape changes also. This change of shape is called magnetostriction; it can be calculated for rotations of the direction of magnetization from eq 6. The forces required to produce the distortion A_{ij} are given by a tensor F_{ij} defined by the relations:

$$F_{ij} = \frac{\partial E}{\partial A_{ij}} \quad (7)$$

E being the total energy of distortion of the crystal, E_θ plus the elastic energy E_{el}

$$E_{el} = \frac{c_{11}}{2}\sum A_{ii}^2 + \frac{c_{12}}{2}\sum{}'A_{ii}A_{jj} + c_{44}\sum{}'A_{ij}^2$$

where the elastic constants have in iron the values

$c_{11} = 0.237 \times 10^{13}$ $\quad c_{12} = 0.141 \times 10^{13}$
$c_{44} = 0.116 \times 10^{13}$ ergs per cubic centimeter

The question is, what are the distortions of the crystal for any given direction of magnetization that will make all the external forces F_{ij} defined by eq 7 vanish? There are 9 equations to solve which will give the 9 tensor components defining the shape of the sample as functions of α_i, α_j, α_k. Instead of these results it is more convenient to use the change in length per unit length of a sample, $\delta l/l$, measured in a direction given by the direction cosines β_i, β_j, β_k, caused by a change in magnetization from any

Fig. 9. Magnetic pattern on a nickel crystal. Direction of applied magnetic field ⟶

given original state to the final state given by α_i, α_j, α_k. Carrying out this operation gives

$$\frac{\delta l}{l} = \sum A_{ii}\beta_i^2 + \sum{}' A_{ij}\beta_i\beta_j + \text{constant} \qquad (8)$$

$$= \kappa_0 + \kappa_1 \sum \alpha_i^2\beta_i^2 + \sum{}' \alpha_i\alpha_j\beta_i\beta_j$$

$$\kappa_1 = -\frac{K_1}{c_{11} - c_{12}} \qquad \kappa_2 = -\frac{K_2}{2c_{44}}$$

To illustrate the application of eq 8, consider the change in length in the direction of magnetization resulting from magnetization to saturation along a tetragonal axis. In this case $\alpha_i = \beta_i = 1$, $\alpha_j = \alpha_k = \beta_j = \beta_k = 0$, and consequently $\delta l/l = \kappa_0 + \kappa_1$. The constants κ_0, κ_1, and κ_2 may be evaluated by a comparison with experiment; for iron they are found to be

$$\kappa_0 = -15.5 \times 10^{-6} \qquad \kappa_1 = 32.0 \times 10^{-6} \qquad \kappa_2 = -12.3 \times 10^{-6}$$

From these and the elastic constants, K_1 and K_2 can be evaluated. Agreement between eq 8 and experiment is fair, but it is possible that a close check requires that further terms in the expansion of E_θ be taken into account. The available experimental data are not sufficiently consistent to settle this point.

Concluding Remarks

In the discussion so far 8 arbitrary constants have been used. The saturation value of the magnetization I, can be accounted for more or less accurately by atomic theory, especially as regards its variation with temperature. Of general interest is the conclusion that the magnetic elements giving rise to magnetization are spinning electrons somewhere near the outer surface of the atoms. The constant c measuring the binding energy between the direction of magnetization and the lattice also can be accounted for roughly on the basis of atomic theory. The other 6 constants, 3 elastic and 3 determining magnetostriction, are purely empirical. One may expect that present notions of atomic interactions can account for them, but the computations are so involved that no successful attempts so far have been made.

The discrepancies between theory and experiment shown in Fig. 2 in fields up to 50 oersteds in all probability can be ascribed to the fact that the crystals on which observations were made were not perfect. Assuming that actual crystals contain randomly oriented distortions varying from point to point within a crystal, it is possible to calculate, using Becker's theory, the resulting magnetization curve. Such calculations show that random distortions not only can account for the rounded curves found experimentally (Fig. 2), but also can predict certain peculiarities at low flux densities which in fact do exist. The conclusion is that in those ferromagnetic crystals so far examined, random distortions of the order of, or somewhat larger than, magnetostrictive distortions are present. (Further discussion of this point will appear shortly in a paper by the author in the *Proceedings* of the Royal Society.)

In closing it may be well to point out, that in spite of the success of the comparatively simple ideas discussed in this article, the phenomena themselves are more complicated. It is well known that magnetic powders may be used to detect inhomogeneities in magnetization along the surface of a ferromagnetic substance. The same method somewhat refined and applied to single crystals has shown that instead of being homogeneously magnetized, as might have been expected, flux leaves or enters the surface in a regular way. For instance, a powder of magnetic iron oxide (Fe_2O_3) allowed to settle slowly out of suspension onto the surface of a nickel crystal, settles in a pattern such as that shown in Fig. 9. The larger periodicity is roughly 0.1 mm. These lines are not permanent structural features, but can be made to move by changing the magnetization. Similar, though characteristically different, results have been obtained for iron and cobalt crystals (F. Bitter, *Physical Review* v. 41, 1932, p. 507). How these patterns can be fitted into theories, or even what part they play in the process of magnetization, is at present a mystery.

A Study of Nitrogen in Metallic Arc Weld Metal

ONE of the most important and most difficult problems involved in electric welding is the control of the nitrogen content in the deposited weld metal. For the most part, research work to date has been concentrated upon the *effect* of nitrogen in the deposited metal and not upon the actual *control* of the nitrogen content of the deposited metal.

In recognition of the importance of this subject, the A.I.E.E. board of directors, acting upon the

recommendation of the A.I.E.E. committee on electric welding, in 1932 enlisted the coöperation and support of The Engineering Foundation toward the underwriting of a research project then under consideration at Massachusetts Institute of Technology. With the Foundation's support, John W. Miller, a graduate of Simpson College (1929) and recipient of a masters degree from the M.I.T. mining and metallurgy department, initiated an extensive research into the subject of nitrogen in metallic arc weld metal. Upon completion of his work, Mr. Miller was awarded the degree of doctor of science. Doctor Miller's thesis has been bound by the A.I.E.E. and placed in the Engineering Societies Library, 29 West 39th Street, New York, N. Y., where it is available for reference purposes.

Doctor Miller's thesis embraces a comprehensive review of the literature, and other topics related to the subject of his research. With specific reference to the nitrogen content of deposited weld metal, Doctor Miller studied and reported the effect of the nitrogen content of the welding atmosphere, carbon content of the electrode, electrode size, amperage and voltage, lime coating on electrodes, hard drawn and annealed, electrodes, and reversed and straight polarity.

In his investigation Doctor Miller found that the nitrogen content of weld metal deposited by the metallic arc process may be diminished by increasing the size or diameter of the electrodes, increasing the carbon content of the electrode, increasing the current density, reversing the polarity, decreasing the nitrogen content of the arc atmosphere, decreasing the voltage used, and using heavily coated electrodes.

A rapid method for the determination of nitrogen in weld metal is outlined in detail and a discussion of the microstructures found in metallic arc weld metal is included.

The author proved, by means of X ray diffraction work and heat treatment, that the needles found in the weld metal probably are due to the presence of nitrogen in the form of the compound Fe_4N which is precipitated and segregated. By the same means, he has shown that the main oxide present in weld metal is the magnetic oxide of iron. Also it was found that the needles may occur at both the grain boundaries and within the grain itself and that they may tend to segregate. The presence of Neumann bands was noted and some discussion given them.

The report shows that conditions leading to the absorption of nitrogen also lead to the burning out of carbon and contamination by oxygen.

A discussion of the gases probably responsible for blowholes in arc weld metal is included. It is explained that the gas most likely to form blowholes in the weld metal is carbon monoxide with perhaps the assistance of hydrogen and hydrocarbons (if such occur) which may be present.

Excellent evidence is shown that, at the high temperatures of welding, an increase in the temperature causes a decrease in the solubility of nitrogen in iron.

Physical test data show that conditions leading to a decreased nitrogen content result in improved physical properties.

Electrical Practices in USSR Steel

On the basis of several years of first hand association the author here describes some of the current electrical practices in the steel industry of the Soviet Union, and indicates the general trend of development.

By
GORDON FOX
MEMBER A.I.E.E.

Freyn Engineering Co.,
Chicago, Ill.

THE GENERAL PROGRAM for the development of the steel industry of the Soviet Union includes some rehabilitation of old plants. To a large degree, however, it involves the construction of complete new plants or new departments. Projects for some 10 complete new plants may be considered as active. While these plants differ individually, in most cases they involve coke ovens, sintering plants, blast furnaces, steel works, and rolling mills, together with a large number of shops and accessory units.

In most instances the steel plants do not stand alone. Brick plants, cement plants, car fabricating shops, etc., having industrial relationship with the steel plants, are located contiguously. Towns for the employees of these industrial districts also are involved.

In a nation where all industry is under the control of a central government, several advantages are possible, both in standardization of practices and in coördination of related enterprises. To some extent, such coördination has been applied in the utilization of energy sources and the provision of energy services to these districts. For instance, by-product gases from coke ovens and blast furnaces are used, not only in the steel works, but in the related plants and in the towns. District heating is, in some degree, associated with power development at the steel plant. Water supplies are sometimes coördinated.

In most cases those steel plant sites that are most favorable in other respects are not favored as to water supply. This perhaps is a principal reason that has dictated the general policy of restricting the size of electrical generating stations in the steel plants. These generating stations are sufficiently large to protect essential consumers, to utilize by-product fuels, to provide bled steam for district heating needs.

The initial steps toward rehabilitation of old

Written especially for ELECTRICAL ENGINEERING. *Not published in pamphlet form.*

General view of the Kuznetsk steel plant, Stalinsk, Siberia, taken in 1932, showing the power house at the left, blast furnaces in the center, and coke oven plant at the right

plants, under German influence, involved the installation of several gas engine driven generators. More recently this policy has been abandoned entirely in favor of turbine generators. A popular size of turbine generator in the larger plants is 25,000 kw, the station comprising 1 to 4 such units. Supplementary power, at these plants, is received from high voltage loop lines usually at 32 or 110 kv. These loops are parts of existing or proposed networks supplied from large and favorably located generating stations.

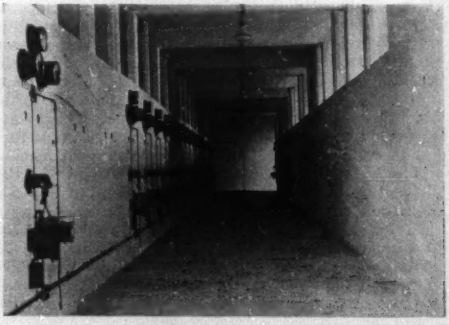
In the matter of power distribution, each plant, of course, is a study unto itself. A general arrangement that has proved advantageous in several cases involves an electrical generating station in conjunction with the blowing station at the blast furnaces. The step-down substation at which supplementary power is received is located in the general vicinity of the rolling mills. This arrangement is attractive because of the predominance of electric power consumption in the rolling mill area. The generating station and step-down substation are connected by tie lines.

Underground distribution of electric power strongly predominates. Greater expected reliability is the principal factor that dictates this practice.

In a few instances tunnels are provided for the underground cables. To a limited extent, particularly for small outlying consumers, armored cables of the parkway type are buried directly in the ground. Preference is growing rapidly, however, for the American system of duct line construction. Fiber duct is favored, but is available only by import. Initially, small sewer tile is being substituted. Cables are paper insulated. Varnished cambric insulation is not yet produced in the Soviet Union, but its manufacture at an early date is contemplated.

In general, new Russian steel plants cover considerably larger areas than would be required in America, and consequently the distribution of electricity and all other services is rendered somewhat more expensive by this condition. Track curves of large radius contribute to this situation, such curves being necessitated by the wide track gauge and by the 4-wheeled rigid-axle cars.

Two systems of primary distribution were carefully compared in connection with several projects. In one system power was to be generated and distributed at 6 kv. The larger motors were wound for this voltage; for smaller motors, 380 volts were used. In the other system power was to be generated at 10 kv. The larger motors were wound for that voltage; intermediate motors were wound for 3 kv, and the smallest motors were rated at 380 volts or, in some cases, at 500 volts. Each of these systems has advantages and disadvantages. Cost analyses indicated that the savings in first cost associated with the use of the 10-kv system were not great, and in general were insufficient to warrant the adoption of this higher voltage in the face of slightly reduced operating efficiencies with high voltage motors and increased extent of transformation. In exceptional cases where large power plants were involved or where transmission distances were extended, the use of 10 kv was thought to be justified. The practice therefore was adopted tentatively to design the windings of large main drive motors for delta connection at 6 kv, and star connection at 10 kv.



Center aisle construction typical of Russian steel mill substations

Protective relays and solenoid operating mechanisms are mounted directly on cell walls. Oil switches can be operated manually by means of removable handles, not shown. Servicing is done from outdoors through exterior doors in each cell

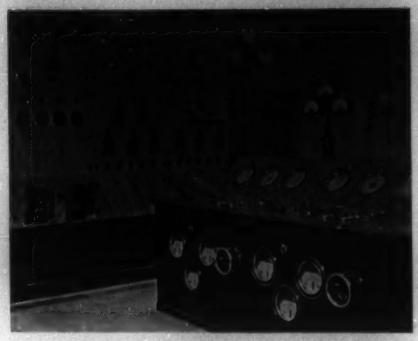
The frequency of 50 cycles is standard throughout the Soviet Union. This frequency is well adapted to steel plant requirements.

In general, it is considered preferable to ground the 10-kv and 6-kv systems through high resistance, in conformity with European practice. The 3-kv systems and 380-volt systems, of restricted extent, are generally ungrounded. Lighting systems are grounded.

Although there are, of course, many variations to suit local conditions, distribution systems are commonly of radial or modified radial types. The Russian tendency was to provide duplicate radial feeders from the main distribution points direct to most consumer substations. This practice has been modified gradually in favor of 2-stage radial distribution in which lesser consumers are sometimes supplied as subfeeds from main consumer substations. The use of emergency tie lines between consumers, rather than duplicate radial feeders in certain instances, also is gaining headway. Loop systems of distribution were considered in several projects, but cost analyses generally were unfavorable. The limitations of Russian made relays now available also militate against this system. Loops therefore are used in relatively few instances.

Substation designs and switching arrangements savor strongly of continental European practice. The prevailing basic scheme is the double bus with 2 sets of disconnecting switches and one oil switch for each connection. The disconnecting switches are manually operated, and arranged to be closed either selectively or simultaneously; oil switches usually are remote electrically operated.

In general the substations are long, narrow buildings, having an operating aisle centrally located between 2 rows of switches. Oil switches are placed in small chambers adjacent to exterior walls, and exterior doors are provided for access to and removal of the equipment. Glass is provided either in or above these doors to serve as a relief valve for gases liberated in the oil switch chamber in the event of an oil switch explosion.



Control room in a Russian steel mill substation

The wide spread adoption of this general switching system and this mode of substation construction results in part from the fact that existing Russian types of oil switches and fittings were designed for and are adapted to such systems. These methods are not confined to the Russian steel industry, but characterize Russian electrical practice in general. American electrical engineers who have coöperated in designing Russian steel plants consistently have criticized and opposed these switching practices and have recommended the adoption of American practice which may very broadly be characterized as entailing:

1. Double bus with 2 selective oil switches per circuit for important generation stations.
2. Single bus for nearly all substations, this bus being sectionalized to promote reliability and flexibility wherever the character of the station demands such sectionalization.

Upper level of switch structure typical of Russian steel mill substations

6-kv buses appear above; disconnecting switches are in the lower compartments

Probably no phase of electrical practice in the Russian steel industry is less advanced than the field of switching and substation design. Three types of Russian made oil switches are available for steel plant use, having rupturing capacities of 250,000, 150,000, and 100,000 kva at 6 kv. Oil blast or deion features have not yet been applied to any of these switches.

Since most of the Russian steel plants are connected to high voltage networks that are expected ultimately to involve large amounts of power, oil switches of rather high rupturing capacity would be indicated. Rather liberal use of reactors has been adopted for the double purpose of limiting short circuit currents and oil switch sizes, and for restricting voltage disturbances. These commonly take the form of feeder reactors. By this means the wide adoption of the 150,000-kva oil switch, an economical selection, has been made possible.

As yet, the use of cubicle and metal clad types of switching are hardly feasible in Russian steel plants except in connection with imported apparatus.

Switching for 6-kv lighting distribution
This view shows incoming feeder and manually operated primary oil switches controlling 2 3-phase transformers

As there is a shortage of rolled steel, and as the Russian electrical factories are unable as yet to meet all demands for equipment, it is hardly feasible to push the "factory built" idea. It is more feasible to erect masonry cell structures in the field.

The great majority of transformers used in Russian steel plants are 3-phase units. Only in the very large sizes is the use of single phase transformers resorted to. The Russians have been reluctant to locate transformers in steel plants out of doors. The practice of housing transformers in ventilated rooms or chambers still prevails, although a few outdoor installations have been projected. Most of the transformers are of oil-insulated self-cooled types. Bouchal's type of temperature relays are adopted frequently, this being inherited practice.

For supplying direct current to main roll drives, motor generators are standard. For supplying direct current to auxiliary drives, motor generators also are used. Existing Russian sets are of slow speed and rather cumbersome, expensive, and limited in commutating ability. Mercury vapor rectifiers, produced in the Soviet Union, are favored by many, and are being tried out in a few plants. If they prove satisfactory, their wider adoption seems likely.

Main roll drives will be of 3 principal types, namely: reversing drives, constant speed drives, and adjustable speed drives. The Russian factories are just starting to build main roll drives. It is probable that, for some time to come, most main roll drives will be imported. Russian designs in all probability, will follow American practice rather closely. Two 7,000-hp reversing motors for driving blooming mills have been built in the Soviet Union, the control being along American lines. The use of synchronous motors for Ilgner sets for reversing drives for rail, structural, and universal mills is seriously considered. It is probable that nearly all constant speed drives will employ synchronous motors. The general tendency will be toward highly subdivided groups with one motor driving 1, 2, or 3 stands. Self-contained parallel-shaft gear units are favored over bevel gears and lay shafts. As yet the Russians display a desire to restrict gearing to rather low ratios.

For adjustable-speed drives for new mills the direct-current motor will be almost universally employed. For these motors 600 volts has been adopted as standard, and Ward-Leonard starting will be usual. Individual drives will be the rule rather than the exception. For auxiliary drives and cranes the use of direct current at 220 volts has been widely adopted for new plants. Some of the older plants retain a-c auxiliaries; others use direct current at about 500 volts. The latter 2 systems represent prevalent European practice.

The Russians have adapted for mill and crane use a "box" type of crane motor, the armature of which is removable through the end of the frame. Steps are being taken to split horizontally the frames of some of the larger sizes. This motor has an armature of rather large diameter and considerable inertia. It is built only in the "bare" type without axle bearings. This motor was adopted as a necessary expedient due to its availability, many Russian engineers realizing its deficiencies. The development of a mill-type motor along American lines is a probable occurrence of the near future.

Inherited designs of Russian controllers are largely of the drum type. The advantages of magnetic control are fully recognized. Russian factories have produced several magnetic controllers designed along American lines. The wide spread use of this type of control is limited only by lack of availability.

New Russian steel plants are designed for rather high illumination intensities. In accord with customary European practice, initial installations are being made on the basis of 220-volt lamps, and 3-phase distribution. This system was adopted because of stringency of copper, although there is a division of thought, many Russian engineers favoring the use of 120-volt lamps. The use of single phase circuits for lighting has been prevented in part by the fact that Russian electrical factories do not as yet produce small single phase distribution transformers. The practice of supplying separate transformers for lighting supply recently has been adopted. In some of the earlier installations a combination 220/380-volt supply for power and lighting was used.

It is anticipated that alloy steels will find considerable demand in the Soviet Union. The production of alloy steels in electric furnaces will be restricted, however, by the high cost of electric power at most steel plant sites. The situation at Dneiprostal (Zaporosche) plant is exceptional. This plant is located on the Dnieper River contiguous to the Dneiprostroy hydroelectric development. Several electric furnaces have been installed there for production of alloy steels. Ferro-alloys will also be produced there in large electric furnaces. Some

of these furnaces will consume marginal power that is not available throughout the entire year.

It should not be considered that the electrical practices sketchily outlined in the preceding paragraphs represent final, fixed procedure in the steel plants of the Soviet Union; the whole situation is in a state of flux. Systems are evolving slowly. To a large extent, usage has been dictated by characteristics of equipment available from Russian electrical factories or by import from sources affording attractive commercial terms. To no small degree engineering has been compromised to necessity.

A consistent and well advised attempt is being made to crystallize and standardize practices as the industry develops. The commission which functions to this end is one which comprises representatives of GIPROMEZ, the general planning institute for the steel industry, and V. E. O., the state electrical trust. As American engineers have been attached to both of these organizations, the earmarks of American practice are seen in many directions.

A New Laboratory for High Voltage Testing

A description of the impulse, power frequency, and high frequency testing facilities now available in a new high voltage laboratory is given in this paper. In particular, a new form of 3,000-kv impulse generator is described wherein size, inductance, and stray capacitance have been reduced to a minimum by a helical arrangement of capacitor units.

By
J. T. LUSIGNAN, JR.
MEMBER A.I.E.E.

H. L. RORDEN
ASSOCIATE A.I.E.E.

Both of the Ohio Brass Co., Barberton, Ohio

IN ORDER THAT present day line insulation problems may be studied fully in the laboratory, it is desirable that the proper voltage generating, measuring, and recording facilities be available. To investigate the lightning insulation necessary for operating voltages up to the present limit of 287 kv, an impulse generator for voltages of the order of 3,000 kv is essential. To take care of normal frequency requirements over the same range, a 60-cycle voltage of at least 1,500 kv to ground is desirable. For special high frequency studies an oscillator having a generating capacity of about 750 kv will suffice.

Although indoor testing with the above facilities affords freedom from unfavorable weather conditions, the need for ample electrical clearances, particularly for full-sized tower and equipment set-ups, dictates that some provision for outdoor studies be made. It was with this in mind that the new laboratory arrangement described herein was planned. In Fig. 1 is shown a plan of the laboratory building and grounds. The main laboratory building is shown at the left, and to the right is the outdoor test area. Here the various tower structures are stored, each mounted on its own car and located on the proper storage track. In this way any structure may be brought to the test track shown, where it is easily accessible for impulse tests up to 3,000 kv to ground and 60-cycle tests up to 2,000 kv to ground. For these tests connection is made either to the portable impulse generator at one end of the building or to the chain connected transformer set at the other, the latter having 2 units outdoors and 1 indoors. In the arrangement shown on the test track in Fig. 1, a single-circuit steel tower insulation assembly is connected in parallel with a wood pole H-frame assembly for a simultaneous impulse flashover test on both to determine the relative insulating properties of the 2 under lightning.

In Fig. 2 is shown a perspective view of the interior of the main laboratory building. The impulse generator, which will be described fully in the following paragraphs, is at the left with the 2,000-kv section connected for test. The 1,000-kv top section is suspended above the door, only the lower insulators of it being visible. On the right is the power frequency test area. The transformer mounted on the porcelain pier in the pit is the first unit of the 2,000-kv chain-connected set and the smaller unit in the corner is for special power frequency tests up

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted May 31, 1934; released for publication July 20, 1934. *Not published in pamphlet form.*

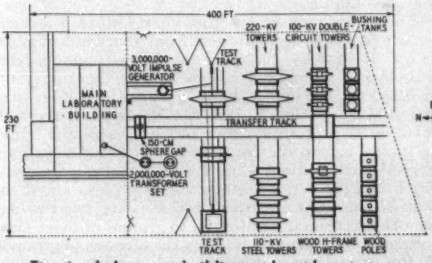


Fig. 1. Laboratory building and outdoor test area

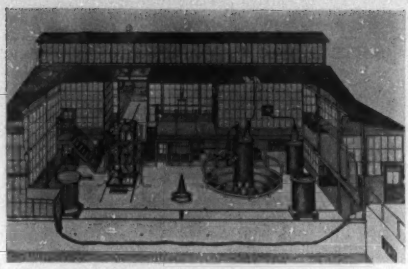


Fig. 2. Interior of main laboratory building

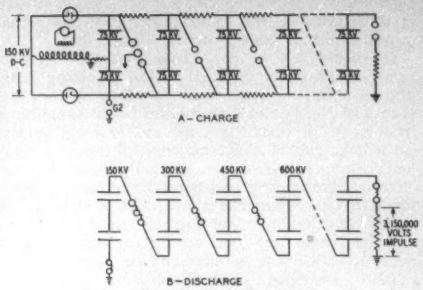


Fig. 3. Circuit of impulse generator

to 300 kv. Mounted on the tracks in the left foreground is the air-insulated transformer coil for high frequency testing. The equipment and rooms in the background are for special test purposes to be described later. The mezzanine platform in the center background provides a safe vantage point for witnessing practically all tests, both indoor and outdoor.

Impulse Generating Facilities

While an upper limit of 3,000 kv was desirable for the high insulation range, it was decided that 2,000 kv would take care of most requirements and therefore would suffice for the indoor installation. Accordingly, a portable impulse generator for 2,000 kv was designed, to which a 1,000-kv section could be added for operation outdoors. As the Marx circuit of parallel charging and series discharging was adapted ideally to such an arrangement, it was chosen for the generator. The particular form used is shown in Fig. 3, which illustrates the parallel charging stage and the series discharging stage. At the completion of the charging stage the 3-electrode gap, G_1, is sparked over by a control circuit surge placed on the middle electrode. This causes all the remaining gaps to sparkover successively, thereby connecting all capacitor units in series as shown in the discharge diagram. Capacitor units each rated 75 kv and 0.33 μf are used, with 2 in series in each bank as shown. There are 42 such units in the set so that a maximum charge voltage of about 3,150 kv may be obtained.

The arrangement of the charging transformer circuit is somewhat different from that used in most Marx generators. Instead of having one of the transformer terminals connected to the midpoint of the first capacitor bank as is often done, this terminal is grounded and a resistance is inserted between this ground point and the capacitor bank midpoint, as shown in Fig. 3*a*. In this way one transformer terminal is always kept at ground potential instead of at a voltage above ground equal to that of one capacitor unit, which latter imposes on the other terminal a potential to ground of twice this voltage. This greatly relieves the stresses to ground of the transformer winding and permits a transformer of lower voltage insulation to be used. The gap G_2 therefore must be inserted below the first bank in order to bring that point to ground potential upon discharge. Another advantage of this arrangement is that it always permits tripping the impulse generator by surging the middle sphere of the 3-electrode control gap with a negative impulse from the oscillograph cathode circuit regardless of the polarity of the main surge. This follows since both outside spheres of the 3-electrode gap are always at a potential from ground of opposite polarity during the charging period instead of one being grounded, as is the case when gap G_2 is omitted and the first capacitor bank is connected to ground.

It is apparent from Fig. 3*b* that during the discharge each successive capacitor unit position from left to right assumes an increasingly higher impulse

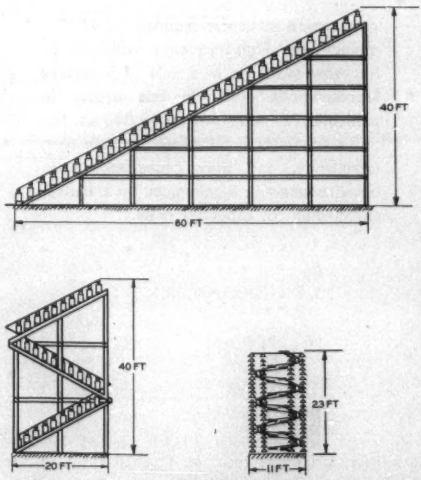


Fig. 4. Forms of 3,000-kv impulse generator supports

Top, triangular; below, zigzag and helical

voltage above ground, and must be insulated for it. In considering the insulating support for this purpose, it was necessary to remember that the complete generator had to be portable and capable of use outdoors. In order to have it portable, it was desirable that it be as compact and mechanically stable as possible. To allow outdoor operation, it was essential that no insulating material be used in the support which would be affected by moisture and therefore incur burning and charring internally or on the surface during voltage stresses. This last requirement precluded the use of wood, paper, molded compounds and the like, and made it practically necessary to adopt porcelain throughout.

In view of all of the above requirements, a generator support was developed wherein the capacitor units were arranged in an ascending helical path, supported by a hexagonal framework of pillar insulators of standard assembly. In this form all of the capacitor units could be mounted on their sides with their bushing terminals turned inward. This horizontal mounting of units resulted in an appreciable saving in height of structure, and reduced the lengths of leads between units and thereby the total inductance of the set. The use of a helical path kept the horizontal cross section of the generator at a minimum, thereby reducing the stray capacitance to ground and increasing the efficiency of the set both in regard to effective testing voltage and freedom from oscillations.

A comparison of the size of the helical mounting and the familiar triangular and zigzag mountings often used is shown in Fig. 4. Typical dimensions of the latter 2 mountings have been chosen for a 3,000-kv set and are found to be appreciably greater than the helical form developed here. The complete 3,000-kv helical set on its motor driven car just outside the laboratory door may be seen in Fig. 5. In Fig. 6 the set has been moved into the building for tests up to 2,000 kv, the 1,000-kv top section now being suspended in the background just inside the door.

The helical arrangement of capacitor units, all mounted horizontally with terminals inward, provides a ready means for controlling simultaneously the spacings of the series spark gaps. To do this, one sphere electrode of each gap is fitted to a radial porcelain rod which can be moved longitudinally through connection to a rotating center stack of pillar insulators. A close-up view (Fig. 7) of the internal structure of the generator illustrates this feature. The rotation of the pillar stack and the consequent adjustment of all gap settings, including the 3-electrode gap, is controlled electrically from the oscillograph room, thereby allowing the entire operation of the set over the whole voltage range to be handled from that point. The circuits for surging the oscillograph cathode and 3-electrode gap, for operating the alarm bell, and for synchronizing with power frequency voltages are actuated by motor driven contactors. By this means successive surges on a test occur automatically so that the operator is free to observe and photograph all cathode ray oscillograph records.

The radial supporting tubes just described for the series spheres, as well as all the charging resistance holders, were made of porcelain in line with the plan of having no insulating material on the generator which could not operate under outdoor conditions.

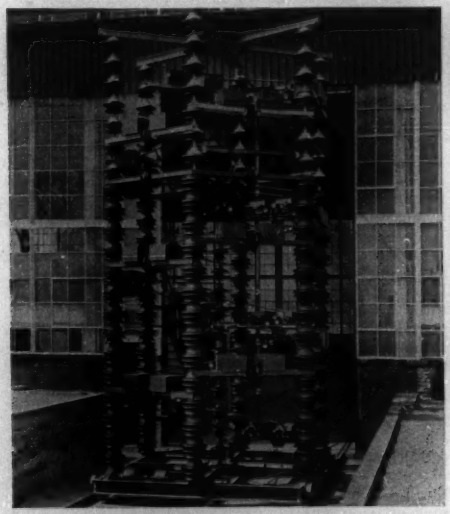


Fig. 5. Complete 3,000-kv impulse generator

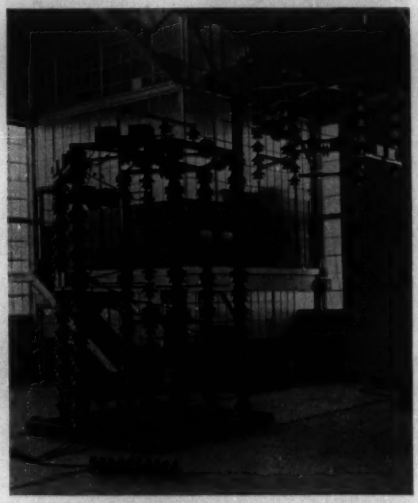


Fig. 6. Impulse generator with upper section removed

The inherent constants of the 2,000-kv section are:

Series capacitance	0.0118 μf
Series inductance	.52 μh
Series resistance (minimum for complete damping)	600 ohms

The calculated value of 600 ohms necessary to effect complete damping of the oscillations due to the inductance and stray capacitance of the circuit produces a wave front of about 1 μsec when no other capacitance is connected in the test circuit.

In Fig. 8 are shown typical cathode ray oscillograms taken with the 2,000- and 3,000-kv sections. The usual resistance type of voltage divider was used for these, a high voltage cable being connected from the lower end of the resistance column to a grounding resistor equal to the cable surge impedance at the oscillograph. The voltage wave across certain taps of the latter resistor was then applied to the oscillograph plates for recording. The voltage divider itself consists of 4,000-ohm units, each made with non-inductively wound wire and mounted in oil filled light porcelain tubes of oval cross section. These resistors may be seen suspended near the center of the 2,000-kv set in Fig. 6. The oscillograph room, which is completely enclosed by metal for shielding purposes, may be seen in Fig. 2 at the right of the impulse generator.

The inherently low series inductance of the generator circuit affords a ready means for securing comparatively high impulse surge currents. Although no high current studies have been made as yet, preliminary calculations and tests indicate that 40-μsec surges of over 100,000 amp at 150 kv may be obtained.

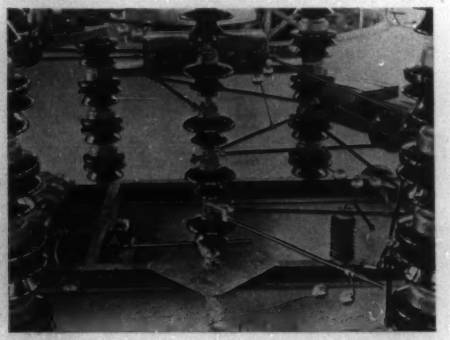


Fig. 7. Structure of impulse generator

Power Frequency Testing Facilities

As noted previously, power frequency tests up to approximately 2,000 kv to ground may be made by means of a 3-unit set of 700-kv transformers arranged for chain connection. Each transformer is of the shell type with the center of the high voltage winding connected to the core and tank. Accordingly, each tank had to be insulated from ground to allow full unit voltage to ground to be developed. To allow for outdoor operation, this insulating mounting was made from special porcelain tile. The tile pier supporting the indoor unit, shown at the right in Fig. 2, and the tank clearances to ground have sufficient insulating properties to permit this unit to be excited by one of the outdoor units so that a power frequency testing voltage of more than 1,000 kv to ground may be secured indoors. With this unit operating as the ground transformer and exciting the 2 outdoor units, potentials up to 2,000 kv to ground may be obtained. Obviously, the outdoor units must have their tanks insulated by the porcelain piers for voltages of the order of 1,050 kv and 1,750 kv to ground, respectively. The availability of these 3 identical units affords facilities for making 3-phase tests up to approximately 1,200 kv between lines. Generator facilities are available for making the above tests at 25 and 50 cycles as well as at 60 cycles, although the reduced frequencies obviously lower the voltage ranges available for tests, due to the saturation limits of the connected transformers.

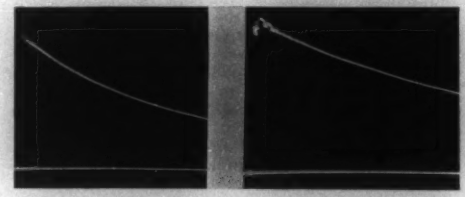


Fig. 8. Oscillograms of impulse generator voltage waves

(Left) $1^1/_2$x40-μsec wave of lower section charged to 2,000 kv
(Right) 40-μsec wave of complete 3,000-kv generator without series damping resistance, showing low amplitude of oscillations; charge voltage, 2,800 kv

On the right mezzanine section of Fig. 2 is located a special room for corona and radio influence tests. It is entirely enclosed with sheet metal to shield radio studies from outside influence, and may be completely darkened for corona observations on insulators. Another room, associated with the laboratory but separated from it to avoid contamination, is available for making special fog, dust, and smoke studies on insulators. Facilities are available here for observing and recording all insulator discharges associated with atmospheric contamination conditions.

For special high-current power-frequency tests on busbars, bushing leads, etc., generator facilities are present from which sustained currents of over 5,000 amp may be secured.

High Frequency Testing Facilities

For special insulation studies, a high frequency oscillator is available which is capable of generating wave trains of frequencies of from 50,000 to 100,000 cycles at potentials up to 750 kv. The air core transformer is shown mounted on a car at the left in Fig. 1 by which it may be moved to the proper test area for the necessary voltage clearances. The same transformer is used for studies, principally on radio insulators, at continuous wave frequencies up to 100,000 cycles. The generating source here is a Poulsen arc set.

Output Wave Shape of Controlled Rectifiers

Methods of estimating the harmonics in the output voltage wave of controlled voltage mercury arc rectifiers are given in this paper. Two limiting conditions are considered: one where the d-c circuit is sufficiently inductive to give substantially a smooth direct current, and the other where the d-c circuit is noninductive. Formulas for the harmonics when the rectifier is delivering load are presented, and curves are given that make it possible to calculate readily the lower orders of these harmonics which appear in the output voltage of 6- and 12-phase rectifiers.

By
F. O. STEBBINS
MEMBER A.I.E.E.

C. W. FRICK
ASSOCIATE A.I.E.E.

Both of General Elec. Co., Schenectady, N. Y.

MERCURY ARC RECTIFIERS when equipped with grids may be given output voltage characteristics very similar to those of a d-c generator. Output voltages ranging from zero to the voltage the rectifier would develop when not equipped with grids may be obtained by shifting the phase of the grid excitation in the proper manner. Unlike the d-c generator, the harmonics present in the output voltage wave are inherent in the normal operation of the device. The purpose of this paper is to discuss the output voltage wave shape of mercury arc rectifiers equipped with grids to control the output voltage under various operating conditions, and to give methods for estimating the wave shape of this voltage in any given case.

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted March 20, 1934; released for publication April 9, 1934. *Not published in pamphlet form.*

Operation of Control Grids

The grid excitation of the rectifiers to be studied is such that the grids cannot stop, decrease, or modulate current flow from the rectifier anode, once this current flow has started. When properly excited, the grids can retard the point at which current flow from the anode starts, thus reducing the portion of the positive half cycle of anode voltage that is effective in producing output voltage. It will be assumed that current flow from the anode will start at the instant the excitation for the grid working with that particular anode changes from negative to positive, providing the excitation of the anode is such as to allow current flow from the anode to start at that particular instant.

In Fig. 1 is shown the output voltage wave shape of a controlled voltage rectifier at no load, with the anode firing period retarded by an amount α. The grid excitation for the working anode changes from negative to positive at point B, thus allowing anode b, the potential of which already is suitable for allowing the flow of current, to start firing. The output voltage wave shape under load is shown in Fig. 2. Commutation between anodes a and b starts at point B and continues until the current from anode a becomes zero at point C.

In analyzing the wave shapes of ordinary 6- and 12-phase rectifiers it has been found that the assumption of a steady direct current gives sufficient accuracy for practical purposes. The usual types of load generally have enough inductance to give a fairly smooth current. When grid control is used and the range of voltage control is not large, for instance 10 per cent, reasonably accurate results will be obtained if a steady direct current is assumed. For a wide range of voltage control the voltage curve at the lower limit deviates considerably from the average, and therefore the current may not be smooth unless the load is highly inductive. Therefore, 2 limiting conditions are considered in this paper: highly inductive loads in which the current wave shape closely approximates that of a perfectly smooth direct current, and noninductive loads in which the current is pulsating and has the same wave shape as the load voltage. When necessary the voltage wave shape can be estimated for the 2 limiting conditions and the wave shape for actual conditions can be determined by interpolation.

Theoretical Wave Shape of a Rectifier Supplying a Highly Inductive Load

The output voltage of the ordinary rectifier has been analyzed by several authors.[1,2] By analyzing the voltage wave of Fig. 2 in a similar manner a

1. For references see list at end of paper.

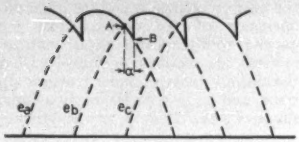


Fig. 1. Output voltage wave shape of controlled voltage rectifier at no load

α = angle of retard

Fourier series is obtained in which the coefficients of the sine and cosine terms for the harmonics of the order mp' are, respectively,

$$a_m = \frac{E_{do}}{2} \cos m\pi \left[\frac{\sin (mp'+1)(u+\alpha) + \sin (mp'+1)\alpha}{mp'+1} - \frac{\sin (mp'-1)(u+\alpha) + \sin (mp'-1)\alpha}{mp'-1} \right] \quad (1)$$

$$b_m = \frac{E_{do}}{2} \cos m\pi \left[\frac{\cos (mp'+1)(u+\alpha) + \cos (mp'+1)\alpha}{mp'+1} - \frac{\cos (mp'-1)(u+\alpha) + \cos (mp'-1)\alpha}{mp'-1} \right] \quad (2)$$

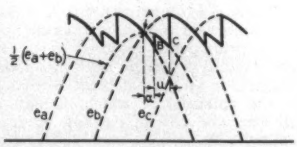


Fig. 2. Output voltage wave shape of controlled voltage rectifier under load

α = angle of retard
u = angle of overlap

The rms value of the harmonic of order mp' is given by the formula

$$h_m = \frac{1}{\sqrt{2}} \sqrt{a_m^2 + b_m^2}$$

The phases of the harmonic voltages referred to the maximum point of the applied voltage can be obtained from eqs 1 and 2.

In these formulas

E_{do} = output voltage at no load with no retard
p' = number of secondary phases
u = angle of overlap
α = angle of retard of anode firing period
m = 1, 2, 3, 4, . . . etc.

It may be noted that the magnitudes of the harmonics depend upon the angle of overlap u, and the angle of retard α. The angle of overlap without grid control is given by the following formula which has been published before:[1, 2, 3]

$$u = \cos^{-1}\left(1 - \frac{IX}{E_0 \sin \frac{\pi}{p}}\right) \quad (3)$$

where

u = angle of overlap
I = load current in each group of transformer secondary windings
E_0 = peak value of voltage to neutral on the secondary side of the transformer
X = reactance of the circuit in which commutation takes place
p = number of phases in each group of transformer secondary windings; p = 3 for the 6-phase double-Y and 12-phase quadruple-Y connections; 6 for the 6-phase star, 6-phase forked, and 12-phase in double-6-phase relation; and 12 for the 12-phase star connection

Equation 3 has been extended to cover the case of rectifiers with grid control[4] and becomes

$$u = \left[\cos^{-1}\left(\cos \alpha - \frac{IX}{E_0 \sin \frac{\pi}{p}}\right)\right] - \alpha \quad (4)$$

where all symbols are as defined previously.

The output voltage with load and with retard of the anode firing period is

$$E_d = \frac{E_{do}}{2} (\cos \alpha + \cos (\alpha + u)) \quad (5)$$

where E_d is the output voltage with load, and E_{do} is the output voltage at no load and with no retard; E_{do} can be calculated from the following formula:

$$E_{do} = \frac{E_0 p}{\pi} \sin \frac{\pi}{p} \quad (6)$$

By substituting in eq 5 the value of u given by eq 4 the following expression is obtained for the output voltage with load in terms of angle of retard:

$$E_d = \frac{E_{do}}{2}\left(2 \cos \alpha - \frac{IX}{E_0 \sin \frac{\pi}{p}}\right) \quad (7)$$

Equations 5 and 7 allow for the effects of retard and overlapping, but do not allow for arc drop or the resistance drop resulting from losses in the transformer windings.

When the circuit constants, the voltage applied to the rectifier, the load, and the desired output voltage to be obtained with grid control are known, the angle of retard α and the angle of overlap u can be calculated by eqs 4 and 7. Using these values the magnitudes of the harmonics can be estimated by eqs 1 and 2. Curves that simplify the calculations for several common types of rectifiers have been plotted from these equations. In preparing these curves the ratio of the controlled output voltage to the voltage the rectifier would develop at the same load without grid control has been used. The latter voltage is obtained by putting $\alpha = 0$ in eq 7. This

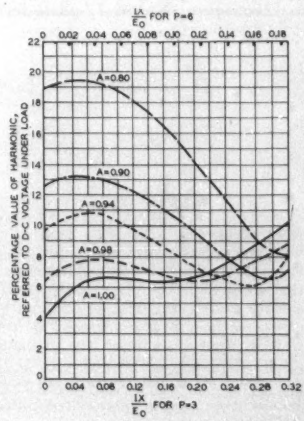


Fig. 3. The 6th harmonic in the output voltage of a controlled voltage rectifier as a function of IX/E_0, for different values of voltage control ratio A

ratio, called the *voltage control ratio* in this paper, is represented by the letter A and is given by the formula

$$A = \frac{2 \sin \frac{\pi}{p} \cos \alpha - \frac{IX}{E_0}}{2 \sin \frac{\pi}{p} - \frac{IX}{E_0}}$$

If for a given load the output voltage is reduced 10 per cent by grid control, the voltage control ratio is 0.90. Percentage values of the 6th harmonic plotted against IX/E_0 (for $p = 3$) for different values of voltage control ratio are given in Fig. 3. Similar sets of curves for the 12th, 18th, and 24th harmonics are given in Figs. 4, 5, and 6. The use of these curves in connection with 6- and 12-phase rectifiers will be discussed later in this paper. If the output voltage is given as a percentage of the no-load voltage with no retard, the voltage control ratio A may be found by referring to Fig. 7 provided the conditions are those to which the curves of Figs. 3 to 6 apply. In order to make the curves of Figs. 3 to 7, inclusive, applicable to a wider variety of connections, a scale is given on the upper part of each figure showing values of IX/E_0 for $p = 6$. This scale is to be used for the connection to which this value of p applies.

It is not necessary to calculate either the angle of overlap u or the angle of retard α in order to estimate the harmonics from the curves of Figs. 3 to 6. In some instances it may be desired to know the values of u and α, and the curves of Fig. 8 have been prepared for that purpose.

The harmonics present on the output side of a 6-phase rectifier are the 6th, 12th, 18th, 24th, etc., harmonics of the supply system frequency. The

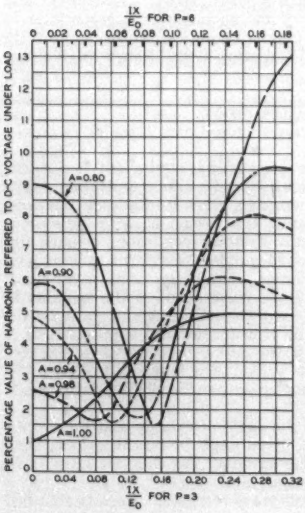


Fig. 4. The 12th harmonic in the output voltage of a controlled voltage rectifier as a function of IX/E_0, for different values of voltage control ratio A

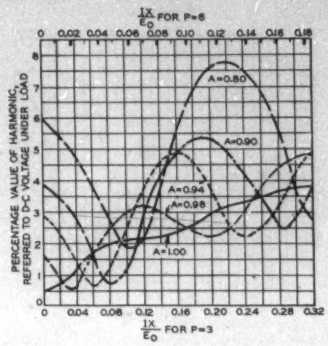


Fig. 5. The 18th harmonic in the output voltage of a controlled voltage rectifier as a function of IX/E_0, for different values of voltage control ratio A

percentage values of these harmonics are given by the curves of Figs. 3 to 6, inclusive. The use of the curves is illustrated by the following numerical example: A 6-phase rectifier is carrying a direct current of 800 amp and the output voltage is reduced 10 per cent by grid control. The transformer secondary windings are connected double Y, 6 phase. The commutating reactance of the transformer is 0.16 ohm and the equivalent reactance of the supply system for the commutating current is 0.01 ohm,[5] making a total reactance of 0.17 ohm for the circuit in which commutation takes place. The secondary voltage from anode to neutral is 540 volts (rms); then $E_0 = 765$ volts (peak). Since there are 2 groups, $I = 400$ amp. Then

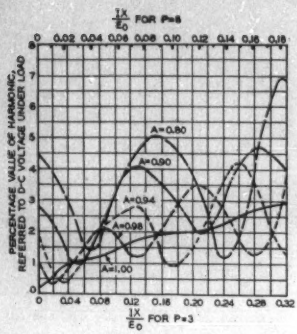
$$\frac{IX}{E_0} = \frac{400 \times 0.17}{765} = 0.089$$

The voltage control ratio A is 0.90. The percentage values of harmonics are read from Figs. 3 to 6 corresponding to 0.089 on the lower scale, since $p = 3$ for this connection, and using the curve $A = 0.90$. The values obtained are

6th harmonic	12.8 per cent
12th harmonic	2.8 per cent
18th harmonic	0.7 per cent
24th harmonic	2.7 per cent

In the 12-phase rectifier the 12th, 24th, etc., harmonics of the supply system frequency are present. The percentage values of these harmonics are the same as in the 6-phase rectifier and can be obtained from the curves. The 6th, 18th, and other odd multiples of the 6th harmonic are theoretically zero, but actually they are present in small amounts for various reasons such as the presence of harmonics in the supply voltage and unequal division of load between 2 groups of 6 phases. In tests on several 12-phase rectifiers without grid control[1] it was found that the average reduction in the 6th and 18th harmonics obtained by the use of the 12-phase connection is approximately 4 to 1 compared with the values that would be obtained with a 6-phase connection.

When harmonics are present in the supply voltage the output voltage wave shape is modified. It has



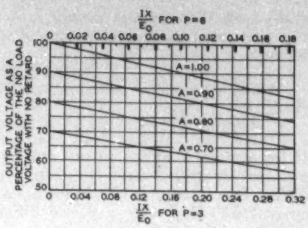


Fig. 6 (left). The 24th harmonic in the output voltage of a controlled voltage rectifier as a function of IX/E_0, for different values of voltage control ratio A

Fig. 7 (right). Output voltage as a percentage of no-load voltage with no retard plotted as a function of IX/E_0, for different values of voltage control ratio A

been shown[1] that in either the 6-phase or the 12-phase rectifier without grid control a 5th or a 7th harmonic voltage gives rise principally to a 6th harmonic voltage. Similarly, an 11th or a 13th harmonic produces principally a 12th harmonic; a 17th or a 19th harmonic produces principally an 18th harmonic, etc. In all these cases the percentage value of the harmonic voltages produced on the d-c side is approximately the same as the percentage value of the harmonic voltage on the a-c side which produces it. In the 6-phase rectifier with grid control the voltage curve is repeated at intervals of $^1/_6$ of a period of the supply voltage, as in rectifiers without grid control, and therefore harmonic voltages on the a-c side go through to the d-c side in the same manner. Similar considerations apply to the 12-phase rectifier with grid control. If the magnitudes and phases are known, the harmonic voltages resulting from harmonics on the a-c side can be combined with the harmonic voltages on the d-c side that arise in the normal operation of grid controlled rectifiers. If only the magnitudes are known the maximum and minimum values that may be expected can be estimated.

Wave Shape of Theoretical No-Load Voltage With a Wide Range of Voltage Control

Referring to Fig. 1, which shows the output voltage wave of a grid controlled rectifier at no load, it may be noted that the voltage of phase a is cut off at point B; and if the angle of retard α is increased, point B is moved to the right along the curve e_a. If angle α is large enough point B will be on the negative side of the zero line and the voltage curve will have negative loops. Such a condition would be approached at light load when the output circuit is highly inductive. Negative loops then would be obtained in the output voltage of a 6-phase rectifier when the angle of retard is more than 60 deg and in a 12-phase rectifier when the angle of retard is more than 75 deg. The average voltage is zero for both rectifiers when the angle of retard is 90 deg.

A somewhat different condition would be approached at light load when the d-c circuit is noninductive. For large values of α the voltage of phase a would be cut off at the zero point because the current would be cut off at that point. The voltage would remain zero until the grid control permits the next phase to fire. Thus in the 6-phase rectifier when the angle of retard is more than 60 deg, the voltage curve would have positive loops with dead spots between them, and an angle of retard of 120 deg would be necessary to reduce the output voltage to zero, as shown in the section entitled "Theoretical Wave Shape With Noninductive Load and Wide Range of Voltage Control."

These considerations show that for a narrow range of voltage control, when the output voltage curve does not reach the zero line, the theoretical no-load voltage is independent of the characteristics of the output circuit. For a wide range of voltage control, when the curve reaches or crosses the zero line the no-load voltage curve which would be approached depends upon the characteristics of the output circuit.

The values of the harmonics in the no-load voltage wave with negative loops are obtained by substituting $u = 0$ in eqs 1 and 2. When the negative loops are cut off a separate analysis is required and eqs 14 and 15 for the harmonics are given later in the section entitled "Theoretical Wave Shape With Noninductive Load and Wide Range of Voltage Control."

Theoretical Wave Shape With a Noninductive Load

If the load on a rectifier is equivalent to a resistance, the current in the d-c side is pulsating. The voltage wave shape at a given load and output voltage is not the same as it would be with inductance in the d-c circuit if other conditions remain unchanged, because the angle of overlap u and angle of retard α are different. For a given pair of values of u and α the voltage wave shape is the same as in Fig. 2, if the effect of the pulsating current upon the inductance of the transformer and supply circuit is neglected, and if the curve does not cross the zero line. When the values of u and α are known the values of the harmonic can be obtained by eqs 1 and 2.

Formulas for the angle of overlap and the output voltage E_d for a given angle of retard α have been obtained by some authors,[6] but they are quite complicated. Formulas and curves obtained by a simplified analysis are given here. Results obtained

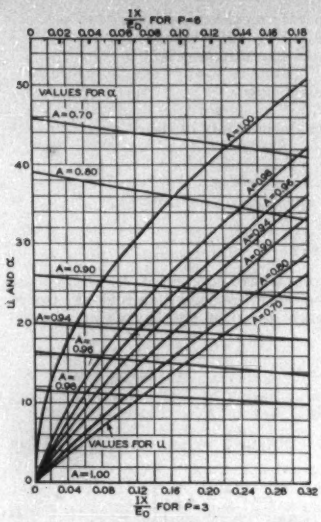


Fig. 8. Angle of overlap, u, and angle of retard, α, as functions of IX/E_0, for different values of voltage control ratio A

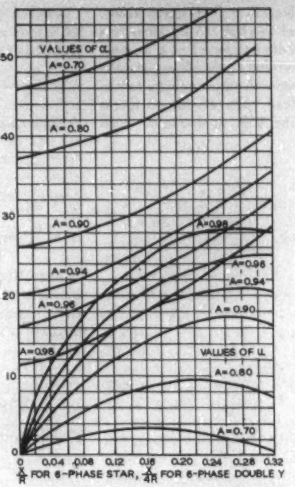


Fig. 9. Angle of overlap, u, and angle of retard, α, as functions of X/R for 6-phase rectifiers, for different values of voltage control ratio A and noninductive load

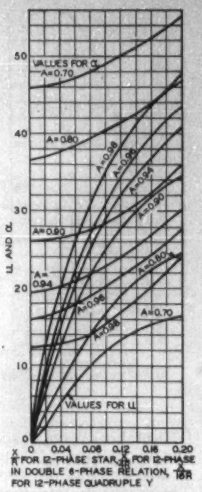


Fig. 10. Angle of overlap, u, and angle of retard, α, as functions of X/R for 12-phase rectifiers, for different values of voltage control ratio A and noninductive load

for the 6-phase star-connected rectifier with the approximate formulas have been compared with results by the more elaborate formulas and have been found to be satisfactory for practical purposes when the commutating reactance is less than $^1/_4$ of the load resistance and the voltage reduction obtained with grid control is not more than 50 per cent. When interphase transformers are used the formulas must be modified and separate sections of this paper are given for rectifiers with 1, 2, and 4 groups of secondary phases.

Rectifier With One Group of Secondary Phases. It is assumed that when there is no overlapping between the currents in adjacent anodes, the current on the d-c side has the same shape as the voltage and is given by the formula

$$i = \frac{E_0}{R} \cos \theta$$

where

E_0 = peak value of voltage to neutral on the secondary side of the transformer
R = load resistance (output voltage divided by load current)
θ = angular distance measured from point of maximum voltage

At the time when commutation begins the current is

$$I_1 = \frac{E_0}{R} \cos \left(\frac{\pi}{p} + \alpha \right) \tag{8}$$

where

I_1 = current on d-c side at beginning of commutating period
α = angle of retard of the anode firing period

If it be assumed that the current does not change during the commutating period, I_1 may be substituted for I in eq 4 which gives the following relation

$$u = \left[\cos^{-1} \left(\cos \alpha - \frac{X}{R} \frac{\cos \left(\frac{\pi}{p} + \alpha \right)}{\sin \frac{\pi}{p}} \right) \right] - \alpha \tag{9}$$

where

u = angle of overlap
X = reactance of the circuit in which commutation takes place

The voltage under load is obtained by substituting eq 9 in eq 5. This gives the formula

$$E_d = \frac{E_{do}}{2} \left(2 \cos \alpha - \frac{X}{R} \frac{\cos \left(\frac{\pi}{p} + \alpha \right)}{\sin \frac{\pi}{p}} \right) \tag{10}$$

The curves in Figs. 9 and 10 show values of u and α plotted against X/R for different values of voltage control ratio defined in the section entitled "Theoretical Wave Shape of a Rectifier Supplying a Highly Inductive Load." Figure 9 applies to the 6-phase rectifier and the curves were obtained by substituting $p = 6$ in eq 10. Figure 10 applies to the 12-phase rectifier and the curves were obtained by substituting $p = 12$.

Referring to eq 8 it may be noted that I_1 is zero when $\alpha = \pi/2 - \pi/p$. For larger values of α there cannot be overlapping and eqs 9 and 10 do not apply. This case will be discussed in the section entitled,

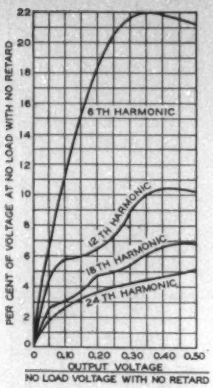


Fig. 11. Percentage values of the 6th, 12th, 18th, and 24th harmonics in a 6-phase rectifier, plotted against the ratio of output voltage to no-load voltage with no retard and with noninductive load

"Theoretical Wave Shape With Noninductive Load and Wide Range of Voltage Control."

Rectifier With 2 Groups of Secondary Phases. The interphase transformer divides the load current equally between the 2 groups so that either group carries a current that at any instant is the average of the currents for the 2 groups when each carries a separate load of half the total load. In the following discussion p represents the number of phases in each group and the angular displacement between the 2 groups is π/p. If the 2 groups are operated as separate rectifier units and the load in each is equivalent to a resistance $2R$, the current in group 1 at the beginning of commutation is

$$I_1' = \frac{E_0}{2R}\cos\left(\frac{\pi}{p} + \alpha\right)$$

At the same time the current in group 2 is

$$I_2' = \frac{E_0}{2R}\cos\alpha$$

When the 2 groups are connected through an interphase transformer and carry a load equivalent to R, the current in either group at the beginning of commutation is

$$I_1 = \frac{1}{2}(I_1' + I_2') = \frac{E_0}{2R}\cos\frac{\pi}{2p}\cos\left(\frac{\pi}{2p} + \alpha\right) \tag{11}$$

Substituting I_1 for I in eq 4 the following formula for the angle of overlap u is obtained:

$$u = \left[\cos^{-1}\left(\cos\alpha - \frac{X}{4R}\,\frac{\cos\left(\frac{\pi}{2p} + \alpha\right)}{\sin\frac{\pi}{2p}}\right)\right] - \alpha \tag{12}$$

For the 6-phase double-Y rectifier $p = 3$ and the curves on Fig. 9 may be used if $X/4R$ is substituted for X/R. Similarly the curves on Fig. 10 may be used for the 12-phase rectifier in double 6-phase relation by making the same substitution.

Rectifier With 4 Groups of Secondary Phases. In this case the groups of p phases each are displaced by an angular distance of $\pi/2P$. If the groups are operated on separate rectifiers and the load on each group is equivalent to $4R$, the current in group 1 at the beginning of commutation is

$$I_1' = \frac{E_0}{4R}\cos\left(\frac{\pi}{p} + \alpha\right)$$

At the same time the currents in the other groups are

$$I_2' = \frac{E_0}{4R}\cos\left(\frac{\pi}{2p} + \alpha\right)$$

$$I_3' = \frac{E_0}{4R}\cos\alpha$$

$$I_4' = \frac{E_0}{4R}\cos\left(\alpha - \frac{\pi}{2p}\right)$$

When the 4 groups are connected by interphase transformers and carry a load equivalent to R, the current in each group at the beginning of commutation is

$$I_1 = \frac{1}{4}(I_1 + I_2 + I_3 + I_4)$$
$$= \frac{E_0}{4R}\cos\frac{\pi}{2p}\cos\frac{\pi}{4p}\cos\left(\frac{\pi}{4p} + \alpha\right) \tag{13}$$

The formula for u obtained by substituting eq 13 in eq 4 is

$$u = \left[\cos^{-1}\left(\cos\alpha - \frac{X}{16R}\,\frac{\cos\left(\frac{\pi}{4p} + \alpha\right)}{\sin\frac{\pi}{4p}}\right)\right] - \alpha \tag{14}$$

For the 12-phase quadruple-Y connection, $p = 3$ and the curves on Fig. 10 may be used by substituting $X/16R$ for X/R.

Method of Estimating Harmonic Voltages With Noninductive Load

In order to estimate the harmonic voltages with noninductive load the values of angle of overlap u and angle of retard α may be obtained from the equations or the curves and substituted in eqs 1 and 2. Sets of curves similar to Figs. 3 to 6 might be plotted from which the percentage values of the harmonic could be obtained directly from the values of X/R and the voltage control ratio, but the formulas in the preceding section show that separate sets of curves would be required for 6-phase rectifiers and 12-phase rectifiers.

However, the curves on Figs. 3 to 6 may be used for the case of noninductive load in the following manner: Find the values of u and α from Fig. 9 or 10, or by the formulas. Then refer to Fig. 8 and find by trial the pair of values of IX/E_0 and voltage control ratio that give the same values of u and α. Then read the percentage values of the harmonics from Figs. 3 to 6 corresponding to these values of IX/E_0 and voltage control ratio. This will be understood better by considering a numerical example. A rectifier connected double-Y 6-phase is loaded on a noninductive resistance of 0.6 ohm. The commutating reactance is 0.17 ohm. The voltage is reduced 10 per cent by grid control. It is desired to estimate the harmonic voltage on the load side for this condition. Since there are 2 groups of secondary phases the ratio $X/4R$ is calculated and found to be

0.071. Then from the curves for $A = 0.90$ on Fig. 9 the values $\alpha = 28$ deg and $u = 8.5$ deg are obtained. Referring next to Fig. 8, it may be noted that A is approximately 0.89 for $\alpha = 28$ deg. Using this as a first approximation it is found that IX/E_0 on the lower scale is 0.065 for $u = 8.5$ deg. Checking again, it may be seen that $\alpha = 28$ deg corresponds to $A = 0.89$ at $IX/E_0 = 0.065$. Referring to the curves on Figs. 3 to 6 and reading the harmonics for $A = 0.89$ and $IX/E_0 = 0.065$ on the lower scale, the percentage values are approximately as follows:

6th harmonic	14	per cent
12th harmonic	5	per cent
18th harmonic	1.3	per cent
24th harmonic	1.4	per cent

Theoretical Wave Shape With Noninductive Load and Wide Range of Voltage Control

It has been pointed out in the subsection entitled "Rectifier With One Group of Secondary Phases" that when the angle of retard is equal to $\pi/2 - \pi/p$, the load current is zero at the end of the conducting period for each phase and there cannot be overlapping. If p is replaced by p', which represents the total number of secondary phases, this relation holds for rectifiers either with or without interphase transformers. In a 6-phase rectifier the current is zero when the angle of retard is 60 deg, and in a 12-phase rectifier when the angle of retard is 75 deg.

When the angle of retard is greater than $\pi/2 - \pi/p'$ (greater than 60 deg for a 6-phase rectifier or 75 deg for a 12-phase rectifier) the voltage curve is cut off at the zero line and is similar to Fig. 12. The voltage curve for this condition has been analyzed to obtain a Fourier series and the coefficients of the mth sine and cosine terms are, respectively,

$$a_m = -\frac{E_{do}}{(m^2p'^2 - 1)\sin\frac{\pi}{p'}}\left[\sin\frac{mp'\pi}{2} - mp'\cos mp'\alpha\cos\left(\alpha - \frac{\pi}{p'}\right) + \sin mp'\alpha\sin\left(\alpha - \frac{\pi}{p'}\right)\cos m\pi\right] \quad (15)$$

$$b_m = -\frac{E_{do}}{(m^2p'^2 - 1)\sin\frac{\pi}{p'}}\left[\cos\frac{mp'\pi}{2} + mp'\sin mp'\alpha\cos\left(\alpha - \frac{\pi}{p'}\right) - \cos mp'\alpha\sin\left(\alpha - \frac{\pi}{p'}\right)\cos m\pi\right] \quad (16)$$

The rms values of the harmonics are obtained by substituting the values of a_m and b_m in the formula

$$h_m = \frac{1}{\sqrt{2}}\sqrt{a_m^2 + b_m^2}$$

The output voltage is given by the formula

$$E_d = \frac{E_{do}}{2\sin\frac{\pi}{p'}}\left[1 - \sin\left(\alpha - \frac{\pi}{p'}\right)\right] \quad (17)$$

where p' is the number of secondary phases, and the other symbols are as defined under eqs 1, 2, and 5. The phases of the harmonic voltages referred to the maximum point of the applied voltage can be obtained from eqs 15 and 16. It may be noted that when $\alpha = \pi/2 + \pi/p'$ (120 deg for a 6-phase rectifier and 105 deg for a 12-phase rectifier) the output voltage is zero.

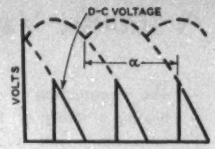


Fig. 12. Output voltage wave shape of controlled voltage rectifier with angle of retard greater than $\pi/2 - \pi/p$

Figure 11 shows the percentage values of the 6th, 12th, 18th, and 24th harmonics in the 6-phase rectifier with noninductive load plotted against ratio of output voltage to theoretical no-load voltage with no retard.

The equations and curves given here apply to rectifiers with 1 group of secondary phases and also to the theoretical case of 2 or more groups of secondary phases with the load current equally divided between the groups at all times. This ideal condition cannot be realized with actual interphase transformers when the load current is less than their magnetizing current. Since the load current is zero at the end of the conducting period when the angle of retard exceeds $\pi/2 - \pi/p^1$, it appears that the curve of Fig. 12 may have to be modified when interphase transformers are used. The output voltage of a 6-phase rectifier with an interphase transformer is discussed in a recent paper[7] and curves are constructed on the basis of certain assumptions. One curve is obtained for values of angle of retard between 60 and 90 deg and another for values of angle of retard greater than 90 deg. The latter curve is similar to that of Fig. 12 and the former could be analyzed into component curves, each of which would be similar to that of Fig. 12. In either case the magnitudes of the harmonics could be obtained with the aid of eqs 15 and 16 by finding appropriate values of α. In the case mentioned last it would be necessary to calculate the phases of the harmonics in the component curves in order to obtain the resultant harmonics.

It may be assumed as a first approximation that eqs 15, 16, and 17 apply to all loads. This neglects the interval of time required for building up the current from zero to the maximum value when each phase begins to carry current. However, the values of the harmonics obtained by neglecting this time interval are greater than those actually in existence because this time interval is produced by the smoothing effect of transformer inductance upon the load current and voltage.

References

1. Current and Voltage Wave Shape of Mercury Arc Rectifiers, H. D. Brown and J. J. Smith. A.I.E.E. Trans., v. 52, 1933, p. 973.
2. Mercury Arc Power Rectifiers (a book), O. K. Marti and H. Winograd.
3. Principles of Mercury Arc Rectifiers and Their Circuits (a book), D. C. Prince and F. B. Vogdes.
4. Grid Controlled Rectifiers and Inverters, C. C. Herskind. Elec. Engg., v. 53, June 1934, p. 926–35.
5. Page 975 of the paper of reference No. 1.
6. Current and Voltage Conditions in Grid Controlled Rectifiers, Kurt Muller-Lubeck and Erich Uhlmann. *Arch. for Elek.*, v. 27, No. 5, 1933, p. 347.
7. Voltage Control of Vapor Rectifiers, Didier Journeaux. Elec. Engg., v. 53, June 1934, p. 976.

A 100-Kw Vacuum Tube

The construction of a new vacuum tube having a rating of 100 kw is described herewith.* This tube has been made possible by the development of water cooling and a satisfactory copper-glass seal.

OVER 500 vacuum tubes in parallel were used for the first transatlantic radio telephone conversation in 1915. Since then vacuum tubes have undergone almost continuous development. The application of water cooling has permitted much larger capacities, and the present long wave transatlantic channel employs but 30 tubes, each of 15-kw rating. Further improvements in design and manufacturing technique have made possible still higher ratings. A tube is now available—the 265*A*—which has an anode dissipation of 100 kw. Six of such tubes will provide a greater output than the 30 employed for the present transatlantic service.

This radical increase in capacity, which has made it possible to obtain outputs of as many kilowatts as have formerly been obtained in watts, has been made possible by 2 developments. The limitation to capacity is largely a matter of dissipating the heat generated in the tube. By employing water for cooling the anode surfaces, however, the amount of heat that can be carried away has been greatly increased. This method of cooling has in turn been made possible to a large extent by the development of a satisfactory copper-glass seal. Neither water cooling nor the copper-glass seal were used for the first time with the new tube, but the technique of employing both of them has been recently improved.

Copper-Glass Seal

A simplified cross section of the new tube, Fig. 1, shows the construction. The copper tube forming the anode is slightly flared at each end, and then these flared ends are carefully machined to a thin knife edge. Next, the anode is supported on an expanding mandrel of a lathe-like machine whose end chucks rotate coaxially and in synchronism. An open ended glass bulb is then mounted in one of the end chucks, and flames for heating the entire mass, and other flames to provide a high concentration of heat, are lighted and the machine is started.

The clean copper surface adjacent to the glass is first allowed to oxidize until the correct surface condition is obtained. This oxide layer must have sufficient elasticity to take up the strains caused by slight differences in the coefficients of expansion of copper and glass. Next, the glass is softened and spread over the copper surface by an ingenious roller tool supported on the center axis of the machine. This same tool also carries a nozzle through which is forced a stream of nitrogen to blow the glass bulb into the final shape desired. Following this, the process is repeated for the bulb at the other end of the anode. After the seals have been made, the ends of the bulbs are temporarily closed with an ionization manometer sealed to one of the bulbs, and the completed anode assembly is evacuated and baked. Manometer readings are then taken periodically over an extended interval to make sure there are no small leaks in the copper or the seal before the filament and grid structures are sealed in.

Water Cooling

The cooling water passes at high velocity in the narrow space between the copper anode and an outer copper sleeve which is brazed to it before the copper-glass seal is made. Two water ports at each end of the outer sleeve give entrance and exit to the water, and also serve as points of support for the tube. This outer sleeve when brazed to the anode is in 2 parts. These 2 parts slightly overlap near the middle and are left open until the final degassing of the finished tube has been completed. Were it not for this provision, the high temperatures attained by the tube during the degassing process would cause a differential expansion of the copper anode and the outer copper sleeve, which being in direct contact with the air is much cooler, and would cause harmful strains in the copper structure.

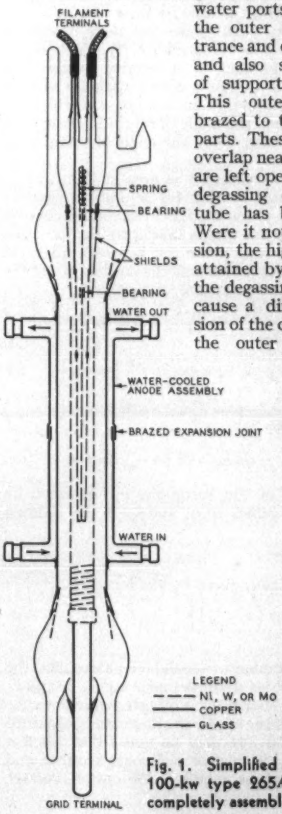


Fig. 1. Simplified cross section of the 100-kw type 265*A* tube. The tube, completely assembled, is over 4 ft long

Filament and Grid Structures

The design of the filament structure is unique in employing no insulating supports at the ends of the V's, and in a very

* Essentially full text of an article "A New 100-kw Vacuum Tube," by H. E. Mendenhall (A'26), Bell Telephone Laboratories, Inc., New York, N. Y., and published in *Bell Laboratories Record*, v. 12, Dec. 1933, p. 98–102. *Not published in pamphlet form.*

simple arrangement for maintaining the filaments under tension. The apexes of the 3 filament V's hang downward and are passed over tungsten hooks within a molybdenum cap which fits loosely over a shoulder on a heavy central support rod. This rod passes through 2 bearings—7 in. apart—at its upper end, and is free to slide in them so that its weight maintains a tension on the filaments. Additional tension is obtained by a large coiled tungsten spring at the upper end which, fastened to the frame, exerts a downward pressure on the rod. The molybdenum supports of the upper ends of the filament V's are cross-connected and welded to the 2 copper leads which in turn are silver soldered into copper rods hollowed out to thin-walled tubing extending to the glass seal. This construction allows a further drop in temperature of the materials between the filaments and the copper-to-glass seals. The main support of the filament structure is obtained from a large copper-to-glass seal enclosing the upper filament rod bearing. This end of the filament assembly is enclosed with nickel sheet to provide a protective electrostatic shield to prevent destructive discharges at the high operating anode potential of 18,000 volts. Other vital points such as the anode seals are also protected by electrostatic shields.

metal parts are heated by external torching, filament glowing, and grid bombardment. During the pumping process the entire structure is maintained at very high temperatures, much higher than exist during ordinary operation, so as to free the high-melting-point metals from occluded gases. The temperature of the anode becomes so great that high velocity air streams for cooling are required to keep it from collapsing. The nickel shields within the tube are degassed by induction heating. It is these high temperatures that necessitate a break in the outer copper sheath to prevent large differential expansion. At the end of the degassing processes the 2 parts of this outer sleeve are brazed together since it and the anode will hereafter be at approximately the same temperature due to the cooling water.

In Fig. 3 is shown a group of completed tubes installed in an experimental transmitter at the Whippany laboratory which has been the proving ground for these tubes. For shipment, the tubes are packed in sturdy crates with spring suspensions so that the tube practically floats in the compartment. The flexible copper braids for the filament leads, which carry approximately 200 amp when the filaments are lighted, are anchored back to a band support collar when not in use.

Fig. 2. Grid structure (left) and filament structure (right) of the 265A tube

The 3 filament V's are connected in parallel and have an active length of more than 4 ft. About 4,000 watts are required for heating, which maintain the filaments at a temperature above 2,500 deg K and give an electron emission of over 30 amp.

The grid structure, which is supported from the opposite end of the tube, is shown with the filament structure in Fig. 2. The grid must be kept below a temperature of 1,100 deg K to prevent the emission of primary electrons when it is negative with respect to the other electrodes. This is accomplished by using relatively more and larger grid verticals and fewer laterals than are normally used, and in employing a large copper support structure which is cooled by the natural upward draft around the tube. Heat readily flows down the large cross section of the grid verticals to the copper support, which has a bright heat shield to reflect from it the heat from the filament that would otherwise be absorbed.

Removal of Gases

The completely assembled tube, which is over 4 ft long, requires a long exhaust process, involving constant attendance for about 24 hr. Special split ovens are placed around the glass parts of the tube, and the

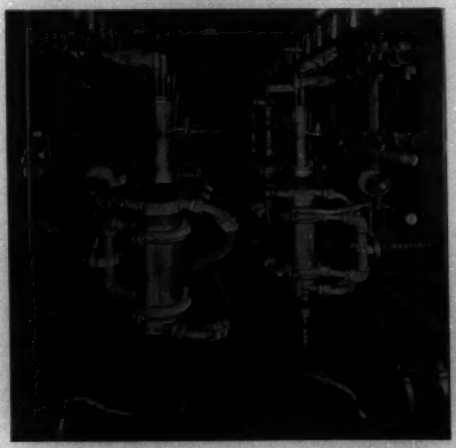


Fig. 3. A group of 265A tubes installed in an experimental transmitter at Whippany

Machine Characteristics for Steady Welding

The machine characteristics needed for steady welding have been analyzed with the aid of a series of tests of the welding process. In addition to describing the method of test, oscillograms and photographs of specially secured metal test strips are presented, and a discussion of the possible theory to explain the results is given in this paper.

By
F. CREEDY
MEMBER A.I.E.E.

R. KOGGE
NONMEMBER

A. O. DANELLO
NONMEMBER

All of
Lehigh University,
Bethlehem, Pa.

AN ATTEMPT to ascertain by a direct study of practical welding operations what the characteristics of a generator really ought to be in order to give the steadiest welding is presented in this paper. It is the consensus of opinion of operators that modern welding generators with controlled transients operate more steadily than the older type. While many suggestions have been made as to why this should be, none of these has been pushed to the point of demonstration.

Method of Tests

The method adopted in the following tests (used previously by Prof. G. E. Doan) has been to lay a bead of metal from a fixed electrode on to a moving strip, the motion of this strip being synchronized with an oscillograph so that the relation between metal deposited, current and volts is made apparent. In order to do this (see Fig. 1) a rest is provided opposite a revolving drum A. This rest, which is of insulating material, is for the welding electrode. The electrode is held in the rest by a skilled welding operator who advances or retires it from the work by hand so as to obtain the best possible arc. It was found that more sensitive regulation of the arc could be obtained from a hand operator than from any automatic device available to us. To the drum is attached a strip of metal screwed to its circumference, which can be replaced as often as necessary. The drum is driven by a small motor through slow motion gear consisting of belts and pulleys E and on the same shaft is a spur wheel B having 120 teeth. A small finger D makes contact with these teeth as the wheel turns, thus completing a circuit and giving a make and break arrangement. In addition a slip ring C serves to carry the current to the work, which revolves with the drum.

At one point the space between 2 teeth is filled in with solder so that at this point contact lasts 3 times as long as elsewhere. If the record corresponding to this point, called the initial point, is included in an oscillogram and we count the number of makes and breaks on it from the initial point to the point we desire to study, which is of course equal to the number of teeth starting from the initial point, we can locate the exact point on the strip which corresponds to any given point on the oscillogram. This is the way in which the synchronization is effected. The circuit through the spur wheel is excited with alternating rather than direct current so that the same oscillograph vibrator may serve at once to give the make and break and a timing wave. The effect of this is shown in most of the oscillograms of this paper, where we see at one point a series of alternations much wider than at others. This is the initial point, of course, and it is followed by a break and this by other series of alternations which correspond to other teeth. The whole apparatus is very simple, and easily arranged and mounted for either direct or overhead welding, and enables us to reach a number of interesting conclusions.

Procedure of Testing

The procedure in making a test is as follows: After all the apparatus has been adjusted, put the drum into starting position, that is with the bead starting at the top of the test strip. The operator then strikes his arc and gets it into a steady condition with the drum stationary. He then sets the drum in motion by pressing a foot switch at the same time

Fig. 1. Device used in tests

Full text of a paper recommended for publication by the A.I.E.E. committee on electric welding. Manuscript submitted Nov. 16, 1933; released for publication Feb. 28, 1934. *Not published in pamphlet form.*

giving a signal to the oscillograph operator who records the film as the bead is laid along the test strip. At the end of the run the operator states his opinion of the type of welding, that is "steady," "unsteady," etc.

When the experiment has been completed, the test strip has to be photographed and enlarged to such a size that the distance between the ends of the parts to be studied is equal to the length of the film. Finally the film and the photograph of the strip must be printed side by side as shown in the figures. A large number of records were made in this manner, some of which show extremely interesting results.

Records which were reported as corresponding to steady welding are shown in Figs. 2 to 7. These records were taken with a number of different types of coated wire. These were merely the kinds that happened to be at hand and no inference must be made from these records as to the relative advantages of these types of coating.

The Long Arc

Of these records possibly No. 3 is the most striking. Notwithstanding the deposition of a fairly heavy bead there was no short circuit of the arc opposite the greater part of the bead; in fact only 3

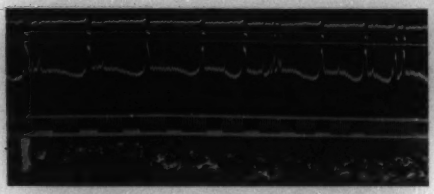


Fig. 2. Steady welding. 135 amp. 32 volts. Electrode positive. Fleetweld electrode

points of momentary short circuit can be seen in the film each of which seems to correspond to a rather larger drop than elsewhere. This seems to show conclusively that metal can be deposited in considerable quantities without short-circuiting the arc and therefore proves that every drop which passes

Fig. 3. Steady welding. 140 amp. 29 volts. Electrode positive. A.W.P. electrode

Fig. 4. Steady welding. 150 amp. 20 volts. Electrode negative. Murex electrode. Series connection coils. Short arc

does not necessarily short-circuit it. This is the type of operation which is found when a rather long arc is used.

This confirms the result reported by E. C. Easton and F. B. Lucas in the discussion (see Trans. A.I.E.E., v. 51, 1932, p. 564) of "Forces of Electric

Fig. 5. Steady welding. 135 amp. 32 volts. Short arc. Electrode negative. Fleetweld electrode

Origin in the Iron Arc," of which one of the present authors was a co-author. It was there shown by synchronizing the oscillograph with a movie camera that no disturbance whatever could be noticed in the current and voltage recorded on the oscillogram when a drop was observed to pass across the arc as photographed by the movie camera. The writers still adhere to the explanation given in that paper of the passage of the drop, namely, that as stated in the reply to the discussion: "According to our view the function of the pinch effect is solely to separate the globule from the electrode and if there were no other forces in existence when the globule had been so separated it would fall to the ground under the action of gravitation. Our view is that the pinch effect separates the globule which is then taken across by the forces measured in the first part of the paper, and these forces, which have nothing whatever to do with the pinch effect and which are measured but not explained in the paper, are those which are responsible for carrying the globule over." [Authors' Note: Since this was written these forces have been tentatively explained as due to a fine spray of particles projected by each electrode.]

Unsteady Welding

The oscillogram reproduced in Fig. 9 is reported as corresponding to unsteady welding. It will be seen that in this case the short circuits are far from being regularly periodic and the mean current also is not constant. This record shows in addition that every drop did not short-circuit the arc while notwithstanding this the deposit consists of a regular series of drops.

Overhead Welding

The oscillograms reproduced in Figs. 9 and 10 show overhead welding. Although there is a deposit which is slighter than with welding in the normal position, there are nevertheless no short circuits shown in Fig. 9 and only a few in Fig. 10,

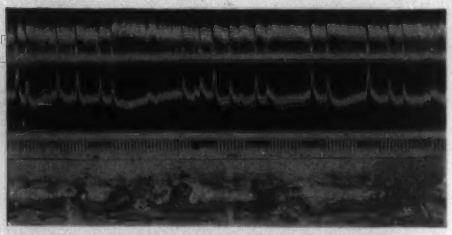


Fig. 6. Steady welding. 125 amp. 32 volts. Electrode negative. G. E. electrode

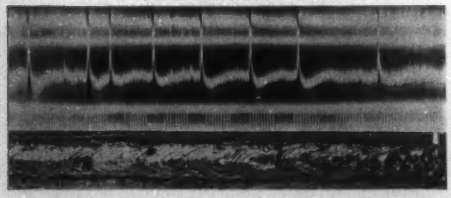


Fig. 7. Steady welding. 140 amp. 28 volts. Electrode positive. G. E. rod

which show again that some other mechanism than short-circuiting the arc serves to transfer the metal. These 3 oscillograms show another striking phenomenon to which we shall return later.

The Short Arc

The oscillograms reproduced in Figs. 2, 4, 5, 6, and 7 are also reported as corresponding to steady welding. These show the conditions corresponding to a short arc. Although there are a large number of short circuits, these are regularly periodic or tend to be so. It should be noted that the generator which was used in these tests was of a modern type with controlled transients and was capable of holding the average current between short circuits nearly constant, notwithstanding variations of arc conditions.

Conclusions From the First Series of Tests

Thus the conclusions we obtain from the examination of these oscillograms are that steady welding may take place either with no short circuits in case of a long arc or with regularly periodic short circuits in the case of a short arc. If the short

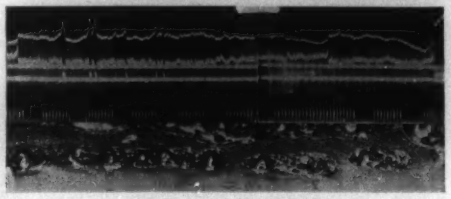


Fig. 8. Unsteady welding. 160 amp. 32 volts. Electrode negative. Fleetweld electrode

circuits are to be regularly periodic, this means that the rate of evolution of heat must be steady so that the tip of the rod is heated to melting point and passes across in the form of a drop at regular intervals. It has been shown that within the welding range (see "Performace and Design of Electric Welders with Controlled Transients," by F. Creedy, Trans. A.I.E.E., v. 52, 1933, p. 268–78) the voltage across the arc is entirely independent of the current and only increases slightly with increase in arc length. Hence for a given arc length the rate of evolution of heat is directly proportional to the current. Thus a steady rate of evolution of heat means a steady mean current. The old argument between "constant watts" and "constant current" is seen to be meaningless since on account of the constancy of the arc voltage constant current results in constant watts.

As a result of the above observations we are now able to state why the modern machine with controlled transients is superior to the older type. It is well known that the best welding is done with a short arc which keeps the mass of metal hot and does not fly around in a way the long arc sometimes does. It is also agreed by operators that with the controlled transient machine it is possible to hold a shorter arc than with the old type.

According to the view here put forward, the shorter limit for arc length is reached when the arc short-circuits so frequently that it is unable to maintain its temperature and so sticks. Of course during the short circuit there is no arc and therefore the amount of heat being evolved is much reduced. As the short circuits become fewer the arc is in existence for a longer period of time and therefore more heat

is evolved. There must therefore be some arc length for which the number of short circuits per second is sufficient to transfer an ample amount of metal and yet few enough to maintain a high temperature. This is the minimum useful arc length. Beyond this limit the amount of metal transferred is reduced with probably very little further increase in temperature and in fact as the electrode is removed from the proximity of the work it

Fig. 9. Steady overhead welding. 140 amp. 35 volts. Electrode negative. Cresta murex electrode

Fig. 10. Steady overhead welding. 150 amp. 32 volts. Electrode negative. Cresta murex electrode

may actually cool. When holding a short arc therefore it will be clear how important a machine with rapid "pick-up" is. If it takes a considerable time for the arc to recover after every short circuit it is clear that if the short circuits per second are numerous the arc will cool and the electrode stick. Hence a machine with slow pick-up compels us to hold rather a long arc with comparatively few short circuits per second.

If, on the contrary, recovery is nearly instantaneous as in the machine used (which was the neutralized welder described in a previous paper) a much greater frequency of short circuit can be permitted before the heat evolved is reduced too much. It is perhaps as well to state emphatically here our belief that the metal is transferred in the form of a rapid succession of drops of about the same diameter as the electrode.

It was seen above that uniform evolution of heat was necessary to steady welding and this depends upon the mean current remaining constant. The older type of machine having large slow-period transients could not maintain a steady mean current but the modern type is far more capable of doing so. If we contrast, for instance, such an oscillogram as that reproduced from an old machine in the lower part of Fig. 7, p. 660 of the A.I.E.E. TRANSACTIONS for June 1931 ("An Improved Arc Welding Generator," by J. H. Blankenbuehler) with those taken by modern machines (for instance, the oscillogram immediately above that just referred to) it can easily be seen that the older type of machine showed marked variations in mean current as well as irregularities in the number of short circuits per second.

The main object of the present paper is to form a rational theory such as that outlined in the paragraphs above of why the modern machines with controlled transients are superior to the older type.

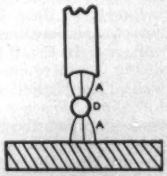
To summarize, in our opinion the improvement is due:

1. To reduced (though not eliminated) current kicks during short circuit.
2. To rapid "pick-up" after short circuit thus maintaining the heat of the arc.
3. To constant mean current due to the absence of slow period current transients.

A number of further conclusions of interest arise from the same study. Although as shown in a paper

Fig. 11. Diagram for possible explanation of current dips

A. Arc. D. Drop



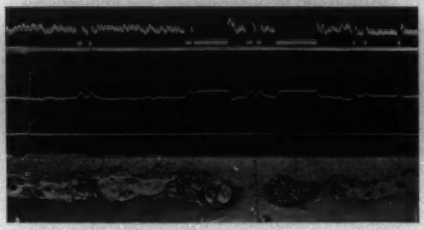


Fig. 12. Welding with ballast resistance. 140 amp. 22 volts. Bare wire negative. Good in places

by one of the writers "Performance and Design of Electric Welders With Controlled Transients" (previously referred to) the machine used gave a rise

of current of only about 30 per cent during momentary short circuit, nevertheless, in actual welding the percentage rise of current seems in some cases to be higher than this. This would seem to indicate that there was still something about the welding circuit not fully explained, probably connected with the actual characteristics of the arc. The rise of current during short circuit is, however, much less than in older types of machine.

Greater Copiousness of Deposit With Coated Rods

Another interesting point brought out by the experiments is the much greater copiousness of the deposit with coated rods. Several explanations may be suggested for this:

1. The reduction of surface tension in the molten drop permits it to separate more easily. This is a true fluxing action.

2. Akin to this explanation is the following: the reduction of the oxide layer on the surface of the molten drop has the same effect of enabling it to separate more easily. This is, therefore, a kind of fluxing also.

3. The mere fact that the coating of the rod is of a material which is a poor conductor of heat serves to blanket it and prevent the escape of heat, thereby leading to more rapid melting.

Current Dip During Overhead Welding

Returning to Figs. 9 and 10 relating to overhead welding, it will be noted that these show a phenomenon just opposite to that of short-circuiting which involves a rise of current accompanied by a drop of voltage. In these figures we see sharp dips in the current accompanied by a corresponding rise in voltage. In Fig. 9 there are no short circuits while in Fig. 10 there are both short circuits and dips as well. The likeliest explanation for these dips is the following. When a drop is detached from the electrode it ordinarily ceases to carry current unless it short-circuits the arc. If it does not short-circuit the arc then the arc continues to carry the current while the drop passes over without doing so. But in certain cases the arc may pass from the electrode to the drop and from the drop to the work in a manner shown in Fig. 11. In this case since there are 2 arcs there will be 2 cathode and 2 anode drops of potential and hence the voltage across the arc will be approximately doubled. If we suppose that this is what happens when a dip of current occurs this will suffice to explain it but of course a more direct proof that this explanation is correct would be desirable.

Welding With Ballast Resistance

In Fig. 12 is reproduced an oscillogram taken when welding was carried out by using the 110-volt supply from a battery with a ballast resistance and self induction in series, instead of using the welding generator. This oscillogram is reproduced chiefly to show the much greater smoothness of the current wave. Nevertheless the high frequency oscillations in the voltage wave are not wiped out so that it would be interesting to know their origin.

Equivalent Circuits in Stability Studies

Representation of "receiving-end" systems by simplified equivalent circuits, for use in steady state stability studies of electric power transmission systems, is discussed in this paper. Various methods of approximate representation are analyzed, compared, and evaluated. Comparative analyses of a specific problem indicates that the simplified method that replaces the receiving-end system by an equivalent generator and an equivalent load is sufficiently accurate for engineering purposes.

By
O. G. C. DAHL
FELLOW A.I.E.E.

A. E. FITZGERALD
ASSOCIATE A.I.E.E.

Both of Massachusetts Institute of Technology, Cambridge

TO FACILITATE stability studies and calculations, the complicated networks comprising electric power transmission systems may often be represented by simplified equivalent networks which may be used in place of the actual networks. In this paper the general problem of "receiving-end" system representation in stability calculations is discussed, and a limited number of comparative analyses based upon somewhat different premises are presented. The particular problem analyzed is that of a hydroelectric station connected by a long transmission line to an existing system (called the receiving-end system) consisting of generating stations, substations, and loads. This paper presents also a method of obtaining the receiving-end system characteristics by use of a network analyzer, which may be of value for the solution of some types of practical problems.

In order to determine the validity and accuracy of approximate methods of receiving-end representation, 2 sets of stability analyses of a specific system were made; the first an exact representation, and the second an approximate representation by an equivalent generator and an equivalent load. As far as it is permissible to draw general conclusions from these analyses of a single although typical and fully representative power transmission system, it is evident that the method involving the equivalent generator and equivalent load representation of the receiving-end system gives results of engineering ac-

Full text of a paper recommended for publication by the A.I.E.E. technical program committee. Manuscript submitted Oct. 26, 1933; released for publication Feb. 21, 1934. *Not published in pamphlet form.*

curacy. Both the resultant power-voltage and reactive power-voltage characteristics are in good agreement with the correct ones when actual load characteristics are assigned to the equivalent load. The power limits obtained by the 2 methods also are in close agreement.

The assumption of constant-impedance loads does not affect the power characteristics materially, but does influence the reactive-power characteristics to an appreciable extent. In the exact method of analysis the use of constant-impedance loads gives rise to essentially the same power limit as when actual load characteristics are used. In the approximate method, however, the power limit obtained with constant-impedance equivalent load deviates to a somewhat larger extent from that based upon actual load characteristics. It is impossible to say, of course, whether the use of constant-impedance loads might not give rise in other systems to larger discrepancies than here indicated.

To sum up, it seems that the simplified method, which replaces the receiving-end system by an equivalent generator and an equivalent load directly at the receiving-end bus, is sufficiently accurate for engineering purposes. For maximum reliability of results it appears preferable to assign load characteristics to the equivalent load, in the manner discussed, rather than to represent it by a constant impedance.

General Problem

In connection with long distance transmission of electric power the problem most frequently encountered is the following: A water power site usually is developed for the purpose of increasing the power available at some large load area. In general the locations of the available water power and the load area are far apart, and transmission over long lines therefore becomes necessary.

At the load area the transmission line ties in with an existing system. This, as a rule, will contain several generating stations, substations, and loads of various categories. In connection with the design of the transmission line it usually is sufficient to ascertain that the hydroelectric station will operate with stability with respect to the receiving-end system. The problem therefore narrows down to an examination of the stability of the line, or rather the transmission system, and is carried out without reference to the stability situation within the receiving-end system itself.

It may be appropriate, therefore, in a situation of this sort to treat the receiving-end system as a unit. This may be done by simulating its performance at the point at which the transmission line ties in (usually the low voltage side of the receiving-end substation) by a set of power-voltage and reactive power-voltage characteristics. These characteristics in general are based upon operation at constant field current of the various main synchronous machines within the receiving-end system and with connected loads of designated values.[1,2]

It is evident that these receiving-end system characteristics are motor characteristics in the sense that they indicate the input to the receiving-end system taken as a whole. In other words, this method of representation treats the receiving-end system as if it were an equivalent motor. In order to determine whether stability is present between the 2 systems, the equivalent motor characteristics may be superimposed on the receiving-end characteristics of the transmission system. The procedure involved (analytical or graphical, as the case may be) is exactly the same as that used in connection with the stability of simple systems with synchronous motor loads.[1,2] The fact that an equivalent motor is dealt with does not change the principles involved in the analysis.

Having carried out the superposition, a resultant power-voltage curve is obtained, as indicated in Fig. 17. In regard to the interpretation of this characteristic, caution must be exercised. It is safe to say that if the curve shows convexity (i. e., indicates that a power increment is associated with a drop in voltage) the transmission system will be stable with the connected loading assumed. While the maximum point on this curve definitely signifies the power limit when an actual synchronous motor constitutes the load, *it has no similar significance in the present case because the receiving-end system is in reality no motor.* This is an important point and should be borne definitely in mind.

It usually is required, however, to determine the power limit of the transmission system when operating at normal voltages. In order to obtain this limit recalculations are in general necessary. Assuming that the first power-voltage curve indicates stability, the loadings within the receiving-end system are increased and its junction point characteristics revamped to correspond to the new load conditions. (Looking at the receiving-end system as an equivalent motor, this procedure is evidently equivalent to changing its capacity.) The stability is checked again by superposition and inspection of the resultant power-voltage curve. Recalculations in this manner are made until the power limit can be ascertained.

It is obviously not necessary to hit at the *exact* load conditions that will correspond to the power limit. The actual value may be obtained by extrapolation when a sufficient number of power-voltage curves are available. The limit is obtained at the point of intersection between the normal voltage axis and a curve representing the locus of maxima (Fig. 17).

This method, involving the use of receiving-end system characteristics based on actual load conditions within the receiving-end system, is an effective and correct one for the particular purpose for which it is applied. It serves to indicate correctly whether or not synchronizing power between the 2 parts of the system, i. e., the transmission line and the receiving-end system, is present. On the other hand, it tells nothing about the internal stability situation in the receiving-end system, which, although entirely satisfactory while operating alone, may be changed by the presence of the transmission system. Hence, if any doubt exists as to the internal stability, it may be necessary also to give attention

1. See bibliography at end of paper for all numbered references.

to this part of the problem. In general, however, when additional power is brought into a load area from a distance, the transmission system definitely represents the weakest link. The analysis, therefore, quite frequently is limited to an examination of its performance with respect to the receiving-end system taken as a whole.

The main inconvenience in using receiving-system characteristics in the manner just described is that they have to be recalculated perhaps several times when the actual power limit is to be ascertained. This inconvenience, however, may be avoided by a modification. Instead of using a single set of receiving-end system characteristics at the junction point, a segregation of the receiving-end system into 2 parts at this point may be made.[1] These 2 parts represent an *equivalent generator* and an *equivalent load*, respectively. The generator characteristics may, or may not, include a part of the load effects within the receiving-end system.

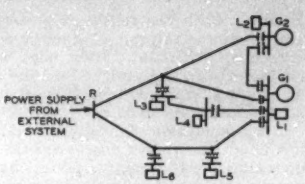
In using this type of receiving-end system representation, the load increments required for the purpose of recalculation in order to determine the power limit, may be applied to the equivalent load directly. Hence, having once determined the equivalent-generator and load characteristics, no complete revamping of the receiving-end system characteristics is necessary, as in the previous case. Therefore, using the approximate representation, the problem reduces to the handling of a 2-generator system with the load connected at the terminals of one of the generators. It should be definitely borne in mind, of course, that *this method is inherently approximate*. Nevertheless, if proper judgment be used in segregating the receiving-end system into 2 parts, and in assigning the appropriate characteristics to each, fairly reliable results may be obtained. That this method involves considerable saving in time and labor is evident.

System Loads

The loads of an alternating current system in general may be subdivided into 4 types: (1) lighting load, (2) synchronous motor load, (3) synchronous converter load, and (4) induction motor load. The loads usually receive power over the distribution network through distribution transformers. The distribution network is connected to the substations which in turn are supplied from the generating stations over overhead or underground transmission lines or feeders. In stability investigations it is *impracticable to include all individual loads properly in the analysis*, and still it is *important to introduce at least the approximate effect of the load action*. Practically this may be done by (1) considering the load concentrated at the substations, or (2) representing the entire power system in the load area by an equivalent load of appropriate characteristics.

In the former case the characteristics of the composite load at the substation must be introduced. Two methods are here possible namely (1) the approximate method of simulating the substation loads by constant impedances, and (2) the determination and use of actual load characteristics at the substations.

Fig. 1. Typical receiving - end system



Load characteristics in general are given best by curves of active and reactive power versus voltage.[1,2,4] In some instances it may be sufficient to represent the load by its power factor characteristic, i. e., a curve of power factor versus voltage.

Should any of the loads include synchronous machines of sufficiently large rating to justify their identity being preserved and their being treated as separate sychronous machine units, this, of course, can be done. Whether or not this is necessary and desirable must evidently be left to the discretion and judgment of the engineer who handles the problem.

Characteristics of Substation Loads

The loads on the substations in a power system may consist of the 4 individual types discussed in preceding paragraphs. In addition, the substations will also carry the active and reactive power losses in the distribution network caused by the various individual load currents. The segregation between different types at each substation evidently depends upon each specific situation. The composite characteristics at the substations may be approximately as indicated in Fig. 12. It is inevitable that for a commercial load the power will decrease somewhat with a drop in voltage and the reactive power will change somewhat in a leading direction.

In determining the substation loads and their characteristics it may be possible to figure back from the individual loads, including at each voltage the power and reactive power losses in the distribution system. However, this complete procedure seldom is followed, and, furthermore, sufficient detailed data frequently will not be available for such an analysis. Usually the power and reactive power at the substation itself is specified or estimated. The percentage of each type of load supplied is also specified or estimated. With this information at hand and using suitable characteristics for the variation in power and reactive power for each individual type of load, the required composite characteristics are made up. The fact that such characteristics are applied at the substations instead of at the individual loads makes very little difference. The uncertain factors and unknown quantities are so many that the inclusion of distribution losses in applying these characteristics will not affect the true result materially.

Sometimes the substation loads are represented merely by constant impedances. Although this may be very convenient from the standpoint of computation, it evidently is an approximation only. In general, constant impedance loads will have neither the correct power nor reactive power characteristics

fully to represent the actual load at all voltages. Only at the value of voltage at which the impedances are determined (usually the normal value) will the representation be exact.

Receiving-End Systems and Their Simplification

For the purpose of the subsequent discussion a *receiving-end* system will be defined as a *compound power system to which power and reactive power are supplied at some point.* It includes, in other words, everything, i. e., machines, transformers, transmission and distribution circuits, and loads located beyond the point in question. The agent supplying power and reactive power to the point may be a generator, a transmission line, or even another power system; in the majority of instances where stability is involved it represents a transmission line fed from a distant station, as already outlined.

For purposes of analysis it is frequently desirable to simplify the receiving-end system as much as practicable. How much can be accomplished in this regard depends upon the actual layout at hand. Every system offers its own problems. Simplification by analytical methods usually involves repeated application of Y-Δ and Δ-Y transformations as well as the more general star-mesh transformations.

When the substation loads are represented by their true characteristics it is usually necessary to retain the substations as definite identities. Only when the loads are represented by impedances can they be treated as network elements proper and be included directly in the process of simplification. In such cases the result is likely to be a system considerably less complicated than when the identity of the substations is retained.

Consider the system in Fig. 1, for instance, representing a receiving-end system with respect to the point *R*. It involves, as may be seen, 2 generating stations and several substations. If the proper characteristics of the loads at the latter are included, no further simplification of this system is practicable. (The Δ-loop 1-2-3, of course, may be replaced by a "Y," but this does not involve any real simplification.) If, on the other hand, the substation loads are considered as impedances, further simplification is possible as suggested in the steps (*a*) to (*g*) in Fig. 2. These steps involve nothing but Δ-Y and Y-Δ transformations. If the distributed constants of the lines are taken into account these may be represented by their proper equivalent π circuits. The presence of the leaks will not prevent simplification from being carried out.

Should the receiving-end system contain only one generating station and, in addition, the substation loads be considered as impedances, it may in general be represented by a single π circuit. Referring to the previous example, Fig. 2, for instance, and considering the generators in station 2 to be removed so as to convert it into a substation, it is evident that by the simplifying steps suggested in that figure the final representation becomes an equivalent π circuit as given in Fig. 3.

Characteristics of a Receiving-End System

As already stated, it is frequently desirable in connection with stability analyses to represent the receiving-end system by its proper characteristics. Such characteristics in general are curves of active versus reactive power for various values of voltage at the point in question. They should include the effects of all generators in the receiving-end system, all transmission and distribution circuits, transformers, substations, and loads. From the standpoint of steady state stability calculations, the characteristics should be for appropriate constant field currents in the synchronous machines and with appropriate fixed angular displacements between these machines. To calculate these characteristics for a practical power system in many instances may be exceedingly complicated. (The consideration of fixed angular relationships is an *assumption* that governs the active and reactive power distribution among the synchronous machines within the receiving-end system. There are, however, also other bases that may be used for this purpose. See, for instance, the paper, "Power Limits of Synchronous Machines," by Edith Clarke and R. G. Lorraine in Electrical Engineering, November 1933, p. 780–7, and particularly the discussions of it in Electrical Engineering, March 1934, p. 475–7, some of which point out possibilities in this respect.)

If the substation loads are to be represented by constant impedances, the first step would be to simplify the receiving-end system as much as practicable, retaining, of course, the identity of the generating stations. Using the simplified circuit layout, expressions for power and reactive power at the point in question may be established. Equations of the type that would be applicable are developed in the literature in several places. Having these equations and using the appropriate excitation voltages and displacements between synchronous machines, the power and reactive power at the point in question

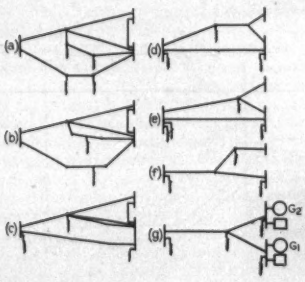


Fig. 2. Simplification of system in Fig. 1 when loads are considered as constant impedances

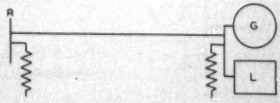


Fig. 3. Further simplification of system in Fig. 1 when generators G_2 are omitted

may be calculated as a function of voltage at that point. Evidently such calculations are possible only when no saturation effects are included. In other words, all circuit elements involved must be linear.

When the proper characteristics of the substation loads are to be used, the problem becomes still more involved and calculations may be so complicated as to be almost prohibitive. It is usually necessary to resort to cut-and-try methods, which evidently also allow saturation to be taken into account in the synchronous machines if desired. If the layout is not too involved it may also be possible to resort to graphical methods. In this case charts must be available for the machines as well as for the various transmission circuits. A system of superposition at junction points is used, and in this manner the nonlinear elements can be brought properly into the picture. It is evidently of no moment to attempt giving specific directions as each individual problem requires its own particular method of attack.

By far the best way of obtaining the characteristics of a complicated power system (receiving-end system) is by the use of a network analyzer (alternating current calculating table). On such an analyzer a true replica of the network can be set up, including synchronous machines and loads. The procedure evidently would be first to adjust the miniature system for conditions of normal operation. This involves adjusting for correct voltages at all buses, the proper field current as well as phase displacement of the synchronous machines, and the proper admittances representing the loads at the substation buses. Holding the field currents in the synchronous machines and the displacement angles between them constant, and a fixed voltage at the receiving-end bus, the phase angle of the latter may be changed. A change in the angle of this voltage will evidently alter the voltage at the substation buses, which in turn requires a new load admittance to be used. By a few trials the correct value of admittance corresponding to the voltage may be obtained. When everything is properly adjusted the power and reactive power at the receiving bus are determined. Proceeding in this manner, enough values for one particular voltage at the receiving-end bus are obtained so that a curve may be plotted. The magnitude of the voltage at the receiving-end bus then is changed to the next desired value and the procedure just outlined is repeated. The correct power and reactive power characteristics at the receiving-end bus are thus eventually obtained.

Characteristics of the receiving-end system indicated in Fig. 5 are given in Figs. 13 to 16. They were obtained on the network analyzer at the Massachusetts Institute of Technology, further details being given in a later section of the paper.

Representation of Receiving System by Equivalent Load and Equivalent Generating Station

It is evident from the foregoing that to obtain the characteristics of a receiving-end system is a rather complicated, laborious, and difficult task, except when a network analyzer is resorted to. Furthermore, as already pointed out, it is usually necessary during a stability analysis to secure such receiving-end characteristics for several load conditions for the purpose of eventually determining the power limits. Hence it would be decidedly helpful to have methods available embodying *simplified equivalent representations* of the receiving-end system. The requirements of such methods are evidently that they be time and labor saving and give results that are correct to engineering accuracy. Such methods, involving a certain degree of approximation, have a further justification in that so many factors, as already pointed out, are somewhat uncertain in stability analyses of large power systems, so that undue refinements are not frequently called for.

The most drastic approximation of a receiving-end system involves the location of an *equivalent generator* and an *equivalent load* directly at the receiving-end bus, as indicated in Fig. 4. The requirements are that the equivalent generator and the equivalent load give sufficiently nearly the same operating characteristics at the receiving-end bus as the actual system.

Equivalent Generator

The size of the equivalent generator is determined from the consideration that the short-circuit kilovoltamperes that it would supply to a symmetrical 3-phase short circuit at its terminals are the same that the receiving-end system would supply to a similar short circuit at the receiving-end bus. It is necessary, therefore, to determine the short-circuit

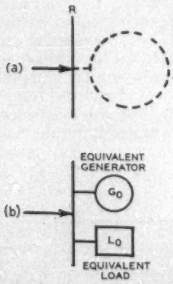


Fig. 4 (left). Receiving-end system and its equivalent representation

(a): Large system containing several generating stations, substations, and loads

(b): Equivalent representation of (a)

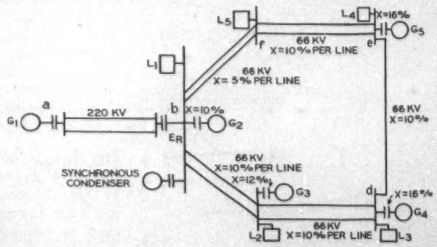


Fig. 5 (right). Diagram of system investigated; reactances are on a 100,000-kva base

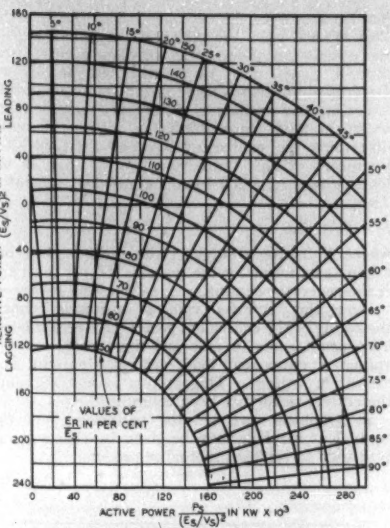


Fig. 6. Transmission line sending chart

Circles give ratio of receiving voltage to sending voltage. Angle lines give displacement between sending voltage and receiving voltage. V_S is nominal value of sending voltage

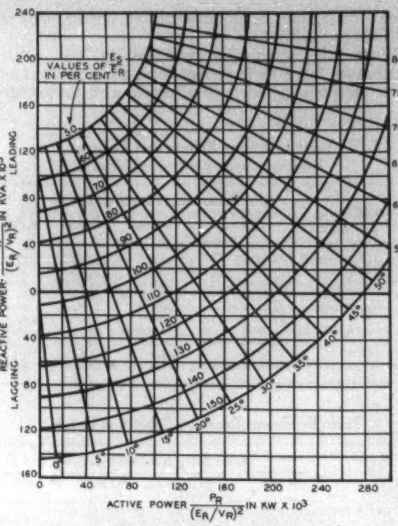


Fig. 7. Transmission line receiving chart

Circles give ratio of sending voltage to receiving voltage. Angle lines give displacement between sending voltage and receiving voltage. V_R is nominal value of receiving voltage

kilovoltamperes of the receiving-end system. This may be done on several bases of which the following 3 are the most important ones: (*a*) with the excitation voltages of all generators phase-displaced by the proper amount and having the proper values to supply the loads on the system, and with the loads attached; (*b*) with the excitation voltages of all generators in phase but equal to their actual values with load on the system, without, however, considering the load in obtaining the short-circuit kilovoltamperes; and (*c*) with the excitation voltages of all generators in phase and equal to unity, and omitting the loads on the system.

It is evident that the first method is the correct one. It is also the one that is the most complicated, however, especially if the results are to be obtained by calculation. If the load characteristics are to be included properly this involves a cut-and-try process of calculation. On a network analyzer, however, the characteristics can be obtained without difficulty.

The second method involves an approximation. If saturation is taken into account, this method also would involve a cut-and-try process unless graphical schemes could be employed. If, on the other hand, saturation is neglected, the characteristics may be calculated by means of the input equations to a general, linear network. These may be simplified since the excitation voltages are all in phase.

The last mentioned method involves a further approximation in that all excitation voltages are considered equal to unity. Ignoring the saturation, the system in this case may be reduced drastically. As a matter of fact, independent of the number of generating stations, the result will be a circuit fed from a single station. If line admittances are to be taken into account this circuit will be an equivalent π. If line admittances are neglected, it becomes a simple impedance only. Evidently there is not much sense in including line admittances when the loads are ignored. Furthermore, since the circuit resistances have only a very minor effect on the short-circuit kilovoltamperes, a reactance system only may be used in the calculations with sufficiently accurate results.

From the values of the short-circuit kilovoltamperes the size of the equivalent generator to be attached at the receiving-end bus may be determined. The usual practice is to give this machine more or less normal generator characteristics. Since, as a rule, the machines in a receiving-end system are turbogenerators it is logical to assign unity short-circuit ratio to the equivalent machine. On this basis its size directly equals the short-circuit kilovoltamperes when the latter are determined by method *c* assuming unity excitation voltages. If another ratio is to be used the rating (G_0) of the equivalent machine is calculated by

$$G_0 = \frac{P}{SCR} = PX_0 \tag{1}$$

where P represents the short-circuit kilovoltamperes supplied by the receiving-end system, SCR the short-

circuit ratio, and X_0 the unsaturated synchronous reactance in per unit.

When the excitation voltages in the actual generators have their proper load condition values, as in methods *a* and *b*, it is logical also to consider the excitation voltage of the equivalent generator different from unity. It may appropriately be taken equal to its value under equivalent load conditions. Even on the basis of unity short-circuit ratio the rating of the equivalent machine then no longer coincides with the short-circuit kilovolt-amperes, and is in general obtained from

$$G_0 = \frac{P}{SCR \times E_0} = \frac{PX_0}{E_0} \tag{2}$$

where E_0 represents its excitation voltage. Since this depends on the current supplied by the equivalent generator to the equivalent load (L_0) and this load in turn upon the rating of the generator (G_0), the calculation of the rating involves a cut-and-try process. This may be carried out as follows: Determine an approximate rating by evaluating eq 2, letting the excitation voltage be unity or equal to an assumed, reasonable value. With this rating determine the equivalent load, as discussed later, by means of eq 5, and from this the part of the load current supplied by the equivalent generator. Then

$$E_0 = E_R + jX_0I_0 \tag{3}$$

where E_R is the voltage of the receiving-end bus taken at its normal value (usually 100 per cent) and I_0 the generator current.

Using this improved value of excitation voltage, the rating of the equivalent generator is recalculated. This again leads to new and more nearly correct values of equivalent load, generator current, and excitation voltage. This process is repeated until the correct rating has been determined.

In graphical analyses the performance of the equivalent machine may be given by charts of the type used to represent actual generators.

Table I—Station Ratings and Outputs

All reactive kilovoltamperes are lagging

Generating Station	Rating in Kva	Station Outputs at Normal Voltage: 1st Step	2d Step	3d Step	4th Step
G_1	100,000	48,000 kw	48,000	48,000	48,000
		51,500 R. kva	58,500	58,000	58,500
G_2	75,000	54,000 kw	54,000	54,000	54,000
		41,800 R. kva	49,300	49,300	49,300
G_3	60,000	42,000 kw	42,000	42,000	42,000
		25,000 R. kva	43,000	43,000	43,000
G_4	60,000	42,000 kw	42,000	42,000	42,000
		25,000 R. kva	43,000	43,000	43,000
Transmission system		153,000 kw	212,000	263,000	284,000
		65,000 R. kva	58,000	86,000	98,400

Table II—Power Taken by Substation Loads

Load	Power Taken at Normal Voltage, Kw: 1st Step	2d Step	3d Step	4th Step
L_1	100,000	120,000	133,000	140,000
L_2	75,000	90,000	99,700	105,000
L_3	40,000	48,000	53,200	56,000
L_4	40,000	48,000	53,200	56,000
L_4	75,000	90,000	99,700	105,000

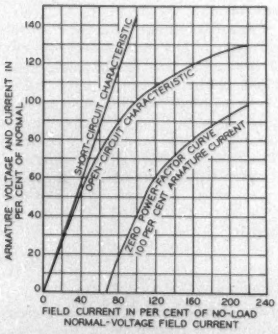


Fig. 8. Characteristics of salient pole generators

Short-circuit ratio, 1.46. Ratio of pole arc to pole pitch, 0.67

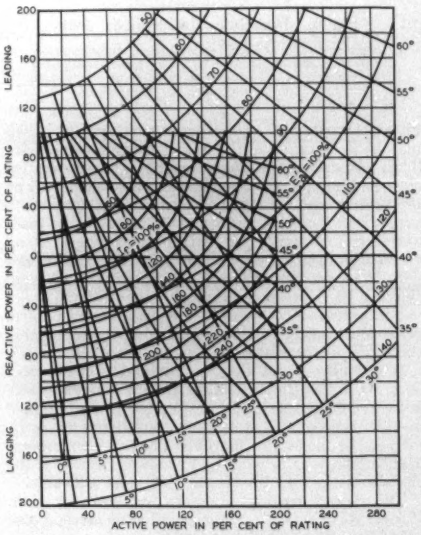


Fig. 9. Chart for a salient pole generator at 85 per cent terminal voltage

Circles represent voltage induced by air-gap flux in per cent of normal terminal voltage. Curves represent field current in per cent of field current at normal open-circuit voltage. Straight angle lines represent displacement in electrical degrees between voltage induced by air-gap flux and terminal voltage. Curved angle lines represent displacement in electrical degrees between excitation voltage and terminal voltage

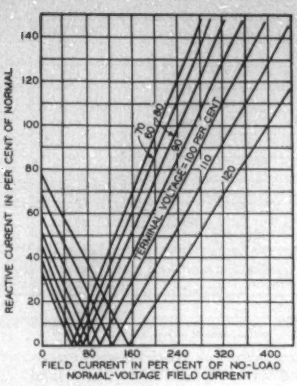


Fig. 10 (left). Synchronous condenser V-curves

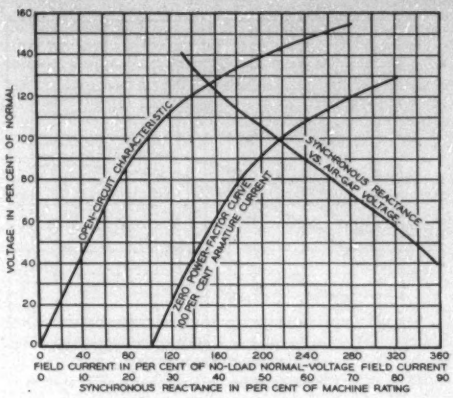


Fig. 11 (right). Characteristics of receiving-end system turboalternators

Equivalent Loads

The total active and reactive power supplied to a system includes the actual loads and all appropriate transformer, distribution, and transmission losses (power and reactive-power losses). The equivalent load representing the load action of the receiving-end system may be considered equal to the total power and reactive power so supplied multiplied by a reduction factor. This reduction factor may be taken as the ratio of the kilovoltampere capacity of the generating equipment outside of the receiving-end system (assuming that all power is transmitted into the latter) and the equivalent generator to the actual total kilovoltampere generator capacity in the system as a whole (including, of course, the capacity outside as well as inside the receiving-end system).

Assume, for instance, that a hydroelectric-station of capacity G_1 supplies power over a transmission line to a large receiving-end system containing 3 generating stations of capacity G_2, G_3, and G_4. The capacity of the equivalent station is G_0. Let the total power and reactive power supplied to the receiving-end system be L. The size of the equivalent load L_0 is then given by

$$L_0 = L\frac{G_1 + G_0}{\Sigma G} \tag{4}$$

where the aggregate generating capacity ΣG is represented by

$$\Sigma G = G_1 + G_2 + G_3 + G_4 \tag{5}$$

In order to obtain the total power L actually supplied, it is necessary to perform several calculations starting at the actual loads of the system, or at least at the loads on the substations. Also it is necessary to know the relationship between the power and reactive power in the load L and the voltage at the receiving-end bus. The same power and reactive-power variation then may be assigned to the equivalent load. Evidently this relationship cannot be determined accurately without a large amount of time and labor, since it would be necessary for accurate analysis to apply the load characteristics directly at every individual load actually on the system. Such a procedure, as previously pointed out, is prohibitive. It is considered sufficiently accurate for the approximate representation to apply individual load characteristics for different types of loads to the aggregate amount of these loads on the system as a whole. Hence, knowing the total power and reactive power of the various types of loads on the system, and having segregated out the distribution, transmission, and transformer losses at normal voltage, the load power and reactive power as well as the losses at reduced voltages may be estimated and the total power and reactive-power characteristics determined in that manner.

Comparative Analyses

System Used. Figure 5 is a diagram of the specific system used in examining the approximate method of receiving-end system representation. Sending and receiving charts[1,5,6] for one circuit of the section *a-b*, comprising a 142-mile, 2-circuit, 795,000-cir mil

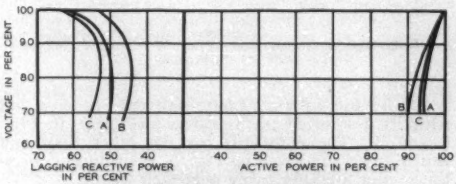


Fig. 12. Composite load characteristics

A: Characteristics for loads L_1, L_2, and L_3
B: Characteristics for loads L_3 and L_4
C: Weighted Average of A and B plus losses in 66-kv lines and transformers (used in approximate set-up)
Active power at normal (100 per cent) voltage is base for per cent active and reactive power

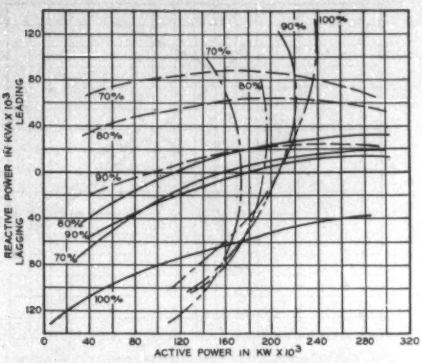


Fig. 13. Superposition of receiving-end system characteristics and transmitting-ability curves for first load condition; for identity of curves, see Fig. 14

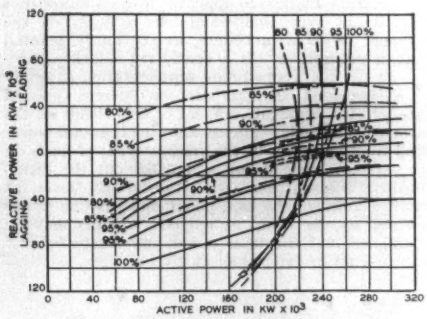


Fig. 14. Superposition of receiving-end system characteristics and transmitting-ability curves for second load condition

Solid lines: Receiving-end system characteristics for exact set-up using load characteristics
Dashes: Same with constant-impedance loads
Dots: Receiving-end system characteristics for approximate set-up using load characteristics
Dash and 2 dots: Same with constant-impedance loads
Dash and dot: Transmitting-ability curves for transmission system
Percentages on the respective curves give values of E_R in per cent for those curves

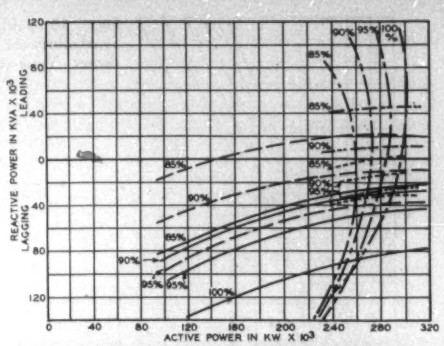


Fig. 15. Superposition of receiving-end system characteristics and transmitting-ability curves for third load condition; for identity of curves, see Fig. 14

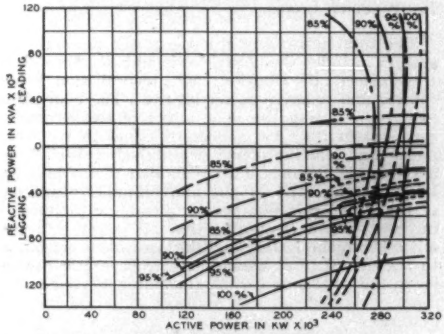


Fig. 16. Superposition of receiving-end system characteristics and transmitting-ability curves for fourth load condition; for identity of curves, see Fig. 14

A.C.S.R. line having 22.5-ft horizontal spacing and with its associated transformers, are given in Figs. 6 and 7. The constants for the other lines and transformers are given in Fig. 5, resistance, capacitance, and leakance being neglected there.

Generating equipment in hydroelectric station G_1 consists of 7 37,500-kva 13,800-volt 60-cycle, 150-rpm generators to which the characteristics of Fig. 8 apply. Performance charts[1,6] for these generators, of which Fig. 9 is typical, were constructed for terminal voltages between 100 per cent and 70 per cent. Synchronous condensers of capacity totaling 125,000 kva and with characteristics given in Fig. 10 are connected at the receiving-end bus b. Terminal voltages on these V-curves refer to the high-voltage side of the condenser transformers. In receiving-end generating stations G_2 to G_5 are located turboalternators with characteristics shown in Fig. 11. Values of the kilovoltampere capacities in these stations are given in Table I.

The connected substation loads L_1, L_2, and L_5 are 60 per cent induction motors, 20 per cent synchronous motors, and 20 per cent lighting and heating; L_3 and L_4 are 50 per cent induction motors, 20 per cent synchronous motors, and 30 per cent lighting and heating. In addition, 10 per cent of the connected kilowatt load is added to include power lost in the distribution system, and 30 per cent of the connected kilowatt load value is taken as the reactive-power loss in distribution. (These figures are actually arbitrary since no specific distribution

system was considered in this investigation.) The composite load characteristics, Fig. 12, are based upon these assumptions, use being made of material given by Evans and Wagner[2] regarding variation of active and reactive power to synchronous and induction motors. When the power taken by the substation loads is increased during the course of the analysis, it is assumed that the incremental load has the same characteristics as the initial load, so that these curves may be used throughout. Total loads at the substations are given in Table II.

Procedure. In order to investigate the validity and accuracy of approximate methods of receiving-end system representation, 2 sets of stability analyses were carried out. In the first set an exact representation of the receiving-end system as it exists was used. The effect of saturation in the machines was included, and variations of the load impedances with voltage were accounted for by means of the load characteristics discussed previously in this paper. As a secondary issue here, the degree of accuracy lost by assuming constant load impedances was determined by carrying through an analysis under this assumption. In the second set the approximate representation of the receiving-end system by an equivalent generator and an equivalent load was used. The effects of saturation and load characteristics likewise were included here, and again the inaccuracy introduced by a constant impedance load assumption was investigated. The results of these 2 sets were then analyzed and compared in order to draw the desired conclusions.

Exact Set-Up. In order to determine the exact receiving-end system characteristics, the receiving-end system, comprising the part *b c d e f* of Fig. 5 exclusive of the synchronous condenser, was set up on the M.I.T. network analyzer.[7] On the analyzer the transmission system, comprising the hydroelectric station, line, and synchronous condenser, was simulated by an additional generator on bus *b*. Values of loads assumed at the substations for the initial step will be found in the second column of Table II. These loads were divided among the receiving-end generating stations and the transmission system in such a manner as to maintain as nearly 100 per cent voltage as possible on all buses in consideration of the ratings of the stations. The resulting outputs of the stations for the initial step are given in the third column of Table I, these figures including the reactive-power loss in the 66-kv lines and transformers.

These distributions then determine the field currents in the machines of the receiving-end system and the angular displacements between their rotors. With these quantities kept constant, it is then readily possible to obtain curves of active versus reactive power taken by the receiving-end system from the transmission system for various values of E_R, the voltage on bus *b*. Such receiving-end system characteristics for the initial step are shown in Fig. 13. Saturation was included by using the curve of synchronous reactance versus air-gap voltage given in Fig. 11, this curve being calculated from the open-circuit and zero-power-factor curves therein presented.

From the portion of the active and reactive load assigned to the transmission system in the foregoing division, the excitations in the synchronous condenser and hydroelectric station can be determined, it being assumed that 100 per cent voltage is maintained at each end of the line and transformers. With these excitations constant, superposition[1] of generator and line charts and synchronous condenser *V*-curves leads to curves of active versus reactive power delivered by the transmission system for various values of receiving-end voltage, E_R. (It also would have been possible to secure these characteristics of the transmission system by means of the network analyzer.) Such transmitting-ability curves for the initial step are given in Fig. 13. Superposition of the curves for the transmission and receiving-end systems then evidently gives the resultant power-voltage curve, Fig. 17, and the reactive power-voltage curve in Fig. 18.

Repetition of this process for increased values of loads leads to the additional characteristics of Figs. 14 to 16 and then makes possible determination of the power limit by extrapolation of the maxima of the resultant power-voltage curves, Fig. 17. Values of active and reactive power assumed at the substations for subsequent steps are given in Table II, and their divisions among the generators in Table I. In making these divisions, the incremental active power was always assigned to the transmission system. As in the first step, the reactive power was divided so as to maintain at the buses as nearly 100 per cent voltage as possible in view of the machine ratings.

Approximate Set-Up. For purposes of comparison, the short-circuit kilovoltamperes of the receiving-end system at the point where the transmission line ties in when a symmetrical 3-phase short circuit is

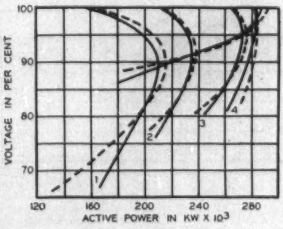


Fig. 17 (left). Power-voltage curves from exact set-up

Fig. 18 (right). Reactive power-voltage curves from exact set-up

Solid lines: Using load characteristics
Dotted lines: Using constant-impedance loads
Numbers on curves refer to steps in analysis

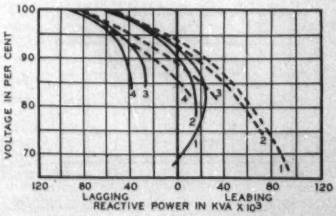


Table III—Equivalent Generator and Load Ratings in Kilovolt-amperes and Kilowatts

For meaning of a, b, c, 1, and 2, see text

	a		b		c	
	1	2	1	2	1	2
Short-circuit kilovolt-amperes	348,000	382,000	358,000	397,000	265,000	274,000
Equivalent generator rating	259,000	263,000	267,000	283,000	265,000	274,000
Equivalent load rating (active power)	371,000	374,000	377,000	389,000	376,000	382,000

Table IV—Summary of Power Limits

		Power Limit	Discrepancy
Exact method	(1) Using load characteristics	288,000 kw	0
	(2) Using constant impedance loads	292,000 kw	+1.4%
Method involving equivalent generator and load	(1) Using load characteristics	299,000 kw	+3.8%
	(2) Using constant impedance loads	315,000 kw	+9.4%

applied at this point was found on the 3 different bases previously discussed, namely: (*a*) with the excitation voltages of all generators phase-displaced by the proper amount and having the proper values to supply the loads on the system, and with the loads attached; (*b*) with the excitation voltages of all generators in phase but equal to their actual values with load on the system; and (*c*) with the excitation voltages of all generators in phase and equal to unity. Each of the 3 cases was subdivided further by using (1) unsaturated synchronous reactances, and (2) synchronous reactances determined by the air-gap voltages from Fig. 11. The load conditions of the second step in Tables I and II were used here. The resulting short-circuit kilovolt-amperes, together with the corresponding equivalent generator and load capacities, are given in Table III. Equivalent loads in Table III correspond to the second step in Table II, the first step having been omitted in the approximate analysis.

Of these values of equivalent generator and load, the ones found by the simplest method, 265,000 kva generator and 376,000-kw load, were used in further investigations. The equivalent generator was given the same characteristics as the other receiving-end machines, Fig. 11, and the equivalent load was given a weighted average between the characteristics used previously for L_1, L_2, and L_3, and L_4 and L_4, with an addition to include losses in the 66-kv lines and transformers (see Fig. 12). The procedure outlined for the exact set-up was repeated to determine the receiving-end system characteristics for the equivalent generator and load. These, of course, might readily have been calculated, but the network analyzer again was used to expedite the solution. These curves for the approximate representation are plotted on Figs. 14 to 16 for superposition on the transmitting-ability curves, leading finally to the power-voltage curves of Fig. 19 and reactive power-voltage curves, Fig. 20.

Results

Stability curves resulting from an exact determination of the receiving-end system characteristics are presented in Fig. 17. Reactive power-voltage curves likewise are presented in Fig. 18, although not required for stability and power limit determination. Two sets of these curves are given: one including the effect of the load-voltage characteristics, Fig. 12, and the other assuming loads of constant impedances fixed by the 100-per cent voltage conditions. Stability curves resulting from the approximate representation of the receiving-end system by an equivalent generator and load are shown in Figs. 19 and 20. The 2 cases involving use of load characteristics and use of the constant-impedance-load assumption also are given here. It may be noted that the capacity of equivalent generator used for these curves is that corresponding to the simplest method of determination, *c*1 in Table III.

For comparison, the power limits found by the different methods are summarized in Table IV.

Bibliography

1. Power System Transients, V. Bush and R. D. Booth. A.I.E.E. Trans., v. 44, 1925, p. 80–103.

2. Studies of Transmission Stability, R. D. Evans and C. F. Wagner. A.I.E.E. Trans., v. 45, 1926, p. 51–94.

3. Calculation of Steady State Stability in Transmission Systems, Edith Clarke. A.I.E.E. Trans., v. 45, 1926, p. 22–41.

4. Static Stability Limits and the Intermediate Condenser Station, C. F. Wagner and R. D. Evans. A.I.E.E. Trans., v. 47, 1928, p. 94–121.

5. Circle Diagrams for Transmission Systems, R. D. Evans and H. K. Sels. *Elec. Jl.*, 1921, p. 530.

6. Electric Circuits, Theory and Applications, O. G. C. Dahl. McGraw-Hill Book Co., Inc., New York, N. Y., 1928.

7. M.I.T. Network Analyzer. Design and Application to Power System Problems, H. L. Hazen, O. R. Schurig, and M. F. Gardner. A.I.E.E. Trans., v. 49, 1930, p. 1102–13.

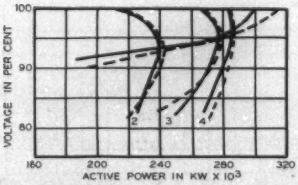
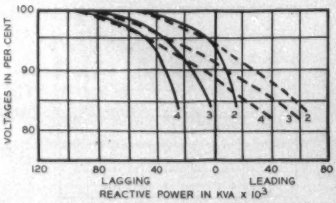


Fig. 19 (left). Power-voltage curves from approximate set-up

Fig. 20 (right). Reactive power-voltage curves from approximate set-up

Solid lines: Using load characteristics

Dotted lines: Using constant-impedance loads



Numbers on curves refer to steps in analysis; that corresponding to step 1 in Figs. 17 and 18 was omitted in the approximate set-up

Low Pressure Gaseous Discharge Lamps—Part II

By
SAUL DUSHMAN
ASSOCIATE A.I.E.E.

General Elec. Co.
Schenectady, N. Y.

Radiation and conduction phenomena in low pressure gaseous discharge lamps are discussed in this paper. Part I was published in ELECTRICAL ENGINEERING for August 1934; the second and concluding part, on electrical conduction processes, is presented herewith.

IN Part I of this paper, radiation processes in low pressure gaseous discharge lamps were discussed. In the present section, conduction processes are covered.

Conduction Processes in Relation to Light Efficiency

To produce visible light, that is, radiation ranging from λ4,000 to λ7,000 (where λ indicates wave length in Ångstrom units, or cm^{-8}), requires, on the basis of eq 6 (see Part I), the impact on atoms, of electrons having kinetic energy ranging from about 3.08 to 1.76 volts. In the case of sodium, 2.1 to 3.0-volt electrons bring about excitation and emission of visible light, but in such cases as neon and mercury, the electrons must acquire a kinetic energy which is 2 to 3 volts in excess of the resonance energy, since the resonance lines of these atoms are in the ultra-violet region and visible radiations are obtained only through transitions from still higher excited states. Thus if V_r denotes the resonance energy, the efficiency of light production in such cases as neon and mercury is approximately $2/(V_r + 2)$. While successive excitation does effect some saving in energy, it is evident that the efficiency of light production in sodium would be expected to be greater than that in mercury, and the latter, in turn, greater than that in neon.

The problems, therefore, of extreme importance in obtaining high light efficiency are, first, to choose the right kind of vapor or gas from the point of view of energy levels, second, to arrange the electrical conditions so that the electrons shall acquire sufficient kinetic energy to produce the maximum yield of excited atoms of the proper energy content, and, third, determine such operating conditions (pressure of gas, design of a discharge tube, etc.) that the atoms in the excited state shall give rise to the largest number of light-emitting transitions. Now the motion of any considerable number of electrons in the gas is possible only if the negative space charge that would result because of their presence is neutralized by positive ions. In fact this is the only function of positive ions in a low pressure discharge—to impart conductivity to the discharge. Furthermore, it is necessary to provide in any discharge some source of supply of electrons, and the energy thus consumed in generating electrons is therefore an "overhead" on the energy actually utilized in production of visible light.

This leads to considering in further detail the conduction phenomena in a discharge. In fact, as C. G. Found has stated,[29] "Any discussion of the production of light in a gaseous discharge must involve a consideration of such a discharge as a conductor of electricity, since the fundamental function of the applied voltage is to establish the passage of current. Any light produced is merely incidental to and a by-product of the processes which render the tube conducting."

Cold Cathode Positive Column Discharge

Let us consider the phenomena in a long discharge tube such as those used in neon signs (Geissler tubes) and containing gas at a low pressure. When a high voltage is applied between the 2 metal disk electrodes, a discharge occurs and the distribution of light is that shown in the lower part of Fig. 8.[30–34]

The following description is taken from the paper by Langmuir and Compton.

"Figure 8 illustrates a typical discharge of this kind. Close to the surface of the cathode a glow, called the cathode glow is observed. Beyond this is the cathode or Crookes' dark space. Then comes the negative glow which is usually of considerable intensity. Passing in the direction toward the anode, the intensity of this glow gradually decreases and becomes a second dark space, called the Faraday dark space, this usually being several times wider than the cathode dark space. Then comes the positive column which begins sharply at a definite position called the 'head of the positive column.' This surface of demarcation is convex on the side toward the cathode. In most cases the positive column is of uniform intensity all the way to the anode. Sometimes, however, it is broken up into striations, which appear to consist of alternations of Faraday dark spaces and short sections of positive column. Close

Full text of Part II of a paper recommended for publication by the A.I.E.E. committee on production and application of light, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted June 7, 1934; released for publication July 6, 1934. *Not published in pamphlet form.*

29. *G.E. Rev.*, v. 37, 1934, p. 269–77.
30. I. Langmuir and K. T. Compton, *Rev. of Modern Physics*, v. 3, 1931, p. 191.
31. C. G. Found and J. D. Forney, A.I.E.E. Trans., v. 47, 1928, p. 747.
32. "Die Elektrischen Leuchtrohren," W. Kohler and R. Rompe. F. Vieweg and Sohn, Akt. Ges., Braunschweig, 1933.
33. "Physik der Gasentladungen," R. Seeliger. 1927.
34. "Electrical Phenomena in Gases," K. K. Darrow. The Williams and Wilkins Company, Baltimore, 1932.

to the anode, especially if this is of small size, there may be an anode glow.

"Typical phenomena such as those illustrated in Fig. 8 are usually observed most readily at gas pressures in the neighborhood of one millimeter of mercury. At any given pressure the positions of the negative glow, the Faraday dark space, and the head of the positive column are fixed with reference to the cathode. Thus, for example, if the anode is moved, these positions do not change, whereas, if the cathode is moved, these boundaries move with it. As the distance between anode and cathode decreases, the anode may reach the head of the positive column so that the positive column disappears. In a similar way, the anode can be moved through the Faraday dark space and even into the cathode dark space. If the pressure is lowered, these distances from the cathode all increase approximately inversely proportional to the pressure. Thus, with fixed distances between the electrodes, on lowering the pressure, the cathode dark space expands until it reaches the anode."

The potential distribution in such a discharge in nitrogen has been measured by C. G. Found[31] using the method of exploring electrodes as developed by I. Langmuir and H. Mott-Smith[32] and is shown in the upper part of Fig. 8. The tube diameter was 6 cm, the nitrogen pressure 0.5 mm, and the current 5 ma. The high voltage drop at the cathode is characteristic of such discharges with cold cathodes and varies from 300 or 400 volts down to as low as 60 according to the nature of the gas and composition of the cathode. There is a slight gradient in the Faraday dark space, but under certain conditions this may become zero or even negative. Throughout the positive column there is a practically constant positive gradient which we shall designate by X, so that the power input per unit length is given by

$$W = Xi \tag{22}$$

where i is the discharge current.

"The drop at the anode may be positive, zero, or negative, depending upon the dimensions of the anode and the current density. However, it is always small and of the order of only a few volts."[31] As will be observed from Fig. 8 a considerable fraction of the total voltage drop between the electrodes occurs at the cathode. If we denote this cathode fall by V_c, the power $V_c i$ is evidently not available for the production of light. K. T. Compton and P. M. Morse[36] have developed a theory in explanation of this cathode fall by assuming that the drop is utilized in accelerating positive ions which liberate electrons from the cathode by a process of bombardment. Furthermore, the electrons thus emitted acquire sufficient energy near the cathode to ionize atoms and thus provide the ions needed for bombardment. The number of ionizing collisions made in this manner by an electron in passing through the cathode fall region is of the order of V_c/V_0, that is, usually of the order of 10. According to the theory of Compton and Morse, practically all the current at the surface of the cathode is carried by positive ions.

35. *G.E. Rev.*, v. 27, 1924, p. 449, 538, 616, 762, 810.
36. *Phys. Rev.*, v. 30, 1927, p. 305.

The fact that the gradient in the positive column is constant leads to the conclusion that the total charge density in this region is zero, that is, the concentration of electrons (n_e) must be equal, or approximately so, to that of positive ions (n_p). That the light produced in the column is all due to excitation and not to recombination of ions and electrons is concluded not only on the basis of measurements of electron velocities, as discussed below, but also from the fact that "Electron and ion concentrations are

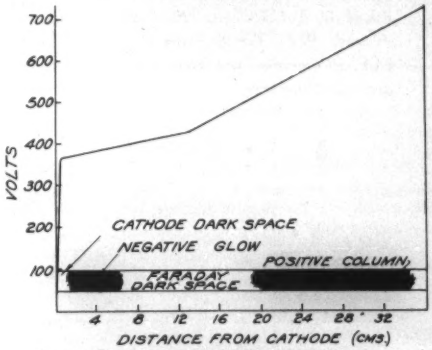


Fig. 8. Distribution of potential in positive column discharge in nitrogen (Found and Forney)

each of the order of 100 times larger in the negative glow than in the positive column, and their velocities are lower. If light in both regions were due to recombination, it should be $(100)^2$ times more intense in the negative glow because of greater concentrations, and still more than this because of lower velocities which favor recombination. Thus, certainly, recombination plays a negligible rôle in the production of light in the positive column."[37]

Evidence for this point of view is also furnished by the observations on the light emission from a negative glow lamp. This may be defined as a Geissler discharge in which the positive column has been completely eliminated, that is, a discharge consisting only of a cathode fall region. The light from this source is practically all due to recombination and is obviously quite low in intensity.

Advantages of Hot Cathodes in Gas Discharges

The disadvantages in the use of cold cathodes have been presented by Found and Forney[38] in the following remarks.

"In a tube with cold cathode, the positive ions strike the cathode with a high velocity due to the high cathode drop, and cause a mechanical disintegration of the cathode. The cathodic sputtering causes a blackening of the tube walls. Another re-

37. K. T. Compton and I. Langmuir, *Rev. of Modern Physics*, v. 2, 1930, p. 123.
38. A.I.E.E. Trans., v. 47, 1928, p. 747–52.

sult of the high cathode drop is a clean-up of the gas, causing the 'resistance' of the tube to increase as the tube is operated. Also, there is a large consumption of energy at the cathode which yields no light and greatly decreases the efficiency. To avoid this large energy loss and consequent heating effect, and in order to decrease the amount of sputtering, the current density at the cathode of a Geissler tube has usually been chosen at about 10 ma per square centimeter.

"Thus we may summarize the effects of the high cathode drop as follows.

"1. It is impossible to construct a low voltage tube.

"2. In order to have good light efficiency, it is necessary to make long tubes in which the ratio of cathode drop to total voltage is decreased.

"3. There is a 'clean up' or disappearance of the gas. This may occur from other causes also, but is certainly increased due to the high cathode drop.

"4. Blackening of the tube is caused by cathodic sputtering, and in order to keep this low, there is a limit to the current density at the electrodes."

If the cold cathode is replaced by a hot cathode capable of emitting electrons in sufficient numbers to supply the discharge current, the cathode drop V_c is reduced to a value which is only slightly in excess of the ionizing potential of the gas and which, in consequence of cumulative ionization, may be as low as the resonance potential. Since V_i has the highest value, 24.5 volts for helium, V_c need never exceed 25 volts. As mentioned in Part I, the probability of ionization is given by eq 10 and in this case the resulting form is

$$P_i = C(V_c - V_i) \tag{23}$$

As a result, it is possible to obtain a sufficient density of ions near the cathode to permit the desired arc current to pass without the necessity of increasing V_c to any considerable extent. C. G. Found has shown in a recent paper[39] that the possibility of drawing large electron currents from a hot cathode in an arc is due to the production of a field at the cathode by the positive ions. This field emission may be as much as 10 times the zero-field emission and evidently increases with V_c. No sputtering occurs if, as has been shown by A. W. Hull,[40] V_c is maintained below a critical value which varies with both the nature of the cathode and the composition of the gas. For thoriated tungsten this "disintegration voltage" is about 27 with neon ions and 17 volts with mercury ions, and with all types of cathodes this voltage is always sufficiently above V_i to secure a practical operating range.[41]

A number of constructions of thermionic cathodes for use in gas discharges have been described by Hull and other investigators.[42] Besides the filamentary type, inside coated cathodes with barium oxide-strontium oxide as active material are used to secure high efficiency of electron emission, and shields are often added to reduce heat losses. It is thus possible to operate oxide coated cathodes in gas discharges at emission efficiencies which are considerably greater than those obtained in vacuum devices.

Since in the following discussion only discharge tubes in which hot cathodes are used will be considered, the classification of these tubes suggested by C. G. Found[43] will be adopted. He classifies them according to the *geometry* of the containing vessel into 2 types: (1) cathodic, (2) positive column; and defines these as follows:

"A cathodic discharge is defined as one which is more or less bulbular in shape and in which the distance between cathode and anode is comparable to the smallest dimension of the bulb.

"A positive column is an elongated tube in which the distance between cathode and anode is several times the diameter."

In general, it may be stated that a cathodic type of discharge operates with a voltage drop which is approximately equal to V_i and may be as low as V_c (owing to successive impacts). A tungar rectifier is an example of such a discharge, and the more recently developed d-c low-voltage sodium lamp is another example. Such an arc may be started on a comparatively low voltage circuit (less than 110 volts) without any auxiliary voltage "kick."

In a positive column discharge the total voltage drop usually exceeds V_i for the gas and while the discharge tube may be designed to operate on less than 110 volts, a starting kick or some equivalent device, such as auxiliary electrodes, is necessary. This initial high voltage is needed to overcome the negative charge on the walls which tends to prevent the flow of electrons. The low-pressure mercury vapor lamp with mercury cathode, and the hot-cathode high-current neon tubes are examples of this type of discharge. The high lumen output a-c sodium lamp developed recently for use on 6.6-amp constant current circuits[44,45] is another example. The main distinction between the 2 forms of discharge is in the fact that in the cathodic type all of the energy from the external source of supply is converted into kinetic energy of electrons at the cathode, and, consequently, there is no voltage gradient outside the region of the cathode fall, as in a positive column. In the latter, there is in addition to the cathode fall V_c, a drop in the rest of the tube which varies with the length, other conditions remaining constant.

Cathode Drop

Consideration will next be given to what occurs in a cathodic type of discharge when a voltage is applied between the electrodes. The electrons emitted from the cathode produce ions either directly or by cumulative ionization and this permits more electrons to flow, thus altering the potential distribution between the electrodes until finally a stationary condition is attained in which the whole fall of potential is concentrated in a thin sheath close to the cathode. The rest of the space between the electrodes is field-free and is known as the plasma.

It has been shown by Langmuir[46] that if the arc

39. *Phys. Rev.*, v. 45, 1934, p. 526.
40. A.I.E.E. Trans., v. 47, 1928, p. 753.
41. A. W. Hull, *G.E. Rev.*, v. 32, 1929, p. 213.
42. L. J. Buttolph, Ill. Engg. Soc. *Trans.*, v. 28, 1933, p. 153.
43. *G.E. Rev.*, v. 37, 1934, p. 269–77.
44. G. R. Fonda, *G.E. Rev.*, v. 37, 1934, p. 331–7.
45. N. T. Gordon, *G.E. Rev.*, v. 37, 1934, p. 338–41.
46. *Phys. Rev.*, v. 33, 1929, p. 954.

current is less than the thermionic emission from the cathode for zero field, then the sheath is actually a double sheath consisting of an electron space charge next to the cathode and a positive ion space charge next to the plasma. Under these conditions the ratio γ between electron current density I_e and positive ion current density I_p at the cathode is given by

$$\gamma = I_e/I_p = \sqrt{m_p/m_e} \tag{24}$$

where m_e and m_p denote the mass of electron and positive ion, respectively. (Table VI shows values of γ for different gases.) The voltage gradient is zero at both the cathode surface and the edge of the plasma (the writer has followed in this discussion the remarks of C. G. Found[39,48]) and the relation between I_e (or I_p), sheath thickness d, and cathode fall V_c, is given by a space charge equation. Calculation shows that for current densities, such as are used in practical lamps, the value of d is of the order of 0.01 cm, which, at one millimeter pressure, is considerably less than the mean free path of an electron, so that most of the electrons that are accelerated in the cathode sheath retain their energy when they enter the plasma. As they drift through the plasma to the anode, this energy is used up in excitation and ionization of atoms of the gas with which they collide (in the manner described in Part I).

In the plasma, the number of ions generated per second by the electron current I_e, is given by the relation derived from eq 23.

$$n_p/I_e = C(V_e - V_i) \tag{25}$$

The fraction f of the ions formed, which flows to the cathode, constitutes the positive ion current density I_p. Therefore

$$I_p = f \cdot C \cdot I_e(V_e - V_i) \tag{26}$$

Since f is determined by the geometry of the bulb and electrodes and by the extent of the region of generation of positive ions (which changes only slightly with current density) V_e can be altered only by varying γ. Under the conditions specified above, that is, with the arc current less than the zero-field emission from the cathode, γ is determined by the nature of the gas, and, therefore, $V_e - V_i$ has a definite value which may be calculated from the known values of C and γ and an experimental determination of f for the particular design of discharge tube used.

In those discharges in which cumulative ionization occurs, V_i is replaced by V_m, the excitation potential of the metastable states, and in this case also $V_e - V_m$ may be calculated by means of eq 26, using the corresponding value of C.

Now it may be deduced very readily that the light production will depend upon the value of $V_e - V_i$ (or $V_e - V_m$). If this is found to be considerably less than 2 volts, it is evident that the electrons which have left the cathode sheath and produced an ion or metastable state by collision with an atom, will not have sufficient energy to excite atoms to such levels as will give rise to visible light, since this latter process requires that the electrons shall have a kinetic energy between 2 and 3 volts. Consequently, with too low a value of V_e, the light output will be very low. That is, in order to obtain high light output from a cathodic type of discharge, $V_e - V_i$ (or $V_e - V_m$) must be of the order of 2.5 volts. Now such a result may be secured by decreasing the pressure, which decreases C, but obviously this involves fewer collisions and therefore low light output. Hence, to secure high light output, it is necessary to decrease the value of the ratio $\gamma = I_e/I_p$, that is, to increase the positive ion current to the cathode. This is accomplished by having the arc current exceed the zero field emission, since the excess current is then obtained by the action of the field established at the cathode by the positive ions. It is therefore evident from these considerations that in a cathodic type of discharge, the efficiency of light production is determined by the relation between arc current and zero-field emissivity of the cathode. This conclusion will be illustrated in a subsequent section by a consideration of the light producing processes in a discharge in neon and sodium.

Primary, Secondary, and Ultimate Electrons.[47] Electron Temperature

Since, as has been mentioned already, there is only a slight probability of a collision between an electron and a gas atom in the sheath, practically all the electrons leave the sheath with the energy V_e. These *primary* electrons may then ionize a gas atom, and the energy $V_e - V_i$ is then distributed between the original electron and the electron liberated from the atom, which together constitute the class known as *secondary* electrons. These secondary electrons may have sufficient energy to cause one or more excitations, and when their energy is reduced to such an extent that most of them can suffer only elastic collisions they are known as *ultimate* electrons. Owing to their low velocity as compared with both primaries and secondaries they constitute the largest fraction of the electrons in the plasma.

The ultimate electrons at any point in the plasma possess a Maxwellian distribution of energies which is defined in terms of an "electron temperature," T_e, and the Maxwell Boltzmann equation

$$n = n_e e^{-V_e/kT_e} \tag{27}$$

In this equation n_e is the concentration of electrons per unit volume in the plasma, and n/n_e is that fraction of the electrons which have an energy in excess of V volts. Since $e/k = 11{,}600$ deg K per volt, we can write the last equation in the form

$$n = n_e e^{-\frac{11{,}600V}{T_e}} \tag{28}$$

The average energy of the electrons corresponding to the temperature T_e is

$$\frac{1}{2} m_e \bar{v}^2 = \frac{3}{2} kT_e \tag{29}$$

Since the electrons move in the plasma in random directions, the random electron current density, that is, the number of electrons crossing unit area per unit time in any given direction is

$$I_e = n_e e \left(\frac{kT_e}{2\pi m_e}\right)^{1/2}$$
$$= 2.48 \times 10^{-14} n_e \sqrt{T_e} \text{ amp/cm}^2 \tag{30}$$

By measuring the current to a fine wire (or small disk) inserted in the plasma, as a function of the potential of the probe, it is possible to determine both I_e and T_e, as has been shown by I. Langmuir and H. Mott-Smith.[48,49] In a cathodic type of discharge, such as that in neon at one millimeter pressure, T_e for the ultimate electrons is about 5,500 deg K, that is, about 0.5 volt. Of these electrons, the fraction capable of exciting a sodium atom (2.10 volts) as calculated from the Boltzmann equation (eq 28) is $\epsilon^{-4.4}$ approximately, or about 0.012.

The positive ions in the plasma do not have a Maxwellian distribution since their motion is governed by the electric fields resulting from the variation in electron concentration in different regions of the plasma. As L. Tonks and I. Langmuir have stated,[50] the positive ions "are supposed to have negligible velocity when formed and to acquire only such velocities as correspond to the electric fields through which they pass. In the case of long mean free paths (low gas pressures) each ion will thus fall freely under the influence of the small plasma fields set up by the electrons and ions themselves until it strikes the tube wall or an electrode. For short free paths (higher gas pressures) the ion will be impeded in its motion by collision with atoms but still will be guided mainly by the electric field in which it finds itself."

In their earlier papers, Langmuir and Mott-Smith stated that the motions of the ions may be described roughly as corresponding to a temperature $T_p = T_e/2$. However, this description applied only to the measurements made with probes in positive column discharges, and cannot be valid for the ions in a cathodic discharge. In fact, as Tonks and Langmuir point out in their more recent paper,[75] "It seems entirely unreasonable that the ion energy should even approach the electron energy in view of the fact that it is the electrons primarily which supply energy to the rest of the plasma and the positive ions with their large relative mass and frequent impact with slow atoms are not adapted to acquiring large random kinetic energies."

If the positive ions had a true Maxwellian distribution corresponding to T_e, the ratio of electron current density I_e to positive ion current density I_p would be given by the relation

$$I_e/I_p = \sqrt{m_p/m_e} \tag{31}$$

which has been given in a previous section for the ratio of currents in the double sheath at a thermionic cathode. Actual observations in positive column discharges have led to the relation

$$I_e/I_p = \sqrt{m_p/2m_e} \tag{32}$$

which may be derived on the basis of theoretical considerations. Table VI gives values of $\sqrt{m_p/m_e}$ and $\sqrt{m_p/2m_e}$ for various gases which correspond to the values of I_e/I_p derived by means of eqs 31 and 32. While it is certain that a similar relation cannot apply to cathodic discharges, it is evident that in this case also, the random electron current density directed toward the walls at any point must be considerably greater than the positive ion current density.

Sheaths on Walls

The fact that the random current densities in the plasma are so different leads to the formation of sheaths on the walls and other insulated surfaces. As pointed out by Langmuir,[51] "If the glass walls of a tube containing a plasma were at the same potential as the plasma itself, the current relationship given by eq 32 shows that the walls would receive electron currents hundreds of times greater than correspond to the positive ions that reach the walls.

Table VI—Mass Relations for Various Gases

Gas	$\sqrt{m_p/m_e}$	$\sqrt{m_p/2m_e}$
Helium (He)	85.6	60.5
Neon (Ne)	192.5	136.1
Argon (A)	270.5	191.3
Sodium (Na)	205.3	145.2
Mercury (Hg)	605.6	428.3

Actually, in a steady state, the number of negative and positive charges which reach an insulated wall must be equal. To render these currents equal, the walls must therefore become so highly negatively charged that they force nearly all the electrons back into the plasma. The walls thus become covered with a positive ion sheath. The potential drop in this sheath can be calculated by means of the Boltzmann equation (eq 28). Since the electron temperature is uniform throughout the plasma, the current density I_w which moves against the retarding field in the sheath is proportional to the electron concentration n and thus eq 28 may be written

$$I_w = I_e \epsilon^{-V_e/kT_e} \tag{33a}$$

where I_e = random current density in plasma."

In terms of ordinary logarithms, this equation becomes

$$2.30 \log (I_e/I_w) = \frac{11{,}600 V_e}{T_e} \tag{33b}$$

where V_e denotes the negative potential to which the walls are charged (that is, the voltage drop in the wall sheath).

The values of I_w and I_e may be determined experimentally by means of probe measurements, thus making it possible to calculate V_e. For instance, in a cathodic discharge in neon at one millimeter, if we substitute the value T_e = 5,500 deg K for the ultimate electrons, and assume that $I_w = I_e/136$, it follows that V_e = 2.33 volts.

Relation Between Light Output and Current in Cathodic Discharge Lamps

In a cathodic discharge the light produced is the result of collisions between atoms in the normal or

47. I. Langmuir and H. A. Jones, *Phys. Rev.*, v. 31, 1928, p. 357.
48. *G.E. Rev.*, v. 27, 1924, p. 449, 538, 616, 762, 810.
49. I. Langmuir, Frank. Inst. *Jl.*, v. 214, 1932, p. 275.
50. *Phys. Rev.*, v. 34, 1929, p. 876.
51. Franklin Institute *Jl.*, v. 214, 1932, p. 275.

excited states with electrons which have acquired their energy in the cathode fall sheath. The extent of the light region is thus governed by the distances which the electrons traverse before their energy has decreased to such a value that they have become ultimate electrons. It is therefore a function of both gas pressure and magnitude of cathode fall V_c. As has been emphasized already, the function of the ions is merely to eliminate the negative space charge that would limit the arc current to a low value if electrons only were present. In consequence, the voltage drop in the arc adjusts itself to such a value for any given arc current that both a sufficiently strong field will exist at the cathode to provide the necessary electron emission and the electrons will have sufficient energy to produce the ionization required by the electron current in accordance with eq 26 and eq 24.

The relation between current and light output varies according to the nature of the processes involved in the production of the light, which, in turn, differ with both the composition of the gas and the magnitude of the cathode fall V_c.

Consider first a discharge in a vapor, such as that of sodium, in which the light emitted is mainly resonance radiation. If the vapor pressure is fairly high (0.01 mm or higher) and the current density not too great, V_c will exceed V_i by about one volt, and therefore the primary electrons will have an energy equivalent to about 6 volts. Since, as has been mentioned previously, P_i increases linearly with V, while P_e for excitation of sodium atoms to the $3P$ state passes through a maximum at about 2.5 volts (see curve in Fig. 2) and decreases slightly for larger values of V, it depends upon the exact value of V_c as to which process will occur more frequently. Both ions and excited atoms in the $3P$ state will be produced, and the primary electrons will lose 5.1 volts in the first process and 2.5 in the second. The secondary electrons which have 0.9-volts residual energy are obviously unable to produce any further excitation and will therefore be ultimate electrons, while the electrons with 3.5-volts residual energy will be able to cause one further excitation before becoming ultimate electrons. However, as the concentration of excited atoms increases, more radiation of the D-lines is emitted and this is reabsorbed by normal atoms with the resulting phenomenon which has been designated in a previous section as "imprisonment of radiation." As a result the number of sodium atoms capable of being excited and ionized decreases and the light output reaches a saturation. Hence, it can be expected that the light output will increase linearly with currents for small values of the latter, but will tend to reach a constant value for higher currents.

If the pressure of sodium is low, the value of P_i is decreased and V_c must increase to 8 or 9 volts in order to obtain sufficient ionization. This is a direct consequence of eq 27. Under these conditions, a primary electron will still retain 2.5 volts after an ionizing collision and will thus be able to excite a sodium atom. In other words, all the electrons leaving the cathode sheath contribute toward the production of D-line radiation. Hence, while the intensity of this radiation increases linearly with current, as before, the efficiency of light production is much greater at the lower pressures. Also at higher currents, saturation phenomena occur as in the vapor at higher pressures.

As a matter of fact, a lamp utilizing a discharge in sodium vapor alone is possible only if some other source of energy is supplied for evaporating the sodium. Therefore, neon or argon at one millimeter pressure, or higher, is used in sodium vapor lamps to function as starting gas, and for the first few minutes (until the vapor pressure of sodium increases to about 0.0005 mm) the spectrum of the light emitted is characteristic of the rare gas. Furthermore, even when the D-line radiation becomes predominant, and until the pressure of sodium becomes much higher (of the order of 0.002 mm), the spectral lines of neon or argon are also emitted and the electrical characteristics of the discharge are practically the same as those in the rare gas alone.

In the case of neon at one millimeter pressure, the value of V_c, as observed by probe measurements, is about 18 or 19 volts under usual operating conditions and it is only when the vapor pressure of sodium increases to values above about 0.002 mm that V_c decreases to about 8 or 10 volts and at the same time the neon or argon lines disappear completely. Since the maximum light output is obtained with the higher values of V_c, it is important to consider more fully the nature of the light producing processes in a cathodic type of discharge in neon at about 1 to 5 mm pressure, in the absence of sodium.

Owing to the fact that V_c in such a discharge is less than V_i, the primary electrons are unable to cause ionization by direct impact, and, as a result, the neon atoms are excited to the lower resonance and metastable levels (the 4 s-states indicated in Fig. 5 at 16.53 to 16.77 volts). The resonance radiation emitted by the states s_2 and s_4 is very strongly absorbed by normal neon atoms, and therefore persists in the gas for very long periods. The metastable states s_3 and s_5, because of their long life, accumulate in concentration and may therefore be excited to the p-states by further impact from the secondary electrons which have retained (19 − 16.5 =) 2.5 volts and higher values of kinetic energy.

An electron accelerated by the cathode fall may collide with a metastable neon atom directly and ionize it. The probability of this process is much greater than that of direct excitation to a p-level. Since the energy required for ionization of a metastable neon atom is 21.5 − 16.5 = 5 volts, the secondary electron which results from the impact of a primary electron on a metastable neon atom with the formation of an ion, still retains 19 − 5 = 14 volts kinetic energy. It is therefore capable of ionizing 2 metastable atoms by subsequent collisions. Thus the ionization produced in a neon discharge must be of the cumulative type, and measurements with probes at different distances from the cathode, of the electron temperatures, have shown that this representation of the phenomena in such a discharge is essentially correct.

From this point of view, a discharge in neon at one millimeter pressure may be regarded as a dis-

charge with a cathode drop of 18 or 19 volts in a gas which has an ionization potential of 5 volts and a first excitation potential of about 2 volts, and it is possible to derive an approximate relation between light output and arc current, as follows:

At any current, the rate of excitation of metastable atoms to higher levels by electron impact and the rate of destruction by diffusion to the walls must be equal to the rate at which metastable atoms are formed by primary electrons. If I denotes the current, and n_m the concentration of metastable atoms, it readily follows that at equilibrium,

$$n_m = AI$$

where A is a constant involving probabilities of excitation.

The light emitted (L) by any line of frequency ν_{km} is given, in accordance with the considerations presented previously, by a relation of the form

$$L_{km} = n_k \cdot h\nu_{km}/\tau_{km} \tag{34}$$

where n_k is the concentration of atoms in state k, and m is the metastable state to which the light-emitting transition occurs.

But as a first approximation,

$$n_k = BIn_m$$

since the atoms in state k are produced by excitation of metastable atoms. Consequently, to a first approximation

$$L_{km} = CI^2 \tag{35}$$

That is, when cumulative ionization occurs, the light output increases with current more rapidly than when such a process does not occur. However, other processes occur by which the light output is decreased, so that eq 35 can be considered as valid only at very small current values. Thus, the excited atoms in the p-levels are destroyed by collisions with electrons of low kinetic energy (collisions of the second kind), and by collisions with the walls; also the rate of ionization of metastable atoms increases with the current because of increased value of V_e, so that the relative number which may be excited to p-states does not increase as rapidly. As a result the light output tends to reach a saturation value in this case also.

The mode of light production in neon at 1–5-mm pressure which contains about 0.001-mm pressure of sodium vapor may now be considered. As has been pointed out by Found,[43] "Since the pressure of neon is several thousand times that of sodium, it is extremely improbable that a sodium atom will be excited or ionized by a primary electron before the latter has lost energy to a neon atom. On the other hand, the secondary electrons are unable to cause any excitation of neon, and although they may have collided several thousand times with neon atoms before striking a sodium atom, they will still be able to excite the latter. Thus in a cathodic sodium lamp the generation of light is produced mainly by the secondary electrons and the light output determined by the number and energy of these electrons." The maximum light output will be obtained with secondary electrons of kinetic energy equivalent to 2.5 volts. Therefore, in a neon-sodium lamp, the light output is greatest when V_e is slightly greater than 16.5 + 2.5 = 19 volts. These considerations thus illustrate the conclusion stated in a previous section that the thermionic characteristics of the cathode are of great importance in determining the light output and efficiency of a cathodic discharge lamp.

The relation between light output and current in a cathodic neon-sodium lamp at constant wattage input (to maintain constant vapor pressure of sodium) is linear over a large range of currents, as has been shown by Found.[29] It has been found that in this range the light obtained is 1,000 lumens per ampere. "This corresponds to the generation of one light quantum per primary electron. When the discharge is all sodium, the linear portion of the curve (lumens versus current) corresponds to only about 500 lumens per ampere."

Reverse Field in Low Voltage Arcs

(A more complete presentation of this topic is given by K. K. Darrow.[52])

From the considerations in the previous sections it might be concluded that the minimum voltage drop between anode and cathode for the operation of a cathodic discharge should correspond to the resonance potential V_r, since obviously V_e cannot be less than this value. However, it is a fact often observed with this type of discharge that the voltage drop between the electrodes may be considerably lower than V_r. For instance, a cathodic discharge in neon at one millimeter pressure may be obtained with an arc drop of 12 to 14 volts (whereas V_r = 16.5 volts); and similar observations have been made with arcs in argon, helium, mercury, and sodium.

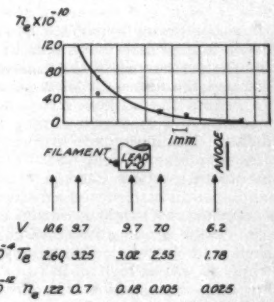


Fig. 9. Distribution of potential, electron temperature, and electron concentration in low voltage arc in argon

The explanation of this phenomenon was first obtained by K. T. Compton and C. Eckart[53] as a result of observations with a probe which could be inserted at different points between a hot cathode and anode in argon at a few millimeters pressure. In Fig. 9 is shown a typical set of data obtained for

52. "Electrical Phenomena in Gases," K. K. Darrow, p. 383–86.
53. *Phys. Rev.*, v. 25, 1925, p. 139.

T_e, n_e and V, the potential shown being with respect to the cathode at the points in the plasma indicated by arrows. The scale of distance is given by the short line marked one millimeter; the observed arc drop was 5.2 volts and the arc current 0.45 amp. The value of V_e for argon is 11.5 volts, and while this set of data shows a maximum potential of 10.6 volts behind the cathode; other data give values of this maximum as high as 11.6, thus showing that V_e is actually about 11.5 volts, as expected, but that there is a reverse field between cathode and anode of about 6 volts, so that the actually observed arc drop is only 5.2 volts.

"The apparent difficulty," Compton and Eckart remark, "which arises from the fact that the electron current (which is practically the entire arc current) flows against an opposing field, disappears on consideration of the concentration gradient of electrons which is shown by the graph. It is obvious from general considerations based upon ionic and electronic mobilities, that this concentration gradient is the equivalent of an electromotive force. J. J. Thomson has called attention[54] to this force which is given by

$$E = \frac{\mu_- - \mu_+}{\mu_- + \mu_+} \frac{e}{kT} \log \frac{N_1}{N_2}$$

where E is the potential difference set up between 2 regions of ion concentrations N_1 and N_2, μ_- and μ_+ are the mobilities of electrons and positive ions, and $(3/2)kT$ is the average kinetic energy of the ions. (It is assumed that this is the same for electrons and positive ions. If this is not true, the equation is more complicated, but the underlying features are similar.)

"Usually this force has been considered as negligible in comparison with that due to the applied electric field. Under suitable conditions, however, it may become of primary importance. The favorable conditions are a long free path for the electrons and a high concentration gradient. The first of these conditions is realized to an unusual degree in argon and probably accounts in the case of this gas for the persistence of the nonoscillatory low voltage arc and the unusually large reverse field in the gas. In helium the authors have observed it only occasionally, and in mercury vapor it is also less clearly defined than in argon. In these gases the maximum observed reverse field was 3 or 4 volts. Measurements in mercury showed concentration gradients similar to those reported here for argon."

Similar observations on the existence of maxima for V and n_e in cathodic discharges in neon have been made by M. J. Druyvesteyn.[55] He found that while V_e was as high as 19 volts, the arc drop was as low as 13 volts, which is in agreement with observations made in this laboratory on the d-c neon and sodium lamp.[45] In this case the maximum value of n_e was 2.4×10^{12}, and T_e decreased from about 30,900 near the cathode to about 11,500 at the anode.

These observations are thus in agreement with the views expressed in the previous section regarding cumulative ionization, and the gradual loss of energy by secondary electrons in excitation of metastable neon atoms.

54. "Conduction of Electricity through Gases," J. J. Thomson, p. 85 (1906).

Voltage Gradient, Electron Temperatures and Concentrations in Positive Column

In a cathodic type of discharge, the electrons acquire a high kinetic energy in the cathode sheath and then lose this energy in excitation and ionization of atoms. Thus the kinetic energy decreases with increase in distance from cathode and finally when the electrons have reached the stage in which their kinetic energy is no longer adequate for excitation (ultimate electrons) the light generation also disappears.

The fact that the light generation is uniform throughout the length of the positive column shows that the electrons must acquire energy for excitation and ionization from some other source than the cathode fall. This energy is supplied, obviously, by the energy input into the column, that is, Xi_A watts per unit length, where X is the voltage gradient and i_A the arc current. The magnitude of X varies with current density and pressure of gas, as illustrated by the data in Table VII given by C. G. Found and J. D. Forney for a discharge in neon in a tube 2.55 cm diameter. It will be observed that the gradient exhibits a flat minimum between 2 and 5 mm; also that it decreases with increase in current, so that the positive column has a "negative" resistance.

According to the theoretical considerations developed by W. Schottky,[56] the gradient in a positive column discharge should vary approximately inversely as tube diameter, when current and pressure of gas are maintained constant. The larger the diameter, the smaller the relative loss of ions and electrons by diffusion to the walls, and hence the smaller the energy input to compensate for this loss of charged particles. The values of X observed by Found and Forney for different diameters were found to be in satisfactory agreement with Schottky's conclusion.

According to A. Guntherschulze,[57] the observed gradients in monatomic gases may be represented as a function of the diameter d, by an empirical equation of the form

$$X = \frac{c}{d\left(1 + \frac{aI}{d}\right)} \tag{36}$$

where c and a are constants, and I is the arc current. In a more recent paper by W. Elenbaas[58] it has been found that the gradient in mercury vapor at different pressures is a function of d and I of the form

$$X = \frac{c}{d^a I^b}$$

where a and b are exponents which vary with the pressure of the gas. At 100 deg C (vapor pressure of 0.276 mm) these constants have the values $a = 0.69$ and $b = 0.12$. Hence Schottky's conclusion can be regarded as only approximately valid.

Owing to the fact that the gradient in the column is constant, the net charge density must be prac-

55. *Zeit. f. Phys.*, v. 64, 1930, p. 781.
56. *Physikal. Zs.*, v. 25, 1924, p. 342, 635.
57. *Zs. f. Phys.*, v. 41, 1927, p. 718; v. 42, 1927, p. 763.
58. *Zs. f. Phys.*, v. 78, 1932, p. 603.

tically zero, as has been mentioned previously. Thus there must be some mechanism by which ions may be produced by impact of electrons on atoms, and the only method available is the impact of high-speed ultimate electrons. While the average kinetic energy of these electrons is much too low for ionization, and may even be too low for excitation, it

Table VII—Variation in Voltage Gradient in Neon With Pressure and Current

Press. in mm	Arc amps	X volts/cm
0.2	2.0	1.95
0.6		1.90
1.5		1.72
3.1		1.65
4.25		1.61
4.9		1.80
0.2	0.5	2.1
	1.0	2.0
	2.0	1.95
	3.8	1.87
	6.8	1.78

should be observed that these electrons possess a Maxwellian distribution of energy corresponding to a temperature, T_e, and therefore have an average kinetic energy of $\frac{3}{2}kT_e$. At any given temperature, the number of electrons per unit volume n capable of causing ionization is given, in accordance with eqs 27 and 28 by the relation

$$\frac{n}{n_e} = \epsilon^{-Ve/kT_e} = \epsilon^{-11,600\ Ve/T_e}$$

where n_e is the total concentration per unit volume. Thus for a value of $T_e = 40,600$ (equivalent to 3.5 volts), which has been observed for a positive column discharge in neon, $V_e e/kT_e = 21.5/3.5 = 6.15$; $n/n_e = 0.0021$, while for $V = 16.5$ volts (the excitation energy for metastable atoms), the corresponding value of $n/n_e = 0.009$. At any given electron temperature there is therefore present a small concentration of electrons capable of either excitation or ionization. The energy lost by these high-speed electrons through the processes of excitation and ionization is supplied by the energy input Xi_A, and in this manner the Maxwellian distribution of energy among the electrons is maintained. The problem of a mechanism for this transfer of energy has been investigated by I. Langmuir[59] who concludes that probably there is an interaction of radiation with excited atoms and electrons.

From these considerations, it follows that the electron temperature is the most important factor in maintaining the ionization and excitation in the positive column. This is shown by the manner in which T_e, the electron temperature, varies with conditions in the discharge. The data in Table VIII, taken from the paper by T. J. Killian[60] show the variation in T_e and in electron concentration with pressure of mercury vapor. These values were observed at an arc current of 5.0 amp in a tube of diameter 6.2 cm.

59. *Phys. Rev.*, v. 26, 1925, p. 609.

The table gives values of X, N_e, the *total* number of electrons per centimeter length of column, and I_p, the positive ion current density to the walls. It will be observed that X and T_e decrease with increase in pressure. From other observations it has been found that T_e in a mercury vapor discharge exhibits a tendency to decrease somewhat with increase in arc

Table VIII—Variation in Electron Characteristics With Temperature

Pressure in mm	X (volts/cm)	T_e	N_e	I_p(ma/cm²)
0.00020	0.0932	38,000	11.1×10^{11}	0.356
0.00103	0.196	27,500	21.8×10^{11}	0.45
0.00533	0.311	19,900	45.7×10^{11}	0.505

current. The data also indicate that N_e and I_p increase with increase in pressure. Since the tube cross section was 30.2 sq cm, the average values of n_e, the concentration per cubic centimeter, varied from 3.7×10^{10} to 15.2×10^{10}. However, as deduced from theoretical concentrations by L. Tonks and I. Langmuir,[61] and confirmed by Killian's measurements, the concentration is a maximum along the axis of the tube and decreases toward the walls, thus establishing a concentration gradient for diffusion.

It is important to realize the significance of a value $T_e = 19,900$. At this temperature, the *average* kinetic energy of the electrons is

$$\frac{3}{2}\ kT_e = \frac{3}{2} \cdot \frac{19,900}{11,600} \text{ volts} = 2.56 \text{ volts}$$

The fraction of the electrons with an energy in excess of 10.4 volts (V_e for mercury) is

$$\epsilon^{-\frac{10.4}{1.71}} = 0.003$$

Furthermore, as mentioned previously, the walls must become charged negatively with respect to the plasma to such a potential that the electron current flowing in that direction shall be equal to the positive ion current. Applying the equations developed by Tonks and Langmuir, it is found that in this case there is a total drop from the axis to the walls of 11.0 volts, of which about 2.5 occurs in the plasma, leaving a voltage drop in the wall sheath of 8.5 volts. Since the magnitude of this drop increases linearly with T_e, it follows that for $T_e = 38,000$, the walls would be charged to a negative potential of 16.2 volts with respect to the outer edge of the plasma.

A very complete set of data on the gradient, electron temperature and concentration in a positive column discharge in sodium and sodium plus neon has been published by M. J. Druyvesteyn and N. Warmoltz.[62] Some of this data is shown in Table IX. The measurements were taken with the tube connected to a sodium reservoir maintained at the temperature indicated in the first column. Since

60. *Phys. Rev.*, v. 35, 1930, p. 1238.
61. *Phys. Rev.*, v. 34, 1929, p. 876.
62. *Phil. Mag.*, v. 17, 1934, p. 1.

the tube itself was at 330 deg C, there was no condensation of sodium along the walls of the tube, and while the second column gives the vapor pressure at the corresponding temperature, the actual pressure in the tube varied with distance from cathode owing to migration of sodium ions. The third column gives the pressure of neon as measured by a gauge at room temperature. The values of X, T_e, and n_e were determined by probe measurements. The last 2 columns give data which will be considered in a subsequent section in connection with energy-balance in a positive column.

It will be observed that, as in the case of measurements with mercury vapor discharges, T_e and X decrease with increases in pressure, while n_e increases. Assuming, according to Schottky's deductions that X varies inversely as tube diameter, d, the relative values of Xd and T_e for the same vapor pressure are found to be higher in mercury than in sodium. This is what would be expected in view of the relative values of V_i (and V_e). The fact that the voltage gradient is increased by addition of neon when the sodium pressure is low and decreased by addition of neon when the sodium pressure is higher, shows that at the low pressures of sodium the ions are supplied by neon, while at higher pressures of sodium the ions are obtained from the latter. That the sodium, even at 0.0021 mm decreases the gradient in neon at 1.1-mm pressure from what it would be in absence of sodium is evident from a comparison of Xd for pure neon as given in Table VII with values at the same pressure of neon in Table IX.

Table IX—Data for Positive Column Discharge in Sodium and Sodium Plus Neon. Tube Diameter = 3.6 cm

t°C	p(Na) mm	p(Ne) mm	Arc amps	X volts/cm	T_e	$n_e \cdot 10^{-10}$	E_R	E_W
							Percentage of total	
255	0.0021	0	0.2	0.432	30,950	1.01	92.2	13.3
		0	1.0	0.398	19,200	4.55	93.7	13.8
		1.1	0.2	1.021	17,600	4.45	92.5	7.1
			1.0	0.504	9,100	39.9	88.8	12.5
		3.0	1.0	0.461	8,050	67.	88.3	10.3
273	0.0044	0	0.2	0.748	22,750	1.25	91.4	6.0
		0	1.0	0.555	12,600	8.64	91.7	8.0
		1.1	1.0	0.481	8,050	39.9	90.5	9.9
		3.2	1.0	0.440	7,600	77.0	87.5	9.4
287	0.008	0	1.0	0.668	9,600	14.8	92.3	6.4
		1.07	1.0	0.517	8,050	39.8	92.0	8.6
		3.1	1.0	0.443	7,100	75.0	90.5	9.6
		5.0	1.0	0.440	6,600	97.0	87.4	8.0

It is extremely probable that in a positive column discharge in pure neon the ions are produced by cumulative action, as in the cathodic discharge. The fact that there is a considerably greater number of electrons with energy sufficient to excite atoms to the metastable state than those with energy necessary for ionization by direct impact, must favor the value of P_e as compared with that of P_i. There is, however, additional evidence from various sources. The measurements of H. Kopfermann and R. Ladenburg,[63,64] which will be discussed in a subsequent section, show that the concentration of metastable atoms in a positive column discharge is quite high and comparable with the values of n_e. In this laboratory, W. F. Westendorp[65,66] has shown that the negative resistance characteristic of a neon positive column and the reactance behavior with a direct current upon which has been superposed a ripple, can be interpreted on the assumption of high concentrations of metastable atoms. In fact, from his measurements of the impedance, Westendorp was able to calculate approximate values of τ, the duration of the metastable state, which are of the same magnitude as those deduced by J. M. Anderson[67] by more exact methods.

Table X—Comparison of Voltage Gradient and Electron Temperature Under Similar Conditions for Helium, Neon, and Argon

Gas	Arc amp	X volts/cm	T_e
Helium (He)	0.2	2.24	49,100
	0.5	2.12	53,000
Neon (Ne)	0.2	1.35	41,400
	0.5	1.34	37,100
Argon (A)	0.2	0.71	27,700
	0.5	0.48	20,700

The data obtained by Druyvesteyn and Warmoltz are in agreement with data obtained in this laboratory by G. R. Fonda and A. H. Young[68] on the characteristics of positive column discharges in neon containing sodium vapor, as influenced by the vapor pressure of the latter. The observations were made on an a-c lamp such as that described in a more recent paper by the same authors[69] and by N. T. Gordon.[70] The diameter of the positive column was 6.3 cm and the arc current 4 amp. With a neon pressure of 1.5 mm the values obtained for T_e as a function of the pressure of sodium vapor, in millimeters of mercury, may be represented by the empirical equation

$$\log T_e = 3.486 - 0.193 \log p$$

which shows that T_e decreases with increase in pressure. It was also observed that T_e decreases with increase in current density. At a sodium vapor pressure of 0.002 mm, T_e, according to Fonda and Young, was found to be about 10,000 deg K, which is of the same order of magnitude as the values observed by Druyvesteyn and Warmoltz under similar conditions.

Before proceeding with the discussion of the relation between these observations and the luminous output and efficiency of a discharge in neon plus sodium, it is of interest to mention a set of data obtained by the last mentioned investigators on the values of X and T_e, under similar conditions of pressure and current, for the 3 rare gases, helium, neon, and argon. This data is given in Table X. The tube used in the measurements was 4.5 cm in diameter, and the pressure 0.5 mm.

63. *Zs. f. Phys.*, v. 48, 1928, p. 26.
64. R. Ladenburg, *Rev. of Modern Physics*, v. 5, 1933, p. 243.
65. *Rev. of Scientific Instruments*, v. 2, 1931, p. 437.
66. C. G. Found, *Phys. Rev.*, 1930.
67. *Can. Jl. Res.*, v. 2, 1930, p. 13; v. 4, 1931, p. 312; v. 7, 1932, p. 434.
68. Opt. Soc. of Am. *Jl.*, v. 24, 1934, p. 31.
69. *G.E. Rev.*, July 1934 v. 37, 1934, p. 331–7.
70. *G.E. Rev.*, July 1934, v. 37, 1934, p. 338–41.

Similar results on discharges in neon have been obtained by R. Seeliger and R. Hirchert.[71] Their measurements also indicate that T_e decreases with increase in current and pressure.

These results show, as has been mentioned already, that under similar conditions, X and T_e decrease with decrease in the ionization (or resonance) potential of the gas. The greater the energy required to form positive ions, the higher the voltage gradient and the higher the electron temperature.

Light Output in Positive Column Discharge

The electrons in a positive column discharge are distributed throughout the whole volume. Therefore, excitation and ionization must occur in all parts of the discharge, and the light production is thus uniformly distributed throughout the length of the column.

Since the probability of excitation increases with the kinetic energy of the electrons (at least for values of V about 0.5 to 1 volt above the excitation value), it follows that a decrease in T_e must be accompanied by a decrease in the fraction capable of causing excitation. Since T_e decreases with increase in pressure, the probability of excitation at a collision decreases, but the actual probability of a collision is increased because of increased pressure. The consequence of these 2 opposing factors is that the light output of a positive column discharge at constant current density increases with pressure for low values of the latter, attains a maximum value, and then decreases. The maximum in light output as a function of pressure at constant current density is usually quite broad.

Let us now consider the effect of current density at constant pressure. The measurements of Fonda and Young as well as those of Druyvesteyn and Warmoltz show that T_e decreases and n_e increases with increase in arc current. From the data in Table IX it is possible to make an approximate calculation of the relative intensities of D-line radiation which might be expected for 2 different current values. Thus for a pressure of 1.1 mm of neon and 0.0021 mm of sodium, the observed values of T_e show that the actual concentrations of electrons with kinetic energy in excess of 2.10 volts, that is

$$n = n_e e^{-\frac{2.10 \times 11{,}600}{T_e}}$$

are as follows

at 0.2 amp, $n = 1.145 \times 10^{-10}$
at 1.0 amp, $n = 2.765 \times 10^{-10}$

Thus while the ratio of arc currents is 5:1, the ratio of number of electrons capable of exciting sodium atoms is 2.4:1. Consequently, the total light output should increase 2.4 fold and since the gradient has decreased to $^1/_2$, the luminous efficiency should be practically the same. The last column in Table IX shows that the total energy radiated (E_R) which includes both visible and infra-red, was approximately constant. While this does not give any information about the percentage in the visible, it is probably justifiable to assume, in view of other results in the same paper on the distribution of E_R between visible and infra-red, that the fraction in the visible decreases with increase in arc current.

This inference is in agreement with the photometric measurements of Fonda and Young which show that the light output per ampere decreases with increase in arc current. Thus at a pressure of sodium corresponding to 200 deg C (with 1.5 mm neon present) the relative light output per ampere decreased from 74 to 42 for a change in arc current from 1 to 5 amp. At very low current densities, the relative lumen output per ampere increased considerably, so that at 0.075 amp and 265 deg C, an efficiency of 315 lumens per watt was obtained, which represents 66 per cent of L_0, the optimum luminous efficiency. A similar result has also been obtained by M. Pirani[72] with sodium vapor discharges in which heat was applied from an external source to evaporate the sodium.

The results obtained by the same investigators on the effect on light output and efficiency of varying the pressure of sodium are in agreement with the conclusion previously stated regarding the existence of a maximum in light output. In this case the maximum values in lumens and lumen per watt are obtained with the sodium at 200 deg C (vapor pressure about 0.0001 mm of mercury).

In the case of a hot cathode positive column neon lamp, it has been found in this laboratory that the light output L varies with current I according to a relation of the form quoted by W. F. Westendorp:[73]

$$L = L_1 I^{3/2}$$

where L_1 is a constant. This relation has been found valid over a large range of current.

These observations, that the light output in a positive column discharge increases less rapidly than the current when the pressure is maintained constant, have been interpreted in the previous paragraphs from the point of view of the effect of increased current on the values of T_e and n_e. It is also of interest in this connection to discuss briefly some of the results which have been obtained by R. Ladenburg and his associates on the variation with current of the concentration of metastable atoms in a neon positive column discharge. (A review of these investigations has been published by R. Ladenburg.[74] This paper gives references to the previous papers on this topic.)

In such a discharge the relative concentrations of metastable atoms in states s_5 and s_3 (see Fig. 5) may be determined by measuring the relative intensities of certain lines in the visible region. By combining such measurements with those on the absorption coefficients for the same lines it is possible to determine the actual concentrations of atoms in different excited states.

Results obtained by these methods for a discharge in a tube 0.8 cm diameter containing neon at a pressure of 1 mm are shown in Fig. 10. The curves give the concentrations of atoms in s_5 state and different p-levels as functions of the current, I. The ordinates, N, give the concentrations in terms of atoms per cubic centimeter.

For values of I less than 60 ma, the concentration

71. *Ann. d. Physik*, v. 11, 1931, p. 817.
72. *Zeits f. tech. Phys.*, v. 11, 1930, p. 482.
73. *Physica*, v. 3, 1932, p. 193.
74. *Rev. of Modern Physics*, v. 5, 1933, p. 243.

of atoms in s_5 state may be represented according to Kopfermann and Ladenburg by a relation of the form

$$N_s = \frac{\alpha I}{\beta I + 1} \tag{37}$$

where α and β are constants. This equation is derived on the basis of the following considerations:

The rate of production of atoms in the s-level is proportional to the current, so that this can be expressed as aI. The rate at which atoms in s-levels are destroyed by excitation and absorption of radiation is given by $bN_s \cdot I$. Finally the rate at which atoms in s-levels are destroyed by collisions with the wall and other causes is given by $c \cdot N_s$, where a, b, and c are constant. Hence at equilibrium

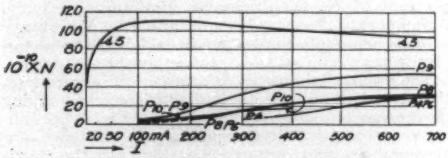


Fig. 10. Concentrations of neon atoms in different excited states, as functions of current

$$N_s = \frac{aI}{bI + c} = \frac{\alpha I}{\beta I + 1}$$

where $\alpha = a/c$ and $\beta = b/c$.

At values of I greater than 60 ma, higher powers of the current have to be taken into account, because of cross interactions between atoms already excited by electron impact. Therefore in the steady state the population of a definite level characterized by the index j can be approximately represented by

$$N_j = \frac{\alpha I + \beta I^2}{\gamma I + \delta I^3} + 1 \tag{38}$$

where α, β, γ, and δ are constants which are determined empirically from the actually observed curve. This last equation applies to the atoms in any excited level and indicates that N_j passes through a maximum at some value of I. Hence the light emitted owing to transitions from these levels must also pass through a maximum with increase in current.

A very important conclusion which is deduced by Ladenburg from curves such as those in Fig. 10 is this: For large currents in the plasma, the ratio of the populations of 2 atomic levels designated by k and j corresponds to a statistical equilibrium at the electron temperature. That is,

$$\frac{N_k}{N_j} = \frac{g_k}{g_j} \epsilon^{-(V_k - V_j)\epsilon/kT_e} \tag{39}$$

where V_k and V_j are the excitation potentials of the 2 states, and g_k and g_j are statistical weights, the values of which for different levels in neon are shown in the right-hand column of Fig. 5. For example, from the values of N for the different p-levels at about 300 ma, the value of T_e calculated by means of the above equation is 20,200 deg K, whereas from actual observations of T_e such as those given in Table X, a value of about 22,000 deg K is deduced for the particular conditions in Ladenburg's experiments. Thus a determination of T_e enables the calculation at least approximately of the relative concentrations of atoms in the different excited states, and hence it is evident that the light output and luminous efficiency are controlled to a great extent by the electron temperature and the conditions, which, in turn, govern the magnitude of this characteristic.

Energy Balance in Positive Column

In their very comprehensive paper on the "Theory of the Arc Plasma,"[75] L. Tonks and I. Langmuir point out that, "The variable quantities involved in the positive column of an arc may be divided into 2 classes, the independent and dependent. Among the former belong the gas used, the tube radius a, the pressure p_g, and the wall temperature, which, in case the atomic mean free path is comparable with a, may be used for the gas temperature T_g. One of the arc variables proper must also be included in this category—experimentally it is usually the total arc current i_A. The dependent variables are, therefore, the axial electric field X, the electron density in the axis n_e, the electron temperature T_e, the positive ion current density at the wall I_p, and the number of ions generated per second per electron β. These variables are 5 in number and 5 equations will be required for their complete determination."

Of these 5 equations, the most important from the point of view of light production is that designated by Tonks and Langmuir as the energy balance equation which expresses the manner in which the power input Xi_A per unit length is distributed between the various individual processes which take place in the positive column discharge.

From the considerations presented in the previous sections, it follows that the energy is utilized as follows (see also discussion by C. G. Found[76]):

(a) *Elastic Collisions, Between Electrons and Gas Atoms.* As has been stated in Part I, the fraction of the energy lost by an electron at each collision of this type is $2m/M$, which has the value 2.72×10^{-4}, for helium, and is considerably less than this for all other gases. It is therefore evident that the total energy lost in this manner, known as the volume energy must be negligibly small, except at pressures greater than about one centimeter of mercury.

(b) *Production of Positive Ions.* At low pressures where recombination between ions and electrons in the plasma itself is extremely improbable, the rate of generation of ions per unit length of discharge column must be equal to the rate at which ions flow to the walls, per unit length of tube, and are neutralized there by an equal current flow of electrons. As has been stated in a previous section, in any discharge the walls become negatively charged with respect to the plasma, and there exists, therefore, a drop, V_w, in the wall sheath. The positive ion current flowing to the wall per unit length, which is equal to the electron current per unit length, is given by

$$I_w = I_p \cdot 2\pi a$$

and the energy transmitted to the wall by the ions in virtue of the energy required in passing through the sheath is $I_w \cdot V_w$. While the average energy of the electrons in the plasma is $(3/2)kT_e$, the energy carried to the walls by electrons is $2kT_e$ per electron, so that the total

75. *Phys. Rev.*, v. 34, 1930, p. 876. In order to avoid confusion with symbols used in the present paper, the writer has used different symbols for some of the variables from those used by Tonks and Langmuir.
76. C. G. Found, *G.E. Rev.*, v. 37, 1934, p. 269–77.

energy given up at the surface of tube because of kinetic energy of electrons is $I_w \cdot 2kT_e/e = I_w\ (2T_e/11{,}600)$ watts per unit length. Also the energy evolved by recombination at the walls is $I_w \cdot V_i$. Hence the total energy delivered to the walls (per unit length) because of flow of electrons and ions is

$$E_w = I_w(V_i + V_s + 2T_e/11{,}000) \tag{40}$$

(*c*) *Production of Excited Atoms.* The energy thus utilized is restored in the form of radiation. Part of this radiation appears as visible light L and if $\overline{V}_\lambda$ designates the average visibility coefficient of the light emitted, the energy converted into light is

$$W_L = \frac{L}{621\,\overline{V}_\lambda} \tag{41}$$

where W_L and L both refer to unit length of tube.

On the other hand, a considerable part of the radiation will be in the infra-red and ultra-violet regions. Some of this energy is transmitted through the walls, while the rest is absorbed and assists in raising the temperature. Let W_I designate the energy transmitted (both ultra-violet and infra-red) and W_A, the energy absorbed by the walls. Then the total energy resulting from the production of excited atoms is

$$R = W_L + W_I + W_A$$

On the basis of these considerations we obtain the energy balance equation in the form

$$Xi_A = R + E_w \tag{42}$$

while the light efficiency is given by

$$L_e = \frac{621\ V_\lambda \cdot W_L}{Xi_A} \tag{43}$$

Energy balance measurements have been made by a number of investigators, but in no case, as far as the writer is aware, have data been published in which all the terms in the last 2 equations are given for the same discharge. The first investigation in which the equations developed by Tonks and Langmuir were tested experimentally was that of T. J. Killian.[77] Some of his observations have been discussed in a previous section. He found that as the value of T_e decreased from 38,000 deg K to 19,900 deg K by increasing the pressure of mercury vapor the energy delivered to the walls by recombination, i. e., E_w, decreased from 48 per cent to 14 per cent of the total input. Consequently the rest of the energy must have gone into excitation (R).

F. L. Mohler has reported results obtained on a positive column discharge in caesium vapor.[78] He found that the first doublet of the principal series at 8,521 and 8,944 deg A (which correspond to the 2 D-lines of sodium) contributes most of the radiation. The vapor pressure ranged from 0.001 to 0.3 mm. The tube used had a diameter of 1.8 cm. With currents of 0.2 amp, practically all the power was radiated. With currents of 1 amp or less and pressures less than 0.03 mm the power input was nearly all accounted for in terms of R and E_w, with the latter gradually increasing in relative amount until at 4 amp, E_w was about twice R. At higher pressures there was an excess of power input which could not be accounted for but was probably due to volume losses and unmeasured for infra-red radiation. "It is reassuring," he states, "to find that over a considerable range the power loss is predominantly radiation of the resonance lines and recombination on the walls. It suggests that an approximate theory can be developed which considers production of ions and of the first excited state exclusively and that other phenomena can be treated independently."

His observations, as Mohler points out, are in agreement with those on the sodium positive column lamp. In the latter, under normal operating conditions the energy radiated in D-lines is about 20 per cent of the power input in the positive column, but if external heating is used, a radiation efficiency as high as 70 per cent may be obtained at low current densities as shown by Pirani and by Fonda and Young.

A most comprehensive investigation from this point of view has been carried out by Druyvesteyn and Warmoltz on positive column discharges in mixtures of sodium vapor with neon. In a previous section, some of their observations have been discussed already. In Table IX, the last 2 columns give their results on the percentages of the total power input utilized in radiation R and wall energy E_w. It will be observed that the total adds up to over 100 per cent in some cases and less than 100 per cent in others. One conclusion however, is evident—that about 90 per cent of the total energy input was utilized in these experiments in excitation of atoms, and the other 10 per cent in recombination at the walls.

As is seen by an inspection of the energy level diagram for sodium (Fig. 3) the radiation emitted by this vapor consists mainly of the D-lines 5,890 and 5,896, and the 3 infra-red lines λ8,200, λ11,400, and λ22,000. The other lines in the visible part of the spectrum emit altogether only about 2 per cent of the total light. Druyvesteyn and Warmoltz do not give data on the manner in which the energy radiated is distributed among the different infra-red lines and the D-lines; but in some other cases they found that the infra-red radiation increases from 12 or 14 per cent at the lowest current densities to 50 per cent at the highest current densities. At high current densities the concentration of excited sodium atoms in the $3P$ state is so large that excitation to still higher levels becomes extremely probable.

At higher pressures of neon and especially at higher current densities, Druyvesteyn and Warmoltz observed a residual input energy in excess of $R + E_w$ which they found to be of the same order of magnitude as that calculated for loss by elastic collision; but in pure sodium even at higher current densities and in sodium plus neon at a low pressure of the rare gas, the measurements show that eq 42 gives a fairly satisfactory interpretation of the processes occurring in such discharges.

In this connection it is of interest to calculate the relative concentrations of excited atoms in the $3P$ state in a lamp such as the 10,000-lumen a-c lamp described recently by Fonda and Young. Since the temperature of the bulb is about 220 deg C, the pressure of sodium is about 0.0001 mm, and the concentration of sodium atoms, n_{Na}, is 10^{13} per cubic centimeter. In a previous section it was mentioned that according to Ladenburg's measurements, the con-

77. *Phys. Rev.*, v. 35, 1930, p. 1238.
78. Bureau of Standards *Jl.*, v. 9, 1932, p. 25.

centrations of atoms in the different states may be calculated by means of the Boltzmann distribution law if the value of the temperature used is that corresponding to T_e. According to measurements by G. R. Fonda, the value of T_e in the positive column part of the a-c sodium plus neon lamp is about 8,000 deg K (equivalent to 0.7 volts). Hence the concentration of atoms in the $3P$ state, n_a, is given in terms of n_{Na} by the relation

$$\frac{n_a}{n_{Na}} = 3 \cdot e^{-\frac{2.10}{0.7}} = 0.15$$

and

$$n_a = 1.5 \times 10^{13}/\text{cm}^3$$

This seems to be a reasonable value in view of the measurements on absorption of resonance radiation and on light efficiency.

(While this paper was being proof read, there appeared a paper by O. Gross,[79] which gives probe measurements on a positive column discharge in argon. The results obtained are in general agreement with the formulas obtained by Langmuir and Tonks and also give energy balance measurements which are in agreement with those obtained by other investigators.)

Concluding Remarks

Ultimately, of course, it should be possible to correlate measurements on the variable in a discharge which Tonks and Langmuir have designated as "dependent," with the concentrations of atoms in different levels, and with the luminous efficiency. In the previous sections, an attempt has been made to give to the reader some idea of the present state of our knowledge in this field. While considerable progress has been made, and there has thus been gained a deeper insight into the fundamental processes which occur in a gas discharge and govern the light production, the actually assured conclusions apply only in the field of low pressure discharges. Thus attempts have been made to extend the probe method to arcs at pressures of a few centimeters of mercury and even to arcs at atmospheric pressure. But no theoretical physicist is certain as yet just how far the conclusions derived by such measurements are valid when applied to such pressures in which new phenomena occur, such as thermal excitation and ionization and recombination of ions and electrons in the plasma itself. Our empirical knowledge in the field of higher pressure discharges is quite extensive and recently there has been a considerable development in the application of a mercury discharge of this nature as a source of light. However, in order to interpret adequately the phenomena in such a discharge it will be necessary to develop new methods by which an understanding can be obtained of the fundamental processes in these cases which compares with that already acquired about low pressure discharges.

In conclusion, the writer wishes to express his indebtedness to C. G. Found for the helpful discussions of the contents of this paper.

79. *Zeit. f. Phys.*, v. 88, 1934, p. 741.

Transient Voltages in Welding Generators

In this paper is given a mathematical analysis of the armature terminal voltage of a d-c welding generator at interruption of the short circuit current, with and without neutralizing transformer. Also, consideration is given to the voltage transients across the field circuit winding of the neutralizing transformer caused by the make and break of the armature circuit. Comparisons are shown between oscillograms and calculations for these transient voltages.

By
A. R. MILLER
ASSOCIATE A.I.E.E.

Lehigh University,
Bethlehem, Pa.

IN A PREVIOUS paper[1] on this topic the calculation of currents in the armature and field circuits was given consideration and some cases were discussed in which a transformer provided interconnection between the field and armature windings. Since the current of a welding generator is large in magnitude, and at the make and break of the armature circuit has a very high time rate of change, the question of the magnitude of the voltages existing under operating conditions naturally arose, for there is little to guide the engineer in estimating their relative magnitudes. The present paper gives this matter consideration, deriving formulas for the terminal voltage when the short circuit is broken, and for voltages induced in various parts of the armature and field circuits. Machines with and without transformer interconnection between the 2 machine circuits are discussed. Oscillograms and calculated graphs are shown in comparison, verifying the formula developed.

Assumptions Used in Making Calculations

When applying electrical circuit theory to arc welding machines, certain simplifying assumptions can usually be made. These are as follows:

1. The excitation of the field is from a constant voltage source. While there are exceptions to this, it is almost general. The machines for which the oscillograms are shown and for which the calculations were made had constant excitation from a battery, with a view toward simplifying the calculations.

Full text of a paper recommended for publication by the A.I.E.E. committee on electric welding, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Oct. 14, 1933; released for publication April 27, 1934. *Not published in pamphlet form.*

2. The magnetic circuit of the machine has small eddy current effects, and magnetic saturation does not exist. For present arc welding generators these assumptions are quite legitimate, since the magnetic circuits are usually laminated, and the voltages under operation are but a fraction of the maximum possible voltage.

3. The series and shunt fields are connected differentially, magnetically, to each other.

4. The rotational speed of the machine is constant under all loads.

A diagrammatic sketch of a d-c generator with a transformer connection between armature and field circuits is shown in Fig. 1.

Assumptions Regarding Currents Under Transient Conditions

The current does not decrease to zero suddenly during the interruption of the armature current, due to the arcing taking place as the electrodes are separated. No rigid equation is possible which would cover all possible cases, but the current may be assumed to decrease exponentially from the initial value to zero, as given by the equation $I\epsilon^{-\alpha t}$. By reference to Fig. 2, the actual current $I\epsilon^{-\alpha t}$ can be obtained mathematically by assuming a current

$$i = -I\,(1-\epsilon^{-\alpha t}) \tag{1}$$

is applied to the machine during the interruption, if the initial current is I. Adding this to I gives $I\epsilon^{-\alpha t}$, the actual current variation. In a large number of instances the current follows approximately a straight line variation from the initial value to zero. In this case the current may be assumed to be made up of the component parts shown in Fig. 3.

Thus, at t_0 the current $-kt$ is applied, followed at t_1 (the instant the current becomes zero) by an application of the negative of the first current. Adding these to that previously existing gives the actual current, as is illustrated by Fig. 3.

When the short circuit is broken it is assumed that the terminal voltage is due to the application of currents, shown in Fig. 2 or Fig. 3, to the impedance of the machine viewed from the point at which the interruption takes place. The voltage across an element of the machine is of course the product of these assumed currents and the impedance of that part of the circuit.

Upon the establishment of a short circuit condition the form of current variation can be calculated, as

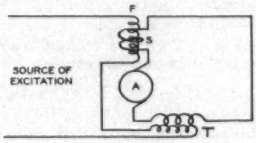


Fig. 1. Wiring diagram

S, series field; F, shunt field; A, armature; T, transformer

was done in the previous paper, since all constants and conditions can be assumed with sufficient accuracy.

In all the analysis which follows the operational method of solution is used with the intention of reducing the formula and procedure to a minimum. No apology need be made for this since many excellent treatises now exist which treat this process.[3]

Voltage Across Terminals of Generator When Circuit Is Broken

The voltage across the terminals of a d-c generator, when the short circuit is suddenly opened, is

$$e_1 = -iZ_1(p) \tag{2}$$

where i is the current (in operational form) which reduces the final condition to that actually existing,

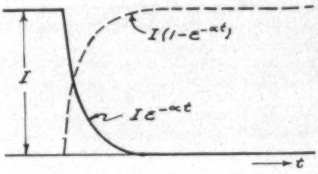


Fig. 2. Decrease of armature current during interruption

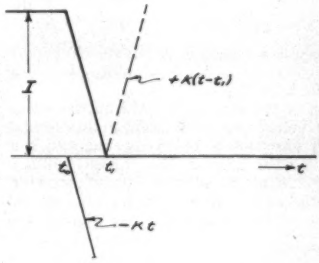


Fig. 3. Components of armature current during interruption. Actual current shown by heavy line

as explained above. $Z_1(p)$ is the impedance of the machine as viewed from the terminals. Thus

$$i = -I\,\frac{\alpha}{p+\alpha} \tag{3}$$

if an exponential decay of current is assumed and

$$i = -\frac{k}{p} \tag{4a}$$

from $t = 0$, to which is added the result of applying

$$i = \frac{k}{p} \tag{4b}$$

at $t = t_1$ (see Fig. 3).

The impedance of the armature circuit viewed from the terminals is obtained from eq 3, Appendix A, of the previous paper[1] and is

$$Z_1(p) = \frac{(R_1 + K_{11} + L_1p)(R_2 + L_2p) - (K_{12} + Mp)(Mp)}{(R_2 + L_2p)} \tag{5}$$

The terminal voltage under these conditions is, therefore,

$$e_1 = \frac{I\alpha[(R_1 + K_{11} + L_1p)(R_2 + L_2p) - (K_{12} + Mp)(Mp)]}{(p+\alpha)(R_2 + L_2p)} \tag{6}$$

Equation 6 contains p to the same power in numerator and denominator; hence, there is an initial voltage at the moment the current interruption begins.

Assuming that the net mutual inductance between the armature and field circuit is reduced to zero by means of an external transformer coupling between them, this voltage becomes

$$e_i = \frac{I\alpha(R_1 + K_{11} + L_1 p)}{(p + \alpha)} \quad (M = 0) \tag{7}$$

The initial value of the voltage is obtained by making $p = \infty$ and neglecting R_1 and K_{11} which gives

$$e_i \text{ (initially)} = I\alpha L_1 \tag{8}$$

as would be expected in a circuit which contains resistance and self-inductance only.

Letting $p = 0$, the terminal voltage after the transient condition has passed over, gives for the terminal voltage $I(R_1 + K_{11})$. Since $(R_1 + K_{11})$ is the ratio of open circuit voltage of the generator to the short circuit current, the final voltage is the open circuit voltage prior to short circuit, as it should be. For any condition in general it is

$$e_t = I\alpha \frac{\left[\frac{L_1L_2 - M^2}{L_2} + L_1R_2 + R_1L_2 + K_{11}L_2 - K_{12}M - \left(\frac{L_1L_2 - M^2}{L_2}\right)(R_2 + \alpha L_2)p + (R_1R_2 + K_{11}R_2) - R_2\left(\frac{L_1L_2 - M^2}{L_2}\right)\right]}{L_2p^2 + (R_2 + \alpha L_2)p + \alpha R_2} \tag{9}$$

The first term of the series gives the initial value of the terminal voltage as an impulse; the second term the voltage variation to normal value, which is dependent only on the form of the applied voltage and the field circuit, as far as time factors are concerned. Thus one exponential term for the second or variable part of the voltage is $Ae^{-\alpha t}$ and the other is $Be^{-\beta t}$ where $\beta = \frac{R_2}{L_2}$.

These results are in conformity with those obtained experimentally. During the period over which the arc is being interrupted the voltage is undergoing erratic and rapid changes, as influenced by the characteristics of the arc and the form of the current to be interrupted, which is dominated by the exponential factor α in the solution. After the arc current has decreased to zero (and the term containing α is at zero value) the exponential term R_2/L_2, which is the exponential factor a transient current in the field circuit unaffected by the armature circuit would have, governs the return of the voltage to normal value. That is, after the current in the armature circuit has been interrupted, the terminal voltage returns to normal open circuit voltage at a rate proportional to the unaffected time variation of the field circuit current.

Perhaps a still better assumption as regards current variation is that made by eq 4a. This seems to be the more prevalent form, from the results obtained in many oscillograms. Substituting eq 4a in eq 2 gives a voltage from $t = 0$ to $t = t_1$, where t_1 is the instant the current is interrupted, as

$$e = \frac{k(R_1 + K_{11} + L_1p)(R_2 + L_2p) - (K_{12} + Mp)(Mp)}{p(R_2 + L_2p)} \quad 0 < t < t_1 \tag{10}$$

Substituting numerical values which pertain to the oscillogram shown in Fig. 4 the solution is

$$e = 637.5(12.65t + 1.077e^{-8.8t} - 1) \quad 0 < t < t_1 \tag{11}$$

At t_1, the voltage is that given above plus the voltage due to the application of $e = kt$, which is the negative of the voltage applied at $t = 0$. That is,

$$e = \text{eq (11)} + 637.5[12.65(t - t_1) + 1.075e^{-8.8(t-t_1)} - 1] \tag{12}$$

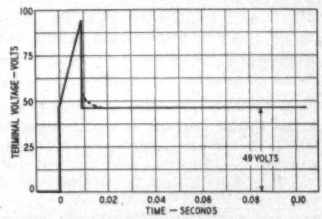
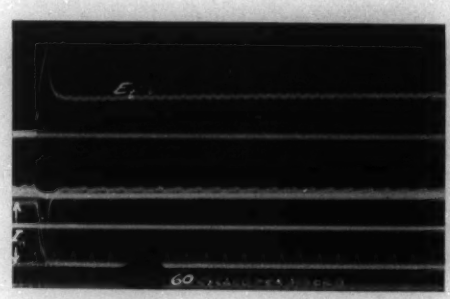


Fig. 5. Oscillogram (below) and calculated graph of armature terminal voltage when short circuit is broken; low mutual inductance

E_t, terminal voltage; I_a, armature current



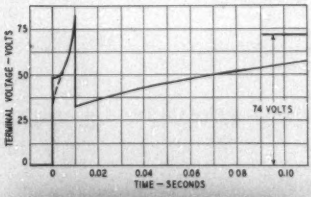


Fig. 4. Oscillogram (below) and calculated graph of armature terminal voltage when short circuit is broken; no transformer

E_t, terminal voltage; I_a, armature current; I_f, field current

for all instances of time after $t = 0$. A plot of eq 12 is shown in Fig. 4, which in general verifies the oscillogram.

In case the mutual impedance between the armature and field circuits is reduced to zero,

$$Z_1(p) = k(R_{11} + K_{11} + L_1p) \tag{13}$$

and the terminal voltage is

$$e = \frac{k(R_{11} + K_{11} + L_1p)}{p} \quad 0 < t < t_1 \tag{14}$$

The solution of this equation is

$$e = k[(R_{11} + K_{11})t + L_1] \qquad 0 < t < t_1 \tag{15}$$

to which must be added, after $t = t_1$, the following voltage,

$$e = k[(R_{11} + K_{11})t - t_1 + L_1] \qquad t > t_1 \tag{16}$$

As it was impossible to reduce the mutual impedance to zero with the apparatus available no experimental verification of this was possible, but in Fig. 5 is an oscillogram taken under conditions closely approximating those of negligible mutual impedance; also there is given a mathematical plot of the solution of the terminal voltage for this particular case, which shows good similarity.

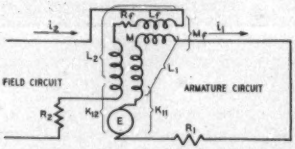


Fig. 6. Equivalent circuit of a d-c generator with separately excited field

The above solutions show that the generator having negligible mutual inductance between armature and field has a tendency toward a greater terminal voltage when the armature circuit is interrupted, but these voltages under the more ideal conditions will not reach excessive values. Arc welding generators are not, except under very unusual conditions, required to operate under such short time intervals of interruption as shown above. In these tests the circuit was broken by large, rather high speed circuit breakers.

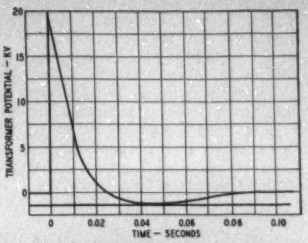
Voltage Across Transformer Terminals on Short Circuit of Machine

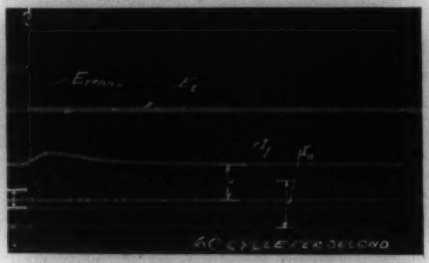
Only the voltage across the transformer winding connected in the field circuit will be given consideration, as the principle involved in the calculation for either winding is the same. The voltage is, for the direction of currents assumed as in Fig. 6, $M_fpi_1 - (R_f + L_fp)i_2$, M_f and L_f being the mutual and self-inductance, respectively, of the transformer winding in the field circuit and R_f its resistance; i_1 is the armature current and i_2 is the transient component of the field current. The values of i_1 and i_2 are given in operational form by eqs 3 and 4, Appendix A, of the previous paper.[1]

Thus, for the transformer secondary winding,

$$e = \frac{EM_fp(R_2 + L_2p) - Mp(R_f + L_fp)}{(R_1 + K_{11} + L_1p)(R_2 + L_2p) - (K_{12} + Mp)(Mp)} \tag{17}$$

Fig. 7. Oscillogram (below) and calculated graph of voltage of field circuit winding of transformer when machine is short-circuited





E_T, transformer terminal voltage; I_f, field current; E_t, armature terminal voltage; I_a, armature current

In this equation M is the net mutual inductance between the armature and field circuits and R_2 is the total field circuit resistance. The numerator is of the same power as the denominator, and there is an initial value of voltage on the application of a short circuit.

The above equation does not contain the voltage due to the resistance drop in the field produced by the normal value of field current for that part of the circuit, for i_2 is the transient component of the field current only. Hence, the voltage recorded on the oscillogram is the sum of that given by eq 17 and the resistance drop in the transformer coil due to the current prior to short circuit.

If $M = 0$, the initial voltage is

$$e_{\text{(initial)}} = \frac{EM_f}{L_1} \tag{18}$$

when the short circuit is established, and in general

$$e = \frac{EM_fp}{R_{11} + K_{11} + L_1p} \tag{19}$$

The solution of this operational equation becomes

$$e = \frac{EM_f}{L_1}\epsilon^{-\gamma t} \tag{20}$$

where

$$\gamma = \frac{R_{11} + K_{11}}{L_1}$$

For the case of a machine in which $M_f = 0.2$ henry and $L_1 = 0.006$ henry (which might be possible values)

$$e = E \times 33.3\epsilon^{-110.7t} \tag{21}$$

E ranges in value from 70 to 90 volts, hence the initial voltage may be as high as 3,000. To this would be added the voltage drop due to the field current.

An oscillogram of the transformer voltage (in the field circuit) for a particular machine is shown in Fig. 7; also a solution of eq 17, which applies in this case, is shown there, experimentally verifying the mathematical solution. Under the conditions of this test,

$$e = E\,(52.75\,\epsilon^{-83.8t} - 12.23\,\epsilon^{-19.9t})$$

The circuit constants are: $M = 0.2$ henry, $M_f = 0.1$ henry, $R_f = 143.5$ ohms, $R_2 = 545$ ohms, $L_2 = 45$ henrys, $L_1 = 0.006$ henry, and $E = 50$ volts.

When the mutual impedance between the armature and field circuits is reduced to zero, the induced voltage in the transformer winding is counterbalanced by a similar induced voltage in the field winding, which must be taken care of in the design of the machine.

Voltage Across Transformer Terminals When Short Circuit Is Broken

The voltage at the terminals of the transformer winding in the field circuit (which in magnitude is the same as that at the terminals of the field winding of the generator, except for the resistance drop) is

$$e_s = M_f p i_1 - (R + Lp) i_2 \tag{22}$$

where R and L are the resistance and inductance, respectively, of the transformer winding inserted in the field circuit. By eq 2 of the previous paper,[1]

$$i_2 = \frac{M_p}{R_2 + L_2 p}\, i_1 \tag{23}$$

Therefore

$$e_s = \left[M_f p - \frac{(R + Lp)}{(R_2 + L_2 p)}\, M p \right] i_1 \tag{24}$$

If $M = 0$,

$$e_s = M_f p i_1 \tag{25}$$

This value is the lowest possible value that may exist. In this case $i_2 = 0$ and the self inductance and resistance of the field circuit play no part. Thus, if the current in the armature is assumed to be given by eqs 4a and 4b, the transformer voltage for the field circuit is

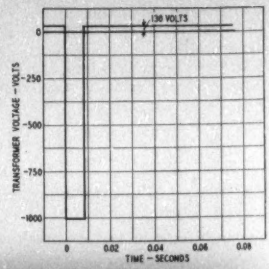
$$e_s = -M_f k \qquad (M = 0) \tag{26}$$

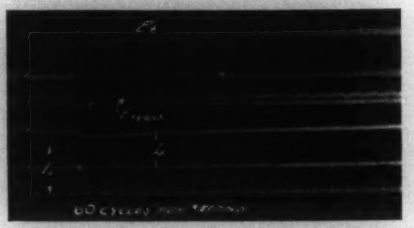
from $t = t_0$ to $t = t_1$. This agrees quite well with the oscillogram shown in Fig. 7 which was taken under the assumed condition.

Should it happen that for a condition other than $M = 0$ the resistance and inductance of the transformer field winding and the machine field winding are similar, by eq 24, the same voltage-time relationship would hold, except for relative magnitude. Since this is approximately so, the voltage across the transformer winding assumes a more or less constant value during the transient state for all conditions under which the oscillograms were taken.

Fig. 8. Oscillogram (below) and calculated graph of voltage of field circuit winding of transformer when short-circuit current is broken

E_T, transformer terminal voltage; I_f, field current; E_t, armature terminal voltage; I_a, armature current





Conclusions

The terminal voltages upon the interruption of the armature current in arc welding generators are not excessive under operating conditions, but are likely to be higher in machines which use transformer coupling between armature and field winding for the purpose of eliminating overshooting of the current upon sudden changes in circuit conditions. The transient value of this voltage is not likely to exceed more than twice the normal open-circuit terminal voltage of the machine. The latter type of machine has an instantaneous recovery of normal open-circuit voltage upon the interruption of the armature current, as may be seen in Fig. 8, which is an advantage from the welder's point of view.

Although in the older types of d-c generators, built without neutralizing transformers, the terminal voltage of the field was of normal value under transient conditions, the neutralized arc welding generator may have terminal voltages of a few thousand across the transformer winding in the field circuit, and likewise across the field winding coils of the generator itself. If care is used in designing the machine the voltage is not of such a value that the proper insulation cannot be provided.

List of Symbols

R_1 = resistance of armature circuit
R_2 = resistance of field circuit
L_1 = self-inductance of armature circuit, including the armature winding, series field, and any reactor or other device which may be in that circuit
L_2 = total self-inductance of the field circuit
M = mutual inductance between the armature and field circuit. Saturation is assumed negligible
K_{12} = rotation voltage constant between shunt field current and

voltage induced by the rotation of the armature in the magnetic field produced by the field current

K_{11} = rotational voltage constant for the series field current

E = open circuit (or induced voltage) produced by the field current prior to a transient condition in the armature

p = d/dt

t = time in seconds

L_f = self inductance of transformer winding in the field circuit

M_f = mutual inductance of transformer winding in the field circuit

R_f = resistance of transformer field circuit winding

α = exponential factor for arc current

β = R_3/L_3

ϵ = base of natural logarithms

$\dot{k}$ = rate of change of armature current

γ = $\dfrac{R_{11} + K_{11}}{L_1}$

i_1 = armature current

i_2 = field current (transient component)

e_t = transformer terminal voltage (winding in field circuit)

References

1. Transients in Arc Welding Generators, A. R. Miller. A.I.E.E. Trans., v. 52, 1933, 260–67.
2. Heaviside's Operational Calculus, Berg. McGraw-Hill Book Company.

Overvoltages on Transmission Lines

Observations of line-to-ground voltages have been made under routine operating conditions on an isolated neutral system, a Petersen coil system, 3 neutral resistance grounded systems, and 2 directly grounded systems. Results of these observations are given in this paper. Measurements were made with oscillographs supplemented, on all but 2 systems, by surge recorders.

C. L. GILKESON
MEMBER A.I.E.E.
Edison Elec. Inst., New York, N. Y.

P. A. JEANNE
MEMBER A.I.E.E.
Bell Tel. Labs., Inc., New York, N. Y.

It has long been recognized that, under certain conditions involving faults to ground, dynamic voltages larger than the normal line-to-line voltage may exist on the unfaulted phases of a system operated with neutral isolated or grounded through substantial values of impedance. Dynamic overvoltage is dependent among other things upon the impedance through which the neutral is grounded. The term dynamic overvoltage, as used herein, includes transient voltages due to an arc at the fault, but does not include high frequency surge voltages due to lightning or switching. Both theoretical and experimental investigations indicate that the magnitude of lightning and switching surges is not dependent upon the method of grounding the system neutral and these types of surges are not considered in this paper. Although conditions other than the type of system grounding may affect the dynamic overvoltage under fault conditions, they are not likely to cause an effect as large as that mentioned above.

A knowledge of the probable magnitudes of dynamic overvoltages is of importance not only in relation to the general insulation level of a system but also in connection with the selection of protective gaps and lightning arresters. Several theoretical methods of estimating the maximum value of dynamic overvoltage on systems isolated or grounded through substantial values of neutral impedance have been published. These are based upon certain assumptions regarding the characteristics of arcs to ground and lead to various estimates of maximum voltage, ranging from 3.5 to 19 times normal.[1–5] Voltages up to 3.5 times normal, as measured in staged tests, have been reported in 2 recent Institute papers.[6,10] There is, however, little published material relating to the measurement of these voltages during operating conditions. This paper gives the results of an experimental study of this matter by one of the project committees of the Joint Subcommittee on Development and Research of the Edison Electric Institute and the Bell Telephone System, in coöperation with 4 power companies. The paper does not provide data regarding overvoltages which may be experienced on cable systems, as the observations were conducted on overhead transmission lines except for one system, in which approximately 20 per cent of the system mileage was cable.

Method of Measuring Overvoltage

In these investigations overvoltages on operating systems have been measured by automatic oscillographs connected through wye-wye connected potential transformers to record the line-to-ground voltages, supplemented in several cases by surge-voltage recorders.

The oscillographs utilized in this investigation are an improved form of the continuous film oscillograph described in an Institute paper in 1929.[7] Features making them particularly well suited for this type of investigation are as follows:

1. The speed of operation is such that, after the tripping value is reached, only about the first cycle of a disturbance is unrecorded.
2. The frequency response characteristic of the string type gal-

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted April 11, 1934; released for publication July 12, 1934. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

vanometers (utilized in all but 2 of the instruments) is practically uniform up to about 3,000 cycles. This is especially advantageous in recording transient disturbances within this frequency range or voltages of irregular wave-shape.

3. The date and time of each oscillogram are recorded by photographing on the film at the end of the oscillogram, a calendar clock, thus providing a means for correlating a particular oscillogram with records from other instruments on the system and with operating records.

To supplement the records from the magnetic oscillograph and provide information on the existence of high frequency surges associated with dynamic overvoltage, or voltage disturbances that might occur before the oscillograph could come into operation, surge voltage recorders were installed on 4 of the systems under study. The instruments were coupled to the line through capacitance potential dividers, and so connected as to minimize the effect of leakage across the insulators.

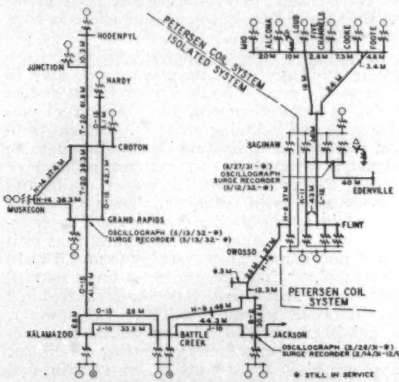


Fig. 1. 140-kv isolated neutral and Petersen coil systems of the Consumers Power Company

Surge voltage recorders utilize Lichtenberg figures[8] as a means of determining the type and magnitude of a surge voltage. The instruments used in this investigation are similar to those which have been extensively used in lightning investigations on power lines, except for certain modifications, such as the use of moving picture film which is automatically stepped forward after each record, and means for photographing a clock thus giving the time and date of each record.

Extent of Available Data

The extent of the data included in this paper and relevant information regarding the systems from which they were obtained are given in Table I. It will be seen from this table that observations were made on 6 systems having a combined mileage of over 2,500 circuit miles, and operating with neutral isolated, grounded through resistance or Petersen coils, or solidly grounded. The records cover periods of observation ranging from 9 months to $2^1/_2$ years.

A sketch of the 60-cycle 140-kv lines of the Consumers Power Company is given in Fig. 1. The Petersen coil system is metallically isolated from the rest of the system, which is operated with neutral isolated. This figure also shows the lengths of the various circuits, the points at which oscillograph and surge recorder observations were made and the period of observation at each point.

The south and west zone 33-kv systems of the Public Service Company of Northern Illinois are shown on Fig. 2, together with the locations of recording instruments and the points of neutral grounding. During part of the period of observation the west zone system was grounded at 2 points through 50-ohm resistors, and solidly grounded at 2 fairly remote points. The relaying was such that for many of the faults the solidly grounded section

Table I—Data Relating to Systems Under Observation

System	Voltage Kv	Type of Neutral Grounding	Length of System Circuit Miles	Period of Observation** Months	Period of Observation** Lightning Seasons	Period of Observation** No. of Records Included in Analysis
Consumers Power Co.	140	Isolated	573–800	29	2.8	350 oscillograms
				25	2.4	157 surge records
Consumers Power Co.	140	Petersen Coil	226–274	25	2.1	166 oscillograms
				20	1.9	38 surge records
Public Service Elec. and Gas Co.	26	75 ohms resistance at 1 point	126 open wire, 32 cable	29	2.3	101 oscillograms No surge recorder installed
Public Service Co. of Northern Illinois, South Zone system	33	50 ohms resistance at 3 points	570 open wire	29	2.5	290 oscillograms
				29	2.5	20 surge records
Public Service Co. of Northern Illinois, West Zone system	33	50 ohms at 2 points, solidly grounded at 2 other points	240 open wire	5.5	0	No oscillograph records above 1.2 times normal
				13	1.4	44 surge records
Public Service Co. of Northern Illinois, West Zone system	33	Solidly grounded at 4 points	240 open wire	10	1	No oscillograph records above 1.2 times normal
				10	1	10 surge records
Illinois interconnected system*	33	Solidly grounded at 2 points	800 open wire	9	1	75 oscillograms No surge recorder installed

Central Illinois Light Co., Central Illinois Public Service Co., and Superpower Co. of Illinois.
Where 2 periods are listed the first applies to oscillograph and the second to surge recorder observations.

was separated from that part of the system to which the recording instruments were connected. However, there has been no indication from oscillograms of an increase of voltage on this system when the solidly grounded section has been disconnected. About the first of February 1933, the resistance grounds were replaced by solid grounds and since that time this system has been operated with solid grounds at all 4 points.

Oscillographic observations only were made on the other 2 systems. On the 33-kv solidly grounded interconnected system in the vicinity of Springfield, Illinois (the power companies concerned are the Central Illinois Light Company, Central Illinois Public Service Company, and the Superpower Company of Illinois), oscillographs were installed at Powerton generating station, the main neutral grounding point, and at East Springfield, a non-

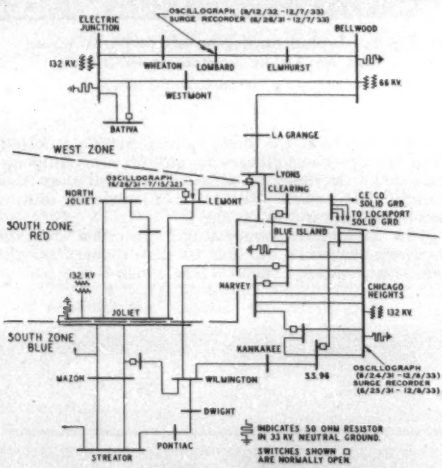


Fig. 2. 33-kv system of the Public Service Company of Northern Illinois

grounded station, the 2 stations being at opposite ends of a 64-mile line. The records of voltage to ground procured from these instruments are incidental to the principal purpose for which the instruments were installed.

The 26-kv system of the Public Service Electric and Gas Company is a radial system, grounded through resistance at the substation at which power is supplied to the system. The oscillograph is located at this point.

Method of Analysis

In the analysis of the oscillographic data all records showing evidence of a disturbance have been included whether or not they were correlated with operating records. Records correlated with or of a type attributable to switching have been omitted, and on one system records of voltage less than 15 per cent above normal have been arbitrarily omitted since it was frequently difficult to determine whether they were due to an actual disturbance or to a slight abnormality in the voltage.

Surge records include those due to lightning and switching surges as well as dynamic overvoltages. Other investigations have indicated that the characteristics of the figures are an indication of the duration and nature of the overvoltage. It has been found that lightning surges produce only positive or negative figures, or figures of a type sometimes classified as highly-damped oscillatory.[9] Switching surges also usually produce highly-damped figures. On the basis of these observations all unidirectional or highly-damped figures have been attributed to lightning or switching and therefore have been omitted from the analysis given in this paper. Medium and slightly damped figures are usually associated only with dynamic voltages either at fundamental frequency or at some higher harmonic frequency, since under fault conditions these voltages may persist and thus produce dense Lichtenberg figures, indicating many reversals or alternations in voltage. There remains a large group of mixed figures having the characteristics of a medium damped figure with a superposed figure of a type associated with lightning or switching. It is often difficult to determine the exact line of demarcation between the 2 types of figures, and to avoid the possibility of eliminating some voltages which may be caused by a fault-to-ground, 2 cumulative percentage curves have been prepared, one from the maximum recorded voltage of all medium damped and mixed figures, the other from the maximum voltage of the medium damped figures and the

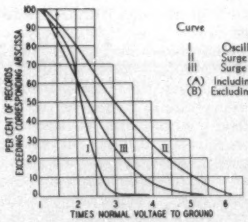


Fig. 3. Magnitude distribution of overvoltages on 140-kv isolated neutral system

estimated medium damped portion of the mixed figures.

In order to simplify and facilitate the measurement of the records from the surge recorders, only those showing voltages 15 per cent or more above normal were utilized.

Typical Lichtenberg figures secured in these investigations are shown in the accompanying illustrations. In some instances when voltage persisted for an appreciable time, records of the type illustrated in Figs. 6*A* and 9*C* were obtained. They

are due to the persistence of the voltage until after the film starts to advance. The film begins to move from 1 to 2 sec after the recorder is tripped and moves forward at the rate of about one inch per second. The extended portion of a record has been considered as well as the main figure and the maximum value indicated by either is the value used for the given disturbance.

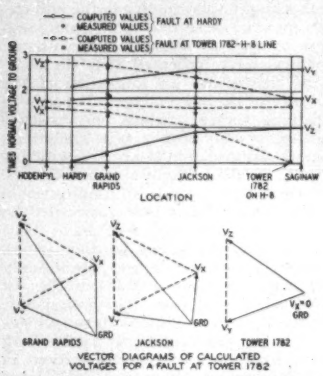


Fig. 4. Comparison of measured and computed line-to-ground voltages on 140-kv isolated neutral system

In cases of one-phase-to-ground faults the magnitudes of the overvoltages on the 2 sound phases were usually different. In preparing the curves, the maximum voltage shown by an oscillogram or surge record was used irrespective of the phase on which it occurred. Where records were obtained at more than one location for a given fault, the maximum voltage recorded, irrespective of instrument location, was used.

In analyzing the oscillograms and surge records the maximum peak or crest value, respectively, of the voltage to ground has been measured. This value is divided by the nominal peak voltage to ground of the system to secure the "times normal voltage to ground" used in presenting the results.

These values, as determined from oscillograms and surge records, respectively, are shown in the form of cumulative percentage curves of the type illustrated in Fig. 3. On these curves the abscissas indicate overvoltage expressed as a multiple of the normal system voltage to ground. The ordinates show the percentage of the total number of records considered which exceed the corresponding abscissas.

Results of Observations—Isolated Neutral System

The highest overvoltages, as would be expected, were observed on the isolated neutral system. By reference to Fig. 3 it is seen that, according to oscillographic measurements, 80 per cent of the disturbances produced voltages to ground equal to or exceeding the line-to-line voltage (1.73 times normal). The maximum value recorded was 3.9 times normal. Fundamental frequency calculations indicate that on an extensive system of this type, involving large charging currents during faults, overvoltages above 1.73 times normal may be expected. This is indicated by Fig. 4, the upper portion of which shows a comparison between measured and computed line-to-ground voltages, for 2 faults of known location. The vector diagrams in the lower portion of this drawing apply for a fault at pole 1782 and show the computed voltages at the locations indicated just above the respective diagrams. They illustrate how far the neutral (ground) point shifts outside the triangle of delta voltage and that the delta voltage remains normal even though the voltages to ground are badly unbalanced. Oscillograph observations also show that normal line-to-line voltage is maintained during one-line-to-ground faults.

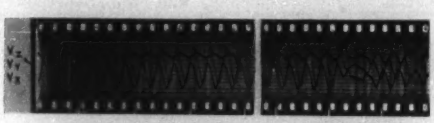


Fig. 5. Typical oscillogram of one-line-to-ground fault on 140-kv isolated neutral system

V_x, V_y, V_z = line-to-ground voltage

The 5 highest overvoltages recorded by the oscillographs were all due to disturbances on the same line, namely, the *H*-8 line which forms part of the eastern side of the system. The highest value was recorded during a fault caused by the boom of a dredge fouling the line. The next 4 highest resulted from insulator arc-over due to lightning.

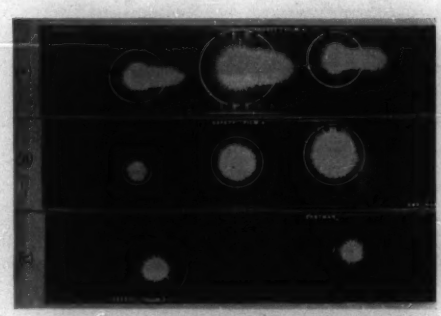


Fig. 6. Lichtenberg figures from 140-kv isolated neutral system

A. Medium damped figure, film in motion before fault cleared
B. Medium damped figure
C. Combination highly damped, medium damped figure

Table II—Comparison of Voltages From Oscillographs and Surge Recorders; One-Phase-to-Ground Faults; Isolated Neutral System

Case No.	Maximum Voltage to Ground (Times Normal) Measured by: Oscill.	Surge Recorder: Type of Fig.	Surge Recorder: Over-all Value	Surge Recorder: Estimated Medium Damped Portion	Correlation With Troubles on the Power System
1	2.9	HM	5.0	2.8	Lightning**; *H*-8 between Saginaw River and Flint
2	2.7	HM	4.8	2.8	Arc between *X*-*Y* conductors and to ground wire. Cause unknown, possibly kite
3	2.0	HM*	4.1	3.2	Lightning; line *O*-15 tripped at Kalamazoo
4	2.5	HM*	4.1	2.8	Lightning; line *H*-8 at tower No. 2,500 between Delhi and Owosso
5	2.2	HM*	4.3	3.0	Lightning; line *H*-8 at tower No. 2,585 between Delhi and Owosso
6	2.4	M*	4.5	4.5	Lightning; line *H*-8 at tower No. 2,580 north of Delhi
7	2.4	HM*	5.4	4.3	Lightning; line *H*-8 at tower No. 2,573 between Delhi and Charlotte
8	2.4	HM*	5.4	3.9	Lightning; line *J*-10 at tower No. 6,083 between Battle Creek and Blackstone
9	2.5	HM*	5.6	4.3	Lightning; line *J*-10 between Battle Creek and Blackstone and line *H*-8 at Charlotte
10	2.4	M	4.1	4.1	Lightning; line *H*-8 north of Garfield Ave.
11	2.2	HM	3.4	1.3	Lightning; location unknown
12	2.5	HM	4.3	2.8	Lightning; line *N*-14 between Croton and Muskegon
13	2.3	HM	4.5	2.5	Lightning; line *T*-20 between Croton and Hodenpyl
14	2.3	HM	2.6	1.3	Lightning; location unknown
15	2.2	HM*	3.3	2.1	Lightning; line *O*-15; location unknown

* Film in motion before fault cleared.
** In all cases reported above as due to lightning, insulator flashover only was involved.
Duration of overvoltage at approximately value shown in column 2 exceeded 20 cycles in all cases.
M = Medium damped figure.
HM = Combination highly damped and medium damped figure.

Sections of an oscillogram typical of the type obtained during a fault on this system are shown in Fig. 5. The left-hand section shows the beginning of the disturbance and the right-hand section the end of the disturbance, including a few cycles of normal voltage. The peculiar flattening of the voltage waves observed on many of the oscillograms at the end of the disturbance has been associated with circuit breaker operation but has not been completely explained.

A considerable number of oscillograms were correlated with switching. These records, which were excluded in preparing the overvoltage curves, were of 1 to 3 cycles duration. They showed voltages ranging up to a maximum of 1.9 times normal but more than 60 per cent of them were below 1.2 times normal.

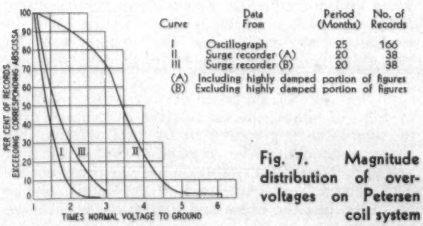


Fig. 7. Magnitude distribution of overvoltages on Petersen coil system

Curves II and III of Fig. 3 are the cumulative percentage curves of the overvoltages recorded by the surge recorders, the former including and the latter excluding the portion of the figures having the characteristics of unidirectional or highly damped surges. These curves are not directly comparable to Curve I partly because the periods of observation with the 2 types of instruments were not the same and partly because faults producing oscillograms sometimes produced no surge records and *vice versa*. The maximum medium damped type of Lichtenberg figure obtained, illustrated in Fig. 6*A*, indicated an overvoltage of 5.4 times normal. It was not possible to correlate this record with any specific power system disturbance, as the clock recording the time of operation was out of order at the time. Other records from this system are shown in Figs. 6*B* and 6*C*.

In general, it was found that, where simultaneous oscillograms and surge records were obtained of the same fault, the latter indicated dynamic overvoltages somewhat larger than those shown by the oscillographs. In order to show the relative comparison between the overvoltages indicated by the 2 types of instruments, 15 cases for which correlation between the 2 have been established are given in Table II together with the maximum line-to-

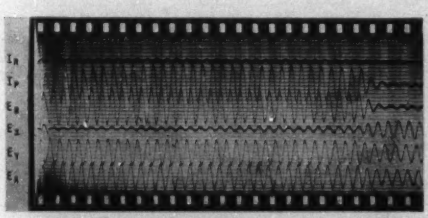


Fig. 8. Typical oscillogram of one-line-to-ground fault on Petersen coil system

I_R = residual current in Saginaw-Emery Junction line
I_P = Petersen coil current
E_R = residual voltage to ground
E_X, E_Y, E_Z = line-to-ground voltage

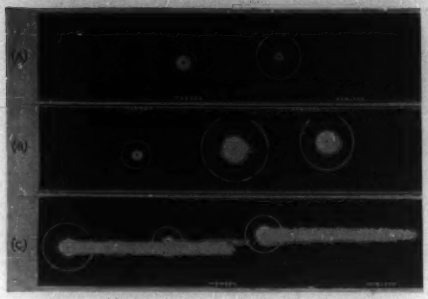


Fig. 9. Lichtenberg figures from Petersen coil system

A. Highly damped figure
B. Combination highly damped, medium damped figure
C. Combination highly damped, medium damped figure. Film in motion before fault cleared

ground voltages indicated by each instrument and the type of the Lichtenberg figure recorded.

Petersen Coil System

In Fig. 7 are shown the results of the observations on the Petersen coil system, curve I applying to the oscillograph and curves II and III to the surge recorder measurements. In Fig. 8 is an illustration of a typical oscillogram and Figs. 9*A*, 9*B*, and 9*C* are types of Lichtenberg figures from this system. Table III shows, for a number of faults for which records on both instruments were obtained, the comparison between the oscillograph and surge recorder measurements. It will be noted that in all cases listed in the table the trouble was attributed to lightning, and as the faults were self-clearing a definite fault location was determined in only one case. In 3 of the cases highly damped types of figures only were obtained and in some others the medium damped portion of the figure indicates voltages less than those shown by the corresponding oscillograms. In general these were cases in which the trouble cleared within 3 or 4 cycles and in which the voltage of each succeeding half cycle decreased in amplitude. On sustained faults the tendency of the surge recorder to show somewhat higher dynamic overvoltages than the oscillograph is in accord with the results of tests made in connection with the installation of the Petersen coil.[10]

Systems Grounded Through Neutral Resistance

Public Service Electric and Gas Company. This system, as previously stated, is grounded at one point only through a 75-ohm neutral resistor. One oscillograph element measured neutral current and gave a positive indication of those faults which involved ground current. Only records due to accidental disturbances and showing neutral current were utilized in this study. The cumulative percentage curve of overvoltages for this system is

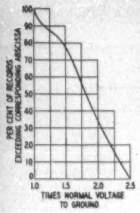


Fig. 10. Magnitude distribution of overvoltages on 26-kv neutral resistance grounded system. Data from oscillograms

Period of observation 2 years, 5 months (7/29/31 to 1/1/34). Total records—101

shown in Fig. 10. A section of an oscillogram typical of the majority of records from this system is shown in Fig. 11*A*. This oscillogram, obtained during an oil circuit breaker bushing failure, also illustrates the development from a 1-phase-to-ground to a 2-phase-to-ground fault at, according to the trouble record, the same point. In Fig. 11*B* is illustrated an intermittent spit-over followed finally by a complete breakdown; this is an example of the apparent extinction and reëstablishment of fault current. The fault was caused by a cable splice failure.

During the course of the observations 3 different series of tests were made by the power company in which a one-line-to-ground fault was produced by closing in a circuit breaker on a grounded conductor. Twenty records were obtained, the voltage to ground ranging from 1.83 to 1.93 times normal. Wave shape was uniform and undistorted.

Public Service of Northern Illinois—33-Kv South Zone Network. Throughout the period of these observations this network was split into 2 parts known as the South Zone Red and South Zone Blue networks, by sectionalizing the bus at the Joliet substation. However, the neutrals of the 2 networks were grounded through the same resistor at Joliet and consequently overvoltages resulting from faults on either network appeared in the other due to the voltage rise across the common resistor. For this reason the oscillographic data on overvoltages as obtained from the 2 networks have been combined for the purposes of this paper. Curve I of Fig. 12 shows the cumulative percentage curve of overvoltage prepared from oscillograms from these networks. The maximum value of overvoltage recorded was approximately 2 times normal. The record was correlated with circuit breaker operation but the cause and nature of the fault was unknown.

Surge records were obtained at only one point on the South Zone network, namely, at Chicago Heights. The results are shown by Curves II and III of Fig. 12. The largest figure attributed to dynamic voltage showed a value of 2.6 times normal and resulted from a bushing failure at a substation not far from the location of the surge recorder.

Public Service of Northern Illinois—33-Kv West Zone Network—Two Neutral Resistor Grounds. The results given in this section apply only to the period during which the network was grounded through 50-ohm neutral resistances at Electric Junction and Bellwood and directly grounded at 2 other

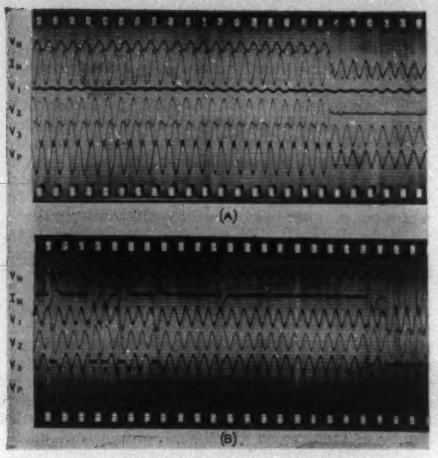


Fig. 11. Oscillograms of line-to-ground faults on 26-kv neutral resistance grounded system

A. Typical record
B. Intermittent spit-over followed by complete breakdown
V_P, V_N = positive and negative sequence voltage
V_1, V_2, V_3 = line-to-ground voltage
I_N = neutral current

points fairly remote from the main portion of the network. During one-line-to-ground faults on that portion of the network centering around the resistor grounded neutrals, the total fault current divided about equally among the 4 neutrals. During the 5.5-month period that oscillograph records were obtained no voltages to ground greater than 1.2

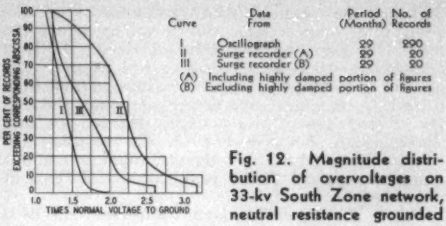


Fig. 12. Magnitude distribution of overvoltages on 33-kv South Zone network, neutral resistance grounded

times normal were recorded. A cumulative percentage curve was not plotted due to the few records of overvoltage obtained.

The majority of the records obtained with the surge recorder showed either a highly damped figure alone or a highly damped figure with a (less than 31-kv crest) very dense center; next in frequency of occurrence were the highly and medium damped figures mixed. A few records showing only medium damped figures were secured. In Fig. 13*A* and 13*B* are sample records from this system. The results of the surge recorder observations are shown by Fig. 14, Curve I being prepared from the voltages shown by the over-all figures and Curve II from the portion of the figures attributed to dynamic overvoltage. Only figures whose medium damped portions exceeded 31-kv crest were used.

Directly Grounded Systems

East Springfield and Powerton Observations. While the oscillographs at Powerton and East Springfield were not installed primarily for the overvoltage study, they provided an opportunity of obtaining data on this subject from a system having solidly grounded neutrals. At Powerton, 1 of the 2 points

Table III—Comparison of Voltages From Oscillographs and Surge Recorders; One-Phase-to-Ground Faults; Petersen Coil System

Case No.	Maximum Voltage to Ground (Times Normal) Measured By: Oscillograph: Voltage	Oscillograph: Duration* Cycles	Surge Recorder: Type of Fig.	Surge Recorder: Over-all Value	Surge Recorder: Estimated Medium Damped Portion	Cycles Duration of Disturbance, From Oscillogram	Correlation With Power System Troubles
1	1.6	49	M	2.5	2.5	49	Lightning; Saginaw River 177 operating open
2	1.3	1	H	3.2		2	Lightning; location unknown
3	2.0	2	H	2.1		4	Lightning; location unknown
4	1.7	68	HM	4.1	1.7	68	Lightning; location unknown
5	1.8	10	H	2.1		11	Lightning; location unknown
6	1.8	33	HM	4.1	1.9	48	Lightning; location unknown
7	1.8	170+	HM	3.9	2.1	170+	Lightning; fault on tower No. 1618, *X* phase
8	1.6	1	HM	3.2	1.3	3	Lightning; location unknown
9	1.5	1.5	HM	3.6	1.3	3	Lightning; location unknown
10	1.5	12	HM	2.8	0.8	12	Lightning; location unknown
11	1.5	26	HM	2.8	1.2	26	Lightning; location unknown
12	1.5	200+	HM	3.4	2.1	200+	Lightning; location unknown
13	1.7	79	HM	3.2	1.7	79	Lightning; location unknown
14	2.2	75	HM	4.3	2.1	75	Lightning; line off Mio to Cook, Emery
15	1.3	1	HM	3.0	1.2	3	Lightning; location unknown

H = Highly damped figure.
M = Medium damped figure.
HM = Combination highly damped and medium damped figure.
* Duration at approximately the value shown.

at which the system is solidly grounded, no records showing any appreciable rise in voltage above the maximum normal values were obtained. At East Springfield, where there is no neutral ground, voltages to ground up to about 1.5 times normal were recorded. A cumulative percentage curve showing the distribution of the voltages recorded at East Springfield is shown on Fig. 15. In preparing this curve only voltages above the maximum normal bus voltage to ground (31-kv peak) at East Springfield were used.

Public Service of Northern Illinois—33-Kv West Zone Network. On about January 30, 1933, the West Zone network was solidly grounded at Bellwood and Electric Junction. Oscillograph and surge recorder observations were continued for about 10 months under this operating condition. Only a few oscillograph records showing voltage above normal were obtained, the maximum being 1.2 times normal, recorded at the time of an oil bushing failure at Bellwood.

A considerable number of surge records were obtained, a majority of them being of the unidirectional or highly damped type. However, some combination figures showing evidence of dynamic overvoltage were obtained. One such figure is illustrated in Fig. 13*C*. The continuous band on this record, obtained while the film was being stepped up in position for another surge, was present on many records, both with the system solidly grounded and when grounded through neutral resistance. Cumulative percentage Curves III and IV of Fig. 14 show the magnitude distribution of the observed voltages producing figures whose medium damped portions exceeded 31-kv crest.

Discussion

A study of the wave shape of the line-to-ground voltages sheds some light on the nature of the fault and the mechanism by which the overvoltage is produced.

Oscillograms from the isolated neutral system showing voltages over 2.6 times normal (300-kv peak) have been carefully inspected as to wave shape and found in all cases to show approximately a sine wave. In these cases the majority of the faults involved insulator flashover due to lightning and consequently arcing, but there is no evidence of the abrupt rises in voltage on the sound phase that would be expected were the fault current restriking intermittently. In a number of other instances the oscillograms indicate a self-clearing fault, with no circuit breaker operation, the condition which would be most likely to cause irregular wave traces.

The majority of the records from the Petersen coil system also show approximately sine wave shape and this was true of the maximum observed value. However, there were several records that indicated at some point during the disturbance a distorted voltage; usually where the fault was clearing, or, in a few cases, where the fault was reëstablished.

The 26-kv system of the Public Service Electric and Gas Company on which observations were made consists of 126 circuit miles of open wire and 32 miles of cable. Records from this system furnish the only cases of severe wave shape distortion having an effect on the magnitude of the larger values of dynamic voltage. A majority of the records from this system have uniform wave shape of the type illustrated in Fig. 11*A*. However, the highest voltages occurred in cases where the fault current, after becoming zero, reëstablished either every half cycle or intermittently, as illustrated by I_N in Fig. 11*B*. The abrupt rise in the voltages on the sound phases through which they adjust themselves to the new state of affairs, is clearly apparent in the oscillogram. It is seen that

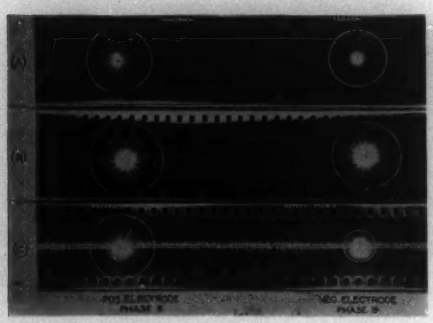


Fig. 13. Lichtenberg figures from 33-kv West Zone network

A. Highly damped figure. 50-ohm resistors in service
B. Combination highly damped, medium damped figure. Resistors in service
C. Combination highly damped, medium damped figure. All neutrals solidly grounded

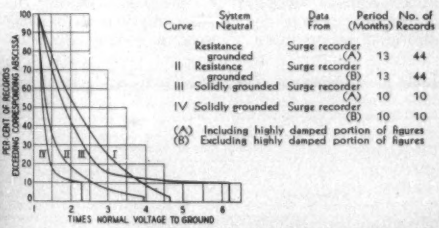


Fig. 14 (above). Magnitude distribution of overvoltages on 33-kv West Zone network, resistance grounded and solidly grounded neutral

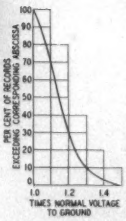


Fig. 15. Magnitude distribution of overvoltages on 33-kv directly grounded system. Data from East Springfield oscillograph

Period of observation 9 months (3/24/33 to 1/1/34). Total records—75

Table IV—Classification of Records of Voltage Above 1.85 Times Normal, Public Service Electric and Gas Company 26-Kv System

Nature of Fault	No. of Records	Max. Meas. Voltage Times Normal
Peaked Voltage Waves		
Cable failure	22*	2.5
Oil immersed insulator failure**	7	2.4
Lightning	1	1.9
Unknown	2	2.4
Sine Voltage Waves		
Lightning	4	2.3
Wire dropped across insulator in station by bird	1	1.9
Unknown	1	1.9

* During incipient cable failure more than one record was sometimes obtained from the same source of trouble.

** All these records associated with a defective oil immersed insulator in a circuit breaker.

when the arc restrikes, the voltages of the sound phases immediately assume a value but little larger than that which they have when the arc is continuous. In this case and in others where the fault current was reëstablished every half cycle, the maximum voltage usually occurred coincident with the appearance of this particular wave shape. In none of the cases was there any indication of the cumulative building up of voltage or of large sustained oscillations in either the current or voltage waves. Table IV classifies for this system all of the records of voltage to ground above 40-kv peak (1.85 times normal) according to the wave shape and nature of the fault. It is seen that a majority of the higher voltages are associated with records of irregular wave shape and that a large number of them are associated with cable failures. All of those associated with cable failures indicate that the fault current, during at least a half cycle has become zero and reëstablished itself.

Records from the remaining systems, in general, showed sine waves with occasional irregularity due to lower harmonic frequencies.

No observations were made on systems consisting entirely or predominantly of cables, and conditions may be different from those experienced on overhead lines. For instance, there is a greater possibility of resonance conditions becoming important on a cable system where the capacitance is larger and the resistance smaller than on an overhead line. Also the characteristics of an arc on a cable may be quite different from those in open air.

The portions of the surge records obtained while the film was in motion suggest certain possibilities regarding the nature of the voltage during a fault. It will be noted that, while the film is moving, there are streamers extending from the dense band, which have the appearance of those usually associated with fairly steep wave front surges. These were noted on surge records from all systems, including the solidly grounded system, and suggest that a series of steep wave front surges frequently accompany faults. When superposed on the high fundamental frequency overvoltage measured on the isolated neutral system, it appears possible that they could account for the large medium damped figures recorded thereon.

Summary and Conclusions

1. Sustained overvoltages larger than line-to-line voltage were frequently observed on unfaulted phases, during line-to-ground faults on systems operated with neutral isolated from ground, or grounded through substantial values of neutral impedance.

2. In general, both the maximum values and the cumulative percentage curves of dynamic overvoltage, correspond in order of magnitude to that of the neutral impedance of the systems, although the Petersen coil system and the West Zone system are partial exceptions to this.

3. The maximum dynamic overvoltage recorded by oscillographs was 3.9 times normal and by surge recorders, 5.4 times normal, both records being from the 140-kv isolated neutral system. The dynamic overvoltages on the 140-kv Petersen coil system were substantially lower, the maximum values from oscillograms being 2.8 times normal, and from surge records, 3 times normal. On solidly grounded systems the maximum value recorded by oscillographs was 1.5 times normal and by surge recorders, 2.3 times normal.

4. The maximum values of voltage quoted above represent one record only and are considerably higher than those shown by the next lower record. Only a small percentage of the voltages approached these values.

5. Comparison of the dynamic overvoltage, for the same faults, as indicated by oscillograms and surge records gives values which are in reasonably good agreement. Although the cumulative percentage curves of surge records indicate higher voltage than similar curves based upon oscillograms the 2 sets of records are not directly comparable, due to the differences in the number of records and periods of observations.

6. There has been no evidence of cumulative building up of overvoltages on unfaulted phases due to successive restriking of an arc to ground. All of the higher values of overvoltages on the isolated neutral and Petersen coil systems were essentially of sine wave shape. Periodic making and breaking of the fault current have been observed on the 26-kv system grounded through a 75-ohm resistance. Most of these faults were due to cable failures. The voltages resulting from these intermittent faults have decided peaks but their magnitudes are not much greater than the sustained value after the fault current has become constant.

7. In these investigations no observations were made on systems consisting entirely of cable; therefore, the conclusions apply only to systems where the preponderance of the circuit mileage is in open wire.

The authors wish to express their appreciation to the power companies coöperating in this study and particularly to those persons, too numerous to mention, who contributed to the installation and maintenance of the instruments and the preparation of the trouble records.

References

1. Der Aussetzende (intermittierende) Erdschluss, W. Petersen. *E.T.Z.*, v. 38, 1917, p. 553–5.

2. Voltages Induced by Arcing Grounds, J. F. Peters and J. Slepian. A.I.E.E. Trans., v. 42, 1923, p. 478–89.

3. Frequency Conversion by Third Class Conductor and Mechanism of the Arcing Ground and Other Cumulative Surges, C. P. Steinmetz. A.I.E.E. Trans., v. 42, 1923, p. 470–7.

4. Elektrische Schaltvorgänge, R. Rüdenberg. (Edition 1926) Article 27, p. 237.

5. Arcing Grounds and Effect of Neutral Grounding Impedance, J. E. Clem. A.I.E.E. Trans., v. 49, 1930, p. 970–88.

6. Experimental Studies of Arcing Faults on a 75-Kv Transmission System, J. R. Eaton, J. K. Peck, and J. M. Dunham. A.I.E.E. Trans., v. 50, 1931, p. 1469–78.

7. Oscillographs for Recording Transient Phenomena, W. A. Marrison. A.I.E.E. Trans., v. 48, 1929, p. 939–47.

8. The Klydonograph, J. F. Peters. *Elec. Wld.*, 1924, v. 83, p. 769–73.

9. Surge Voltage Investigation on Transmission Lines, W. W. Lewis. A.I.E.E. Trans., v. 47, p. 1111–21.

10. Petersen Coil Tests on 140-Kv System, J. R. North and J. R. Eaton. Elec. Engg., 1934, v. 53, p. 63–74.

Discussions

Of A.I.E.E. Papers—as Recommended for Publication by Technical Committees

ON THIS and the following 15 pages appear discussions of A.I.E.E. papers received in complete and acceptable form at Institute headquarters, and subsequently reviewed by various technical committees and recommended for publication, as follows: (1) remaining unpublished discussions of 1934 winter convention papers; (2) discussions of papers presented at the A.I.E.E. North Eastern District meeting, Providence, R. I., May 16–18, 1934 (except those papers not yet published in ELECTRICAL ENGINEERING); and (3) discussions of papers on electrical communication subjects presented at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Authors' closures, where they have been submitted, will be found at the ends of the discussions on their respective papers.

Members anywhere are encouraged to submit written discussion of any A.I.E.E. paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions should be: (1) concise; (2) restricted to the subject of the paper or papers under consideration; (3) typewritten and submitted in triplicate not later than 2 weeks after formal discussion at an A.I.E.E. meeting or convention to C. S. Rich, secretary, technical program committee, A.I.E.E. headquarters, 33 West 39th Street, New York, N. Y.

Corona Losses From Conductors of 1.4-In. Diameter

Authors' closing discussion of a paper published in the December 1933 issue, p. 854–60, and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 470–1, and in the April 1934 issue, p. 600–1.

J. S. Carroll, Bradley Cozzens, and T. M. Blakeslee: The authors are particularly pleased to note that their paper was of sufficient interest to call forth so much discussion and comment. We wish to thank those who took the time and trouble to point out certain things in which they were interested and also for the suggestions which are helpful in planning future tests.

The weather seems to be the main general topic of discussion. Would that we could control the weather in the field at the Ryan Laboratory where these experimental lines were located. Although humidity variations for the tests were between 20 and 62 per cent, the effects of the variations in this range are still negligible as it is generally conceded that the humidity factor for conductor corona loss does not become appreciable until percentages above 60 are reached. Barometric variations were also negligible, being less than 2 per cent. Temperature variations of less than 8 per cent, based on the absolute scale, existed for the tests, but since this factor was beyond control and no generally accepted correction formula is available, the data were presented as found.

The subject of corona loss during rain raised considerable comment. It must be remembered that for the greater portion of its length the proposed transmission line for which these corona loss measurements were made is to cross one of the driest sections of the United States. With this in mind the authors studied the effect of dust that might possibly be deposited on the conductors erected in the desert and reported the results. As mentioned, rain was not an important factor in the consideration of the type of conductor for the proposed line; however, every available opportunity for loss measurements during rain was made use of. Unfortunately sufficient consistent data were not obtained to justify publication. There again we could not control the rate of rainfall, size of rain drops, wind, etc., the result being that the test conditions for the different types of cables tested were not the same. Besides the observations reported in the paper concerning rainfall, it was noted that when the conductors were free from grease the rain drops on striking the surface spread out and ran to the underneath side of the conductor. This was the case even for the type *C* cable. In the case to which Mr. Peterson refers, i. e., the 1924 paper, the water drops actually stood out on the side and top of the cable. This particular cable had never been washed to remove the grease and had not been up a sufficient length of time for the grease to have been weathered off.

The majority of measurements investigating corona loss from large-diameter conductors during rain have been made at the Ryan Laboratory, and as yet no really definite conclusions have been drawn by those intimately connected with the work. It is felt that attempted conclusions based only on portions of the available data are unjustified. If any of the companies consider this factor of rain of sufficient importance to warrant the expense, from previous study it is believed to be physically possible to erect a sprinkler system over the present test line at the Ryan Laboratory which would enable the study of corona loss from different types of conductors under controlled conditions.

Along this matter of controlled conditions, a careful study is being made of some of the weather factors affecting corona loss. Some of this preliminary work is reported by Hegy and Dunlap in ELECTRICAL ENGINEERING, Feb. 1934, p. 272–3.

The matter of die grease was mentioned in all of the discussions. This was without exception the greatest difficulty in the way of making comparison of the different types of cables. Past tests have definitely shown that it is absolutely necessary to remove this grease to approximate the losses on weathered cable. The justification for this comparison is given in the author's 1933 paper (A.I.E.E. TRANS., v. 52, 1933, p. 55).

We wish to answer the comment made by Professor Harding in the second paragraph of his discussion by referring to the latter part of Mr. Peterson's first paragraph. With respect to the calculation Professor Harding makes in paragraph 4, as nearly as we can make out he is assuming that the cable showing the highest losses in the group will be operated at 330 kv, or he has selected a critical potential of 430 kv on the 1.4-in. type *C* conductor. The facts are that the latter cable was chosen for the job and the maximum operating voltage will be approximately 285 kv which, by the same process of calculation used, will show an approximate loss of 1 kw per mile of line at an elevation of 3,500 ft and desert temperatures.

As for the transfer of single-phase measurements to what would be expected on a three-phase line, we checked the method carefully with an actual three-phase set-up before attempting to use single-phase measurements to calculate three-phase losses. As stated in the paper, this method has its limitations and is not recommended where three-phase measurements are possible.

Concerning Professor Harding's point regarding the value of corona loss in the attenuation of surges with steep wave fronts, it must be remembered that the surge voltages are from 6 to 10 times normal line voltage. Corona formed by these higher voltages is little affected by minor variations in size or shape of the conductor.

In regard to the degree of accuracy of the measuring equipment referred to by Professor Harding, reference should be made to the previously mentioned 1933 paper which discusses the care taken in the actual calibration of instruments and equipment. Checks of the complete system of measurement have shown that the normal errors of reading instruments are much greater than the errors introduced by the equip-

ment itself. An example of the accuracy may be obtained from the plotted points on the insulator loss curve, Fig. 8 of the paper referred to, where values as low as 2 watts at 200 kv were recorded. It was because of this high degree of accuracy developed at the Ryan Laboratory in measuring corona loss that the City of Los Angeles Department of Water and Power felt justified in having the measurements made there.

Mr. Peterson's question of the economic feasibility of cleaning conductors resolves itself into a question of the characteristics of the weathering process. This process on a new, uncleaned conductor may cause a roughening and consequent increase in corona loss due to unequal weathering of the grease-covered surface. On a thoroughly clean conductor the weathering process is uniform over the entire surface with a consequent tendency for a reduction in corona loss. These considerations, together with the very great adverse effect of grease on corona loss demonstrated may justify the erection of cleaned conductors in transmission line construction.

While the corona loss tests reported in this paper were made possible by the Department in their thorough search for a suitable conductor for the 275-kv transmission line from Boulder Dam, it is distinctly and obviously true, as stated by many commentators on the paper, that the final choice for the transmission line was not based on corona loss measurements alone. The regular mechanical and other properties of the cable were principal factors with the Department in the cable selection. Time did not permit the thorough study of each cable surface over complete ranges of weather conditions, an investigation which would be highly desirable, but the tests were carried out primarily in the effort to determine just how much weight should be given the corona loss factor in the selection of high voltage transmission line conductors.

Portable Schering Bridge for Field Tests

Authors' closing discussion of a paper published in the January 1934 issue, p. 176–82, and presented for oral discussion at the electrical measurements session of the winter convention, New York, N. Y., Jan. 25, 1934. Other discussions of this paper were published in the March 1934 issue, p. 478–81, and in the April 1934 issue, p. 618–22.

C. F. Hill, T. R. Watts, and G. A. Burr: The reasons for preferring the inverted Schering bridge are:

(a) It is direct reading and requires no correction or vector subtraction of the impedance to ground through the transformer.

(b) The shield at testing potential is a great advantage in testing transformer bushings. The difficulty of removing the transformer lead from the bushing as required by other methods has probably been the principal reason why so few transformer bushings have heretofore been tested.

The placing of the ground at C_1R_3 and galvanometer terminal at the left hand corner of the bridge diagram, Fig. 1, page 177, January 1934 ELECTRICAL ENGINEERING, will probably not eliminate errors due to overhead interference, because part of the picked-up interference current would flow to ground through C_1 directly and the rest through the parallel path composed of C_2, R_4, and R_3 in series.

The sensitivity of the bridge is such that an unbalance of 0.0005 in the power factor reading will give a 1-mm deflection when testing a bushing of 200-$\mu\mu$f capacitance with normal power factor. The curve in Fig. 5 is applicable to all sizes of condenser bushings.

The test method using only voltage and current readings will without doubt discover condenser bushings with broken down layers or with general depreciation far progressed. It does not give the complete analysis provided by the power factor and capacitance determination. The use of the straight Schering bridge in England for field testing was not known by the writers at the time of publication. The Schering bridge will not read the resistance of segregated wood members, but in the test procedure bridge readings are taken on the bushings with the circuit breaker open and closed and faults in the wood members are located as parallel leakages. They are traced and eliminated with the aid of a megger.

The power factor, capacitance, watts, or current can all be calculated either from the bridge method or the wattmeter-ammeter method. For our method of analysis we prefer power factor and capacitance readings as only these 2 values are necessary for complete determination of condition.

Laboratory tests would indicate that the power factor reading, coupled with the capacitance reading to show that there are or are not any punctured layers, will give a fairly consistent determination of the 60-cycle voltage that a condenser bushing will stand. We believe that when the same materials and methods of construction are used it should also give an indication of relative impulse strengths.

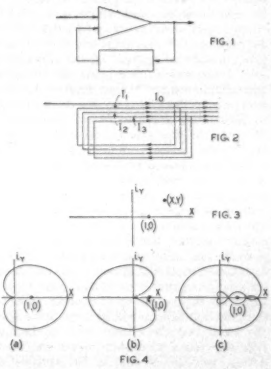
Stabilized Feed-Back Amplifiers

Discussion of a paper by H. S. Black published in the January 1934 issue, p. 114–20, and presented for oral discussion at the communication session of the winter convention, New York, N. Y., Jan. 24, 1934. Other discussions of this paper were published in the March 1934 issue, p. 461–2, and in the April 1934 issue, p. 590.

Harry Nyquist: I wish to comment on feed-back amplifiers with reference to the freedom from singing. When an amplifier is constructed so that a portion of the output energy is fed back (Fig. 1) to the input, there is danger that a sustained condition of singing may occur. For the purpose of studying the singing condition, it is permissible to regard the feed-back phenomenon as a series of waves (Fig. 2). Let I_0 be the wave in the output of the amplifier element due to an external signaling wave when there is no feed-back included. Then this wave I_0 is followed by another wave I_1 which is the result of I_0 being fed around the circuit and being modified by the feed-back wave and by the amplifying element. Similarly I_1 gives rise to wave I_2 and so on indefinitely. The total wave in the output of the amplifying element due to the external signal wave is the sum of all these.

It will be convenient to use a short name for the ratio of the steady-state value of any one of these waves to its predecessor. This ratio may be called the feed-back ratio. It is the same as the quantity $\mu\beta$ in Mr. Black's paper. The feed-back ratio, being the ratio of any one of these waves to its predecessor, is generally a complex number and may be represented by a point (x, y) in a diagram as in Fig. 3.

It is relatively easy to see that when the feed-back ratio is less than unity, a stable condition exists. Suppose, however, that a circuit has been constructed such that



Conditions for feed-back amplifier singing

the feed-back ratio is materially greater than 1, say it has the value 10, then the steady-state value of each one of these waves is 10 times as great as its predecessor and it is natural to assume that a singing condition exists. In fact, one is tempted to assume that a singing condition exists whenever the feed-back ratio exceeds unity so that each one of these waves is greater than its predecessor. Experience shows that this conclusion is incorrect, which is fortunate because the utility of feed-back amplifiers would be very much less than it is if the feed-back ratio had to be limited to values less than unity. The defect of the theory just hinted at is that it fails to take account of the building-up processes. While it may be perfectly true that each one of these waves is 10 times as great as its predecessor in the steady state, it does not follow that this is true at any specified instant because the later waves have not had time to build up to a steady-state value.

An accurate summation of these waves taking full account of the building-up processes ("Regeneration Theory," H. Nyquist. Bell System *Tech. Jl.*, Jan. 1932). leads to interesting results. Since these processes play an important rôle it is not surprising to find that the transmission properties of the whole frequency range are of importance. Briefly, the criterion which is found for stability is that if the feed-back

ratio is applied on this diagram for all frequencies from 0 to infinity, the point unity should lie outside of the locus thus formed in order to have a stable condition (Figs. 4*b* and *c*). If it lies inside, there is a singing condition (Fig. 4*a*).

It may be seen that the feed-back ratio may have any value provided it is not positive and greater than unity at the frequency where it is positive (Fig. 4*b*). It is possible to go even further than this and to assert that the feed-back ratio may be positive and greater than unity at some frequencies provided that care is taken that the point unity is not included (Fig. 4*c*). If this is done, the building-up processes will be such that singing does not occur. A qualitative description of what happens may now be stated as follows: These waves may be considered divided into three classes. In the first class are those which have reached their steady-state value substantially. In the second class are those which are in the process of building up. In the third class are those which have not yet attained appreciable values. If we limit our attention only to the first class, we should be led to the erroneous conclusion indicated above. However, if the second class is included and if the network is designed to satisfy the criterion indicated, the sum total of the second class will substantially cancel the sum total of the first class at any instant.

It is of interest to consider further the special condition which occurs in a stable circuit which has feed-back ratios which are positive and greater than unity (Fig. 4*c*). As shown in the diagram, this circuit is stable. Now, however, if the gain of the amplifier is decreased, the effect will be that the point unity will be included within the locus and the circuit will be singing. We have then the paradoxical condition that a decrease of gain in the amplifying element results in passing from a stable to an unstable condition and conversely an increase in gain results in passing from an unstable to a stable condition.

Induction Motor Locked Saturation Curves

Discussion of a paper by H. M. Norman published in the April 1934 issue, p. 536–41.

P. H. Trickey: Mr. Norman states that his method does not cover the case where the tooth tips are saturated by slot leakage flux. I believe that this case is very important, especially for totally closed rotor slots.

I am giving below a method of accounting for saturation based on a different method of attack than that of Mr. Norman's. The data given were obtained in a rather rough manner, and not expected to be particularly accurate, but only to illustrate the method of attack.

A series of standstill readings were taken on an induction motor with closed slots, varying the current through the windings. From the readings of current, watts, and applied voltage the locked impedance, resistance, and reactance were obtained. The several components of the reactance were calculated as accurately as possible. An 0.05 opening above the rotor slot was assumed in calculating the zigzag leakage. Subtracting other components, the slot leakage was obtained as a function of current in the windings. From the slot leakage, all terms were eliminated except the slot constant and from that was subtracted the constant for that part of the slot between

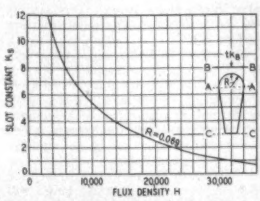


Fig. 1. Slot constant for portion of slot between *AA* and *BB* from test assuming 0.05 opening in calculating zigzag leakage

$H = \frac{CK_w\Phi I_2}{S_s W t k_B}$ where

C = Total series conductors per phase
K_w = Product of pitch and distribution factors
I_2 = Secondary locked current referred to primary
S_s = Secondary slots
W = Width or stacking of rotor
tk_B = Thickness of closed slot bridge

AA and *CC* (Fig. 1) which is easily calculated.

The remainder was plotted as a function of the current in the rotor, turns, number of slots, stacking of the rotor, and the thickness of the bridge.

The results of this test are shown in Fig. 1. Obviously, there are many inaccuracies which could be overcome by more tests on enough motors to obtain a good average. However, the reactance of the saturated bridge will probably vary from 50 per cent to 150 per cent because of punching strains in the bridge unless the rotor punchings are annealed, and even then the bridge thickness will vary due to manufacturing tolerances, so that any great refinements are unnecessary. There should be a separate curve for each value of bridge radius. The figure also shows that for low values of *H*, the reactance may become very large. This would occur if the bridge were too thick or if the motor were greatly underrated.

Switching at State Line Station

Author's closing discussion of a paper published in the January 1934 issue, p. 148–56, and presented for oral discussion at the session on electric power switching of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 456–61.

T. C. White: It is interesting that one of the problems most generally discussed is that of oil fire hazards; it so happens that we at State Line have also been giving a great deal of study to this question. Beyond doubt, this is a very serious problem, as evidenced by the numerous fires reported in late years. While no fires have occurred at this station, the hazard is well appreciated and we have endeavored to take all the precautions that experience at other plants has shown desirable.

However, when this problem is analyzed from the viewpoint of the increased hazard due to the metal-clad gear over that inherent in the standard oil filled equipment to be found in the average plant, that is, in transformers and oil circuit breakers, it is rather difficult to see how the relatively small total quantity of oil incident to the metal-clad equipment materially increases the hazard. Considering the equipment shown in Fig. 6, p. 151 of the paper, the total amount of oil located in the switchyard is about 416,000 gallons; of this amount, about 56 per cent is contained in transformers, 23 per cent in reactors, 9 per cent in oil circuit breakers, and 2 per cent in potential transformers. Only about 10 per cent is involved in the metal-clad portion of the switchgear. This latter oil is contained in a very large number of small strong enclosures, as contrasted with the large volume enclosed in relatively weak tanks in the case of transformers. The transformer oil fire at Hell Gate described by Mr. Hall illustrates the great hazards due to transformers in practically all installations. Perhaps one of the most prevalent hazards in general is in the case of potential transformers, especially at the higher voltages where comparatively large oil volumes are needed and adequate protection is difficult to provide. At State Line, however, the highest voltage potential transformers used are 22 kv. It is to be hoped that recently introduced non-combustible insulating mediums can be developed at reasonable costs; until then, oil filled equipment should be designed to contain a minimum of oil consistent with adequate clearances.

Replying to Mr. Sporn's statement concerning disastrous fires which have occurred in oil filled switchgear, we know of no case where a serious fire has occurred in equipment at all comparable with that at the State Line station.

The question of weather protection for work on the outdoor switchgear under adverse conditions in some locations may certainly be very troublesome. Whether the proper solution is enclosure in a building shell as Mr. Sanderson suggests or a construction which would be designed with the parts needing regular maintenance completely surrounded and protected by the structure of the gear is a question, but it is agreed that maintenance and to some extent operating costs would be decreased if either were done, however, as pointed out in the paper, no serious difficulty has arisen to date and it has been possible so far to schedule routine outdoor work in seasons of favorable weather. The one big maintenance item is oil circuit breaker overhauling, which is done annually. Possibly the adequacy of such a general routine may be open to some question, but so far has been entirely satisfactory. Undoubtedly the problem of scheduling such work for favorable conditions will become more difficult as equipment becomes more extensive. Emergency work may, of course, be necessary under unfavorable weather conditions, but tent-

like shelters and other temporary expedients can be used and in fact were used during construction. In weighing the advantages and disadvantages of outdoor gear such as that used at State Line, the difficulties of outdoor exposure cannot be ignored, but they must be considered in the light of the amount of regular work absolutely necessary and the probable need of emergency work.

I agree that the question of the relative advantage of duplicate buses as against a single bus with a transfer bus must be answered by consideration of the service and other conditions involved, and no set rule can be laid down.

Answering Mr. Hall's question, ground fault protection is provided at State Line and the method employed is described in Mr. Rossman's paper (reference 5) in the A.I.E.E. TRANSACTIONS, v. 49, 1930, p. 400. The degree to which sectionalized ground fault protection on metal-clad gear should be carried is almost entirely determined by economic considerations; metal-clad gear permits the use of a very selective relay scheme, both between main and reserve buses, sections of a bus, or individual phases, depending upon how many insulating joints and individual grounding transformers are supplied for the bus enclosures. In the case at State Line, it was felt that additional selectivity between main and reserve buses could not be justified economically.

In discussing generator sizes, Mr. Hall notes that Unit No. 2 is 50,000 kw smaller than Unit No. 1. Unit No. 2 is a single-element double-winding generator, taking up about half the space of Unit No. 1 and having twice the capacity of the largest of the 3 elements of that unit, that is, the electrical capacity of each winding of Unit No. 2 is about the same as that of the largest element of Unit No. 1.

Answering Mr. Sporn's criticism of the scope of the paper, perhaps it should be pointed out that the intention was to prepare the paper along the lines proposed by the committee, that is, to review the art of switching in the light of actual operating experience, showing how far the equipment actually fulfilled or fell short of the design objectives and present day requirements, incidentally pointing out its serviceability and reliability and indicated trends. I believe, however, that another symposium on this subject, covering the basic principles of future, as well as existing practice, would be very timely and desirable.

Pantograph Trolleys
I—Design Features

Discussion of a paper by W. Schaake published in the January 1934 issue, p. 182–9, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 451, and in the April 1934 issue, p. 589.

P. E. Wade: Mr. Brown is to be commended for emphasizing the importance of limiting normal contact wire height to the lowest value consistent with operating safety. Some years ago the question of asking the American Railway Association to consider a standard rule prohibiting the use of box car tops by trainmen within electrified territory was debated, and dismissed as being impracticable in switching yards and on some mountain grades. Every foot removed from such height would be of great help in connection with collector design and performance and system costs. In 1914 the American Railway Engineering Association recommended a minimum clearance of 9 ft $1^1/_2$ in. between car running board and contact wire to guarantee safe conditions for trainmen giving signals with lanterns. Shortly after this the maximum box car height called for a 24-ft 2-in. wire height.

In view of these facts it is interesting to note wire heights as of today given in Table I.

Table I—Wire Heights

Road	Date Installed	System Voltage	Wire Height Ft	Wire Height In.
Virginian	1925–26	11,000	24	6
C. M. St. P. & P.	1915–19	3,000	24	2
Norfolk and Western	1915–25	11,000	24	0
D. L. & W.	1930–31	3,000	24	0
Great Northern	1927–29	11,000	24	0
Illinois Central	1926–29	1,500	22	0
N. Y., N. H. & H.	1907–27	11,000	22	0
Pennsylvania	1915–34	11,000	22	0
Reading Company	1931	11,000	22	0

This table suggests the following comments:

1. Safety clearances specified in 1914 are not required or the movement of trainmen on box cars is restricted.
2. If not already done, the A.R.A. should cancel their 1914 clearance diagrams and approve the 22-ft wire.
3. The 22-ft wire would offer no relief, as to collector design, to roads with 24-ft wire and the existence of 2 standard heights on the same road is questionable from a legal standpoint in case of damage suits.

Mr. Brown's statement about the lack of coördination of contact system and collector design is likely to be misleading. American collector designers who deal with high speed heavy traction have always dealt with contact system design and fittings, and have fully appreciated the necessity of such coördination for all classes of work. C. J. Hixson in a 1915 A.I.E.E. paper emphasized coördination. Our designers have been called upon to furnish collectors to work with systems designed and built by the railways and also to specifications furnished by the railways. The systems involve considerable variation in design detail, workmanship, track conditions, and maintenance of overhead and track, and specifications vary as to range, head-room, collecting capacity, pan lubrication, and sensitiveness. On account of relatively long and variable intervals between electrification projects and the other variables cited it is difficult for the designing manufacturer to justify investment in improvement research, which would properly be conducted under actual service conditions in each case. Furthermore it is difficult to fix upon a definite yardstick for measuring results obtained. In other words, just what strip or pan life and minimum contact wire life are considered satisfactory in each case?

The reference to an auxiliary pantograph carrying a collector shoe is presumably made to a device similar to the auxiliary bow commonly used on European collectors. The great value of this feature has been recognized but the added weight in combination with American requirements as regards range, clearances when at or near collapsed position, collection capacity, etc., do not favor its adoption. European conditions and practice permit the use of a bow fitted with aluminum contact strip and the common use of 2 collectors, with no reserve in case of wreckage. American specifications call for a single collector meeting the demands of the locomotive or car, with all the more difficult attending conditions. Even if American railways, in common, abandoned the reserve feature, the problem would still be a difficult one. The feature is important enough to justify exhaustive coöperative study on the part of the railways and designing manufacturers.

Messrs. Pickens and Brown consider the change in wire height, due to temperature change, and the rise in wire height due to direct collector pressure, all with 300-ft structure spacing and span length, as being objectionable, and the point is well taken. They do not, however, include the vertical movement of the contact wire, in fact, the entire assembly, in spans adjacent to locomotive or cars due to load being removed from the messenger by the collectors. The resultant movement and effect on collector are dependent upon length of span, speed, weight of catenary assembly, details of messenger suspension, and collector design. This movement may add to or subtract from that due to direct collector pressure in the adjacent span ahead. A combination of 300-ft structure spacing and 150-ft catenary spans mentioned by Mr. Brown with lifting hangers may go a long way toward solving the new high speed problem. This may increase cost but it also may not be unreasonable to expect an increase to meet the new conditions.

The use of lifting hangers for smoothing out the contact wire and improving collection has been advocated in the United States for many years, and they have been and are widely used in foreign countries. The engineers of the Reading Company are to be congratulated on having the initiative and courage to install a large mileage of lifting hangers and will in time be in a position to furnish valuable information on the subject.

Pantograph Trolleys
II—Operating Features

Discussion of a paper by B. M. Pickens published in the January 1934 issue, p. 190–4, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 451–2.

A. M. Wright: In view of the prevailing interest in high speed train operation, the Pickens paper is valuable as the first analysis of the mechanics of the pantograph that has appeared. If train speeds are to exceed,

80 mph the dynamic reactions between the pantograph and the contact wire become of the greatest importance, and it must be necessary to determine in advance what the behavior of the collecting system will be. To build an overhead system for operation at 100 mph, say, only to find that it is impossible to maintain contact with the wire, would be disastrous. Nothing is known of the conditions for proper stability of the contact system at such speeds. There is the well-known theory that a wave in the wire accompanies the pantograph at high speeds, but, at least in hot weather when the wires are slack, all the writer has been able to observe is a violent jiggling of the wires with certain types of construction. With other designs the wires seem to be fairly stable at all times. From observation alone, unbacked by any mechanical theory, the writer has come to the conclusion that the best system for high speed operation is the "simple" catenary with inclined catenary on curves, using wires as large as possible at as high a tension as possible.

The use of the simple catenary, comprising a single messenger and a single contact wire, raises the question of the desirability of flexibility in the hangers. American practice has been to use a loop type, or lifting hanger. The Reading Company has in operation about 87 miles of simple catenary on its main line electrified tracks near Philadelphia, over which speeds of 60 to 70 mph are regularly attained. To avoid damage due to arcing at the loop hangers, sleeves and jumpers are installed as has been described ("The Reading Railroad's Suburban Electrification," G. I. Wright. ELECTRICAL ENGINEERING, March 1933, p. 155–61). A similar type of construction is used on the Great Northern electrification ("Inclined Catenary on the Great Northern." *Railway Elec. Engr.*, April 1928) where, however, comparatively low speeds are encountered. Experience with the simple catenary on the Reading has been eminently satisfactory at all speeds, the smoothness of pantograph operation being superior to that of the compound catenary on the same railway. No evidence of burning at the loop of the hangers has been observed after 3 years of operation. In the writer's opinion, the fear of damage to the messenger due to arcing where lifting hangers are used is unfounded, at any rate where moderate currents are collected, and where jumpers are installed. Abroad, where simple catenary is more or less standard, the practice has been in some cases to use flexible hangers, and in others to clamp the hangers to the contact wire and messenger without any flexibility. While the train speed on the Reading electrified tracks is not particularly high in regular service, test runs have shown that good current collection can be obtained with the simple catenary up to 75 or 80 mph and the indications are that the system would be satisfactory at much higher speeds.

This would appear logical, inasmuch as jiggling and vibration of the contact wires with other types of construction are undoubtedly due to reflections and reinforcements of small waves. In any contact system, the analysis is complicated by the presence of the messenger. A vertical wave traveling along the contact wire will not have a uniform amplitude from span to span, but will induce a wave in the messenger. This wave in the messenger will be reflected at the end of the span and will induce a second wave in the contact wire, traveling in the opposite direction from the first. This second wave, meeting an oncoming pantograph at high speed, may cause the contact to be broken, with resultant arcing. The use of heavy wires and high tensions will reduce the amplitude of the waves (if they exist at all) and the use of as few wires as possible will eliminate some of the reflections and reinforcements.

In designing a pantograph for high speed operation, it should not be overlooked that the power required to move the pantograph through the air can become quite large. A standard pantograph for a contact wire height of 22 ft, for example, requires 73 hp at 100 mph, indicating a pressure of 274 lb on the frame. If speeds of the magnitude that are talked of today are to be realized, it will be necessary to shroud the base mechanism and to use a special cross section for the frame members. For high speed operation, the support of the contact shoe will require special attention. It is well known that the motion of an elongated body through a fluid will generate eddies, which in some cases cause oscillations of the body. Such oscillations cannot be permitted in a pantograph shoe without destructive arcing. A perfectly designed contact system will be unsatisfactory under such conditions, and even lubrication of the shoe will be of little use. The writer does not consider that the problem of current collection at high speeds is by any means solved, and a great deal of investigation is necessary before we can lay out an overhead system, and design a pantograph to collect current from it, with certainty that successful operation will result.

The last paragraph of the paper should be studied by all who contemplate high speed electric operation. The paper would have been more interesting had the derivation of the equation for the equivalent weight been given, and it should be supplemented by a paper analyzing the motions of a catenary system under the influence of a moving pantograph.

P. E. Wade: The upward camber in the collector shoe is a detail of design that has merit, as claimed by Mr. Brown, and is worthy of careful study in connection with collector design. This detail is used with practically all auxiliary bows on pantograph type collectors in Europe, and probably originated with bow collectors for tramways. Its application to present American designs would require some general changes to avoid an undesirable increase in distance between line of contact and axis of pan rotation.

If the collector leaves the wire, as assumed by Mr. Brown, protection afforded by the side guard is questionable as the guard would probably be wrecked by the first pull-off or steady device encountered, or the aluminum pipe burned and sawed through, creating more trouble than the horn alone. For low approach wires, however, these guards do function, the degree of protection being dependent upon height of contact wire and collector frame design which determines the angle between guard pipe and horizontal plane. Such protection should be very much in evidence on Cleveland Union Terminals with 18.5-ft wire height, and at points of low head-room on other roads.

Trolley Wire Lubrication Improved

Discussion of a paper by J. V. Lamson published in the November 1933 issue, p. 771–6, and presented for oral discussion at the transportation session of the winter convention, New York, N. Y., Jan. 23, 1934. Other discussions of this paper were published in the March 1934 issue, p. 449–50.

S. R. Negley: Mr. Lamson, by means of his tests, has proved a very good case against the use of copper wearing strips on copper contact wire unlubricated. However, his statement that "operation of any electric traction system without effective lubrication obviously would be destructive, unsatisfactory and costly," cannot be accepted as being developed by these tests. Most of us having to do with the operation of electric traction systems feel that lubrication of some sort is desirable. Frequently, due to steam operation over the same tracks, we believe it unwise to use a grease which might collect grit particles from locomotive blasts and result in an abrasive substance which would increase the wear on the wire.

The Reading Company has been operating electric multiple unit cars in their suburban service for nearly 3 years, and due to the presence of steam traffic have thought it undesirable to lubricate with the lubricants ordinarily used for this purpose. Cars were placed in service with pantograph strips of rolled steel, which collect current from a 55 per cent conductivity bronze contact wire. In certain sections of the line which we have had occasion to examine, after a period of 2 years during which time the wire was subjected to 88,000 pantograph passes the wear amounted to 1 per cent of the total area of the wire. The surface of the contact wire is smooth and polished a dark brown color, giving no evidence of the excessive abrasive action found by Mr. Lamson with his tests of copper on copper.

The several other points of difference between actual operating conditions and the test set-up are as follows:

	Reading Co.	Mr. Lamson's Test
Pantograph pressure per shoe per wire	18 lbs	7.5 lbs
Material of wearing strip	Steel	Copper
Contact wire	Bronze, 55 per cent cond.	H.D. copper
Av. current collected	70 amp a-c	200 amp d-c

The above table therefore, presents a wide field for additional tests, *viz.*, the effect of varying pressures, varying pantograph strip materials, and current densities per pantograph.

The effect of varying current densities may have had considerable effect in the results of Mr. Lamson's tests with the

solid graphite block, for it is conceivable that since no effort was made to insulate the block from the pantograph wearing strips, the decrease in current density may have contributed largely to the small amount of wear obtained.

The addition of a device for lubricating the contact wire in the manner suggested by Mr. Lamson tends to complicate and increase in weight a mechanism in which simplicity and lightness are paramount factors. I presume it can be shown that lubrication is desirable, but I believe the results of further tests could be made more valuable if an attempt is made to obtain lubrication by the application of dry lubricant between the pantograph wearing strips, thus eliminating additional complications to the pantograph itself.

Shunt Resistors for Reactors—II

Discussion and authors' closure of a paper by F. H. Kierstead and L. V. Bewley published in the March 1934 issue, p. 411–8, and presented for oral discussion at the transmission and distribution session of the North Eastern District meeting, Worcester, Mass., May 16, 1934.

C. W. McGill: There has been a wealth of calculation, testing data, and discussion stressing the increased surge voltages due to reflections and oscillations caused by the presence of inductance either in the form of choke coils, reactors, transformers, feeder regulators, or end turns of station equipment. The choke coils have been removed, the transformers have been redesigned to be "surge proof," and some of the reactors have been eliminated by changed ideas in station layout, such as more segregation, synchronizing at the load, transformer-generator units, circuit breakers of larger rupturing capacity, etc.; but there still remain many cases requiring reactors.

Surges do cause stresses and oscillations within the reactor, but external protective means are not justified with the present designs having sufficient mechanical strength, copper, and insulation.

As has been pointed out by calculation and by test, a resistor shunting the reactor tends to reduce the reflected and the transmitted surges; but, like so many other protective devices, each installation must be carefully studied to determine the economical justification.

Thus, for a station having only a few outgoing feeders, the shunting resistor does not reduce the reflected voltages, and dangerous potentials appear on the incoming line and bus. Lightning arresters on the lines would be necessary for their protection and, in turn, would also serve to protect the reactors and station equipment. The authors mention that this case may be disregarded, but there is a growing tendency to reduce the number of feeders directly connected to a bus section. Protection of the bus or station equipment in this case might be more economically obtained with bus lightning arresters or some type of wave modifier, such as a combination of shunting condenser and arrester or a Ferranti absorber. It must be kept in mind that when the voltages on both sides of the reactor, due to multiple reflections, are nearly equal, the thyrite resistor is of no aid, no matter what the value of the surges.

Stations having many feeders are not materially helped with respect to bus voltages by the shunting resistors due to the low surge impedance of the combination at the bus, but the incoming line carrying the surge receives some protection. Therefore, a comparison with arresters should be made. Considerable calculation would be required in such a study as the efficacy of the resistor reduces as the surge impedance at the station becomes smaller, as occurs with underground cable. As in other such problems, the previous history and records of faults on the station or lines in question, the type of service required, and the station design or method of operation must be considered in justifying the expense.

F. H. Kierstead and L. V. Bewley: Mr McGill in his discussion of our paper states that "for a station having only a few outgoing feeders, the shunting resistor does not reduce the reflected voltages, and dangerous potentials appear on the incoming line and bus." Referring to Table I of our paper it will be noted that for no outgoing feeders the bus voltage is reduced by the thyrite resistor from 1.77 to 1.05; for one outgoing feeder the reflected voltage is reduced from 0.97 to 0.72 and the bus voltage from 0.87 to 0.48; for 1.8 outgoing feeders the reflected voltage is reduced from 0.95 to 0.59 and the bus voltage from 0.55 to 0.39; and for 4.3 outgoing feeders the reflected voltage is reduced from 0.96 to 0.49 and the bus voltage from 0.39 to 0.26. This is a substantial reduction in voltage for a few outgoing feeders.

Mr. McGill states that "stations having many feeders are not materially helped with respect to bus voltages by the shunting resistors due to the low surge impedance of the combination at the bus, but the incoming line carrying the surge receives some protection." With many feeders and the proper thyrite resistors an impulse voltage passes through without appreciable reflection. Therefore, the impulse voltage on the feeder side of the reactor is reduced to approximately half the value it would have had if it had not been shunted by a resistor.

Mr. McGill also states that "protection of the bus or station equipment in this case might be more economically obtained with bus lightning arresters." It is true that more complete protection can be obtained by lightning arresters but at considerably greater expense, since the thyrite resistor is a very inexpensive device and, being installed in the center of the reactor, entails no installation charges. It should be realized that an arrester connected to the bus does not limit impulse voltages on the feeder side of the reactor and therefore to obtain protection on this side of the reactor with arresters it is necessary to install an arrester on each feeder. However, by shunting the reactor with a thyrite resistor a large measure of protection is obtained. The resistor thus permits the bus arrester to afford a much more extensive protection to the system.

Summarizing, the shunt thyrite resistor should not be used in lieu of but as a very effective supplement to the bus arrester.

Theory of Primary Networks—Part II

Discussion of a paper by F. M. Starr published in the March 1934 issue, p. 426–31, and presented for oral discussion at the transmission and distribution session of the North Eastern District meeting, Worcester, Mass., May 16, 1934.

C. A. Corney: It is believed that this paper will tend to dispel some of the uncertainty that has existed in the minds of those interested in the question of emergency unbalanced loading of network units with respect to its effect upon reserve transformer capacity. Certain limits have been established in the first portion of this paper which will serve as a guide in any economic evaluation of this subject in making comparisons with other methods of supply.

It is of interest to note that with, say, 4 per cent impedance mains, small network systems up to 8 units may be designed to balance the load evenly among the remaining units with one feeder out of service. In the larger systems, if feeders are interleaved, a 10 per cent maximum increase in load on any one unit may be expected with one feeder out of service, and if not interleaved, that is, if adjacent units are supplied from the same feeder, a maximum increase of about 30 per cent may occur. In actual practice the possibility of providing a certain amount of interleaving will likely occur accidentally so that the increase in load which might be expected can be assumed to lie somewhere between the limits of 10 per cent and 30 per cent.

It has been stated that bus differential protection can be provided if needed. It might not be amiss, however, to point out that it would be desirable before doing so to examine carefully the possibility of incorrect operations occurring on through faults because of the breakdown of current transformer ratio on high currents. In connection with this general type of protection, it would be extremely helpful if manufacturers would have available standard current transformer ratio curves up to 50 times full load or even more, instead of up to 10 or 15 times, as now supplied.

It has been fairly well demonstrated by operating experience that the relay equipment now available is adequate to provide proper selection when applied to a network system. There may be some doubt, however, as to the efficacy of the instantaneous reclosing cycle now being advocated when applied to a network system, inasmuch as the switch at one end of the network feeder might complete its round trip before the breaker at the other end opened, in which case there would be no initial interruption of the arc.

In considering the question of the coordination of fuses with relay settings, the relay equipment of network units may be required to conform to a particular relay curve having somewhat different characteristics from the present relay operating curves, in order to permit the various transformer and branch fuses to clear the trouble with the minimum circuit interruption. This phase of the network protection problem should be given careful thought by the designers of this equipment.

In connection with the derivation of the short-circuit current values on a network,

it may be of interest to remark that our engineers working independently on a particular problem obtained by the longhand method of calculation a value of 5,750 amp, and by means of the calculating table a value of 5,500 amp, which is a sufficiently close agreement for all practical purposes.

A Graphical Solution of Steady State Stability

Author's closing discussion of a paper published in the April 1934 issue, p. 566–8, and presented for oral discussion at the electrical machinery session of the North Eastern District meeting, Worcester, Mass., May 18, 1934.

H. B. Dwight: In reply to an inquiry as to why an adjusted value of synchronous reactance should be used: The reason is that it gives results which are usually nearer to measurements than those given by the "unsaturated" value of synchronous reactance, obtained by short-circuiting the machine at its terminals.

Table I—Maximum Power

	Unsaturated Sync. React. and Sat'n. Curve	Adjusted Sync. React. and Sat'n. Curve		Unsaturated Sync. React. and Air Gap Line
	kw	kw	kw	kw
Two dupl. mach..... 8 amp f.c. Table I[1]	136 ..	260 ..	287[4]..	377
Two dupl. mach..... 9.4 amp f.c. Table III[1]	86 ..	146 ..	137 .. (Test)	304
Gen., sync. cond., and load[2].....	50,000 ..	81,300[3]..	80,400[5]..	170,000

1. A.I.E.E. Trans., 1926, p. 1.
2. A.I.E.E. Trans., 1924, p. 98.
3. *G. E. Review*, Dec. 1932, p. 614.
4. Calculated by Nickle and Lawton.
5. Calculated by E. B. Shand.

In Table I are shown 3 cases of maximum power, each calculated by 3 ways of using synchronous reactance. The first, and oldest way is to use the "unsaturated" value of synchronous reactance, and to take the excitation voltage from the no-load saturation curve. The second way is to use adjusted synchronous reactance as in Appendix A of my paper, and the third way is to leave out saturation completely, using the unsaturated synchronous reactance and taking the excitation voltage from the air gap line. The first way gives too small a value of maximum power and the third way gives too large a value, unless the field current is small, such as that required for no load.

Other useful problems are to calculate the power angle and the rate of change of power angle. However, if a method of calculation gives an error in the maximum power, it will almost inevitably give a similar error in other power calculations. For instance, the curve of kilowatts and angle for a uniform air gap machine is often practically a sine wave, and if the height of the sine wave is 40 per cent too great, then all other readings from the curve will be 40 per cent too large.

The complete vector diagram involving armature ampere turns cannot be used directly if the field current is specified in advance. Methods of solution of steady-state problems by families of curves, as used by E. B. Shand and Nickle and Lawton in the papers referred to in Table I, and by O. G. C. Dahl in his book "Electric Circuits," have good accuracy, as has also Professor Dahl's synchronous reactance method described in Electrical Engineering, April 1934, p. 604. A method will shortly be published by C. Kingsley, of Massachusetts Institute of Technology, which does not sacrifice accuracy and which gives good promise of shortening the time of computation materially.

The alternative method of computing the general contents of a transmission system, published in A.I.E.E. Trans., v. 41, 1922, p. 781–4, and mentioned in my paper, is for series connections and not for the calculation of branches in parallel.

Irregular Windings in Wound Rotor Induction Motors

Discussion and authors' closure of a paper by R. E. Hellmund and C. G. Veinott published in the February 1934 issue, p. 342–6, and presented for oral discussion at the electrical machinery session of the North Eastern District meeting, Worcester, Mass., May 18, 1934.

P. L. Alger: I have been interested in the theory of irregular polyphase windings for many years, and have tried to develop systematic methods of determining the optimum distributions for least reactance, least magnetic vibration, least unbalance, and least stray load losses. Prof. A. A. Bennett has worked with me in this field, and has derived some very interesting results, but we have never been sufficiently satisfied with their form to publish them.

Of the published methods for calculating the differential leakage reactance, I have found that given by Chapman in his "London Electrician" article of 1916 the most satisfactory, as developed (p. 508) in my paper "The Calculation of the Armature Reactance of Synchronous Machines" in the A.I.E.E. Trans., v. 47, 1928, p. 493–513. My conclusions at that time were that the differential leakage for a regular 3-phase winding is best calculated by formula 17a, and that the leakage for an irregular balanced winding can be taken as roughly twice that given by this same formula (p. 503). This formula gives for the regular 6-pole, 3-phase, 36-slot, $^5/_6$-pitch stator winding of the motor described in this paper a differential leakage reactance equal to

$$X_D = \left(\frac{13\pi^2}{9}\,\frac{\sin^2\frac{\pi}{12}}{\sin^2\frac{5\pi}{12}} - 1\right)X_M = 0.023X_M$$

where X_M is the magnetizing reactance of the motor per phase.

For the balanced, irregular, 27-slot, $^5/_9$-pitch rotor winding, the formula gives

$$X_D = \left(\frac{425.2\pi^2}{486}\,\frac{\sin^2\frac{\pi}{9}}{\sin^2\frac{8\pi}{9}} - 1\right)X_M = 0.040X_M$$

and we may take twice this, or 0.080 X_M, as the expected result.

For the irregular, unbalanced, 24-slot, full pitch rotor winding, the formula gives

$$X_D = \left(\frac{178\pi^2}{243}\sin^2\frac{\pi}{8} - 1\right)X_M = 0.058X_M$$

The fact that this winding is unbalanced as well as irregular will appreciably increase the differential reactance, so we may arbitrarily take the expected result as 2.5 times this, or 0.145 X_M.

From the test power factor and impedance results given in the paper, I estimate the no-load current of the motor must have been close to 2.5 amp, giving a magnetizing reactance per phase wye of 52 ohms. On this basis, the total differential leakage reactance of the motor with the 27-slot rotor in place should have been

$$(0.023 + 0.080)(52) = 5.4 \text{ ohms}$$

and with the 24-slot rotor

$$(0.023 + 0.145)(52) = 8.7 \text{ ohms}$$

which compare with the total reactance values derived by the authors from breakdown torque tests of 6.6 and 9.8 ohms, respectively. The relatively small slot and end leakage reactance, which should be the same for both rotors, readily accounts for the difference of 1.2 ohms between the calculated and test results.

No claim is made that this method of calculating the differential leakage reactance is accurate, since the arbitrary factors of 2 and 2.5, respectively, are used regardless of the many variations in winding distribution pattern that can be selected. The check is sufficiently close, however, to show that the previously published article affords a practical means of estimating the performance of such irregular windings.

C. J. Koch: Although the subject of irregular windings has received considerable attention in the past, the same study has not been extended to those windings which are unbalanced as well as irregular. The present paper constitutes an addition to this study.

When the number of poles, slots, and phases is such that the winding will be unbalanced as well as irregular, there are a great many possible groupings of the stator coils. In the past the designer has usually striven to arrange this group so that the 3 phases are as nearly as possible displaced 120 electrical degrees from one another.

There is a growing realization that a winding so distributed is not always the best, as it is often more desirable to minimize the additional differential leakage reactance and to minimize the noise.

In general, the differential leakage reactance of any winding may be defined as the sum of the magnetizing reactances of all the harmonic fields produced. As an alternative to the method described by the authors, the additional leakage reactance of an irregular winding may be calculated by determining the pitch and distribution constants of all harmonic fields produced, and then summing up their magnetizing react-

ances. This method is somewhat laborious but it has the advantage that it gives at the same time an idea of the relative magnitudes of the harmonic fields that will be present. This is a decided advantage in passing judgment on the noise qualities of the motor which will result. For example, in laying out a 12-pole, 120-slot, 3-phase winding, from the point of view of quiet operation, it is much more important to minimize the 8-, 10-, 14-, and 16-pole fluxes than it is to balance up the 3-phase currents exactly.

At the present time, when the designer is being called upon more and more to improve characteristics without the use of additional material, and to reduce the noise produced by motors, there results a growing tendency to increase sufficiently the variety of punchings used to eliminate windings of the irregular unbalanced type.

C. G. Veinott: Mr. Koch and I are in complete agreement on the fact that the presence of only a slight voltage unbalance in an irregular winding is not a reliable indication that the winding is satisfactory and also we are in agreement that there is a growing tendency to discontinue the use of irregular unbalanced windings.

Mr. Koch, by his definition, includes the zigzag leakage in the differential leakage. There has been much confusion on this subject because some authors do not include the zigzag leakage and others do. Mr. Alger, in his 1928 paper on synchronous machine reactance, considers air gap leakage as being made up of 2 components, namely, zigzag leakage and belt leakage.

Mr. Hellmund and I have brought out that in the case of irregular windings, there is yet a third component of the air gap leakage which, to our knowledge, has never before been mentioned in literature. This might well be called irregular distribution leakage; and how to calculate its exact magnitude may well be left for future investigation.

The following distinctions between the 3 components of air gap leakage should be noted. Zigzag leakage varies cyclically through a slot pitch (unless the effect is averaged out by skewing). Belt leakage, as commonly understood, varies cyclically through a phase belt. The irregular distribution leakage varies cyclically through a greater distance; it may be a pole pitch or even a complete revolution of the rotor, if both windings are irregular. Another distinction is to be noted: while zigzag and belt leakage vary with rotor position, they do not unbalance the phases as does irregular distribution leakage. Irregular distribution leakage is present in both the 27-slot irregular balanced winding and the irregular, unbalanced 24-slot winding though, in the former case, for practical purposes it is negligible.

Mr. Alger mentions his formula for calculating the differential leakage of a regular polyphase winding, a formula he developed in 1928 for his paper on synchronous machine reactance. I think he must have made a slight error when he calculated the differential leakage coefficients for fictitious regular 27-slot and 24-slot windings, for his figures of 0.040 and 0.058 would apparently indicate a difference of 45 per cent in differential leakage due solely to this slight difference in number of slots and chording. I compute coefficients of 0.0500 and 0.0587 for the 27- and 24-slot windings, respectively, when I use his formula.

Mr. Hellmund published figures on differential leakage coefficients in regular polyphase windings in his E.T.Z. article of 1909 (see reference 5). In this article, Mr. Hellmund does not include the zigzag as a part of the differential leakage. I calculated the zigzag leakage by means of Adam's formulas (see reference 1) in order to compare Mr. Alger's and Mr. Hellmund's figures. An interesting comparison of the total air gap leakage coefficient as computed by the separate methods of Adams in 1904 and Hellmund's in 1909 with Alger's formula published 19 years later is given in Table I.

Table I

	With 27-Slot Rotor	With 24-Slot Rotor
Zigzag coefficient (Adams)	0.0550	0.0680
Belt leakage coefficient for stator (Hellmund)	0.0055	0.0055
Belt leakage coefficient for rotor (Hellmund)	0.0070	0.0075
Total air gap leakage coeff. (Adams & Hellmund)	0.0675	0.0810
Diff. leakage of stator (Alger)	0.0230	0.0230
Diff. leakage of rotor (Alger)	0.0500	0.0587
Total air gap leakage coeff. (Alger)	0.073	0.0817

The check is truly remarkable! The figures given by Hellmund and Adams show that in these cases more than 80 per cent of the "air gap leakage" is due to zigzag. Mr. Alger's figures show that in both cases, the rotor contributes twice as much as the stator to the "air gap leakage."

I do not think that any multiplying factor should be applied to the 27-slot winding but that Mr. Alger's suggested figure of 2 might be applied to the 24-slot winding. On this basis, I find the calculated leakage reactances in ohms to be as follows:

	27-Slot Rotor	24-Slot Rotor
Magnetizing reactance	47.40	44.20
Slot & End Leakage	2.54	2.74
Stator "diff. leakage" (Alger)	1.09	1.02
Rotor diff. leakage	2.37	5.20
Total	6.00	8.96
Test Reactance	6.60	9.85
Difference	0.60	0.89

The slight difference between tested and calculated results is more than explained by the skewing of the rotors. So, therefore, the additional results given above further corroborate our conclusions given in the paper that the differential leakage of the 27-slot winding, despite its irregularity of distribution, is not appreciably different from what it would be if it were a regular winding in 27-slots, but the 24-slot winding has a large component of differential leakage which would not be present in a regular winding. The paper gives means for predicting when large additional leakage is to be expected and some idea, by comparison with the differential leakage for an equivalent regular winding, how large this additional leakage may be.

Stray Load Loss Test on Induction Machines

Discussion and authors' closure of a paper by T. H. Morgan and P. M. Narbutovskih published in the February 1934 issue, p. 286–90, and presented for oral discussion at the electrical machinery session of the North Eastern District meeting, Worcester, Mass., May 18, 1934.

P. L. Alger: I welcome this paper, as I believe the college laboratories can contribute much to the electrical industry by undertaking more searching and making analytical measurements of the power losses in machinery. Under the pressure of commercial requirements in industry, there is a tendency to be impatient of details, and to rest content with superficial methods so long as there is no obvious commercial advantage to be gained by greater precision. The student seeking knowledge regardless of its immediate commercial value, by examining into details of the most familiar processes, can often discover more new and useful information than by any amount of searching in entirely new fields.

Professor Morgan's paper is particularly timely, as it is presented just when committees of the N.E.M.A. and the A.I.E.E. are endeavoring to formulate a test code including practical methods for measuring stray load losses in induction machines. Up to the present time, these very elusive losses have been neglected in the Institute Standards, simply because there was no convenient means of determining them. While the value of stray loss found in the motors tested by the authors is very much higher than in usual designs, the fact that stray load losses of 1 per cent in large machines and up to 4 per cent in small motors are commonly present shows that it is desirable to include them in all efficiency determinations.

There are 2 fundamentally distinct methods of measuring stray load loss. One is to measure the loss exactly as it occurs under operating conditions, by means of input-output or other direct loading tests. All such methods involve difficulties and inaccuracies, because the result must be obtained by measuring a small difference between the quantities. The simple dynamometer test, in which the motor input is measured with wattmeters and its output by torque and speed measurements, involves numerous sources of error and is satisfactory only for small machines. By repeating the dynamometer test with power flow reversed, using the motor as a generator, and averaging with the results of the motor test, the errors can be greatly reduced. In this way, for example, if the mechanical power as measured is too low, or the electrical power too high, the motoring losses will be higher and the generating losses lower than their true values, but the average will be closely correct. By the authors' pump back scheme the errors are further reduced, since all power measurements are made with the same meters. In our experience, the greatest accuracy with direct measurements has been obtained by a pump back test, in which the duplicate machines are rigidly connected on the same shaft and

are fed from two sources of power of slightly different frequencies.

A fundamentally different method is to measure exactly an artificially produced loss that is nearly the same as the actual stray load loss. This can be done, for example, by measuring the rotational loss produced when the machine is excited with direct current and separately driven. This "short circuit core loss" method is used with excellent results on synchronous machines, and in our experience has been found very satisfactory for induction machines also. Tests have indicated in fact that the stray load loss produced by a given current is very nearly the same over a wide range of impressed voltage and flux of the machine.

While the layman will naturally prefer the former method, thinking the test inaccuracy less objectionable than an unknown discrepancy between the real and the equivalent loss, the designer will often prefer the latter method, which gives a definitely repeatable result.

The new test code in process of formulation should rightly include each of these methods of test for use and its proper range of application. It is to be hoped, therefore, that others will follow Professor Morgan's example of making directly comparable tests by various methods, so that the industry may soon develop confidence in and actually adopt stray load loss measurements as a regular part of efficiency determinations.

P. M. Narbutovskih: I would like to make a few comments concerning the method of dividing the stray load loss between the 2 machines. Of the 2 methods suggested in the paper, the graphical one is the most accurate for, assuming an accurate draftsmanship, any desired precision in the final curve E (Fig. 2) can be obtained by successive approximations; yet in engineering practice it may appear somewhat long and cumbersome. Besides, it requires a continuous curve representing the stray load loss as a function of the sum of machine currents. In view of this the remarks I wish to make concern the value of the numerical method suggested in the paper, where the stray load loss is assumed to be proportional to the square of the load current. This method is quite simple and the stray load loss can be divided even if only one value of it for some particular value of load is available.

On the basis of the above assumption the division of load between the 2 machines can be obtained from the following relations: for certain values of the motor load current (I_m), and the generator load current (I_g) let the value of the stray load loss in both machines be $A = L_m + L_g$. Then we can write 2 simultaneous equations:

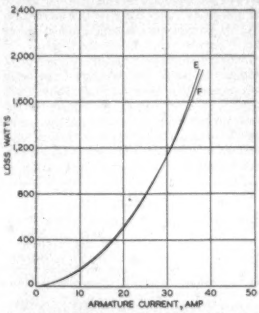
$$L_m + L_g = A$$

$$\frac{L_m}{L_g} = \frac{I_m^2}{I_g^2} = K^2$$

Solving these equations for L_m,

$$L_m = \frac{AK^2}{1 + K^2}$$

A curve of the stray load loss (curve F) as a function of current obtained by this method is shown in Fig. 6. Curve E is obtained by the graphical method as described in the paper, and is plotted here for comparison. As may be seen from the graph, the difference between the 2 curves is quite small. Expressed numerically it is of the order of 50 watts maximum for the



Comparison between curve of stray load loss obtained by 2 different methods

highest load, which constitutes approximately 3 per cent of the stray load loss, 1.7 per cent of the total loss, and 0.5 per cent of the motor efficiency. It appears that, for the particular motor considered, the discrepancy is within the limits of engineering accuracy. In case of motors with a low value of stray load loss the numerical method of loss division will, in all probability, give practically the same value of motor efficiency as a graphical one. To reach a more definite and more general conclusion concerning the validity of the numerical method of loss division, more tests with motors of various sizes and types are necessary.

Transformer Reactance and Losses With Nonuniform Windings

Discussion and authors' closure of a paper by H. O. Stephens published in the February 1934 issue, p. 346–9, and presented for oral discussion at the electrical machinery session of the North Eastern District meeting, Worcester, Mass., May 18, 1934.

A. Boyajian: Judging by the eminently readable style of the mathematical paper by Mr. Stephens (with not a single equation in it), one would hardly suspect the fact that it is a major contribution to the mathematics of reactance and as such, deserves to be studied in academic halls just as much as in engineering offices. It opens up a new field of mathematical research for engineering instructors and students, and may well form the subject matter for many theses. I wish, therefore, to make some comments that may be helpful to those who may wish to undertake such research.

The method of calculation outlined by Mr. Stephens is not merely some little trick applicable to leakage reactance of concentric transformers, but is a method broadly applicable even to the self-inductance problems in which there is apparently no question of leakage between 2 coils carrying opposite currents. For instance, if a solenoid is wound like a helix with considerable pitch, so that the space between adjacent turns may not be ignored in the calculation of self-inductance, or again, if a cylindrical winding consists of a stack of disk coils with ventilating ducts between the disks, the effect of the gaps on the self-inductance of the winding can be calculated by resolving the winding into 2 components, one a uniform solenoid with no gaps, the other an interleaved transformer with alternate positive and negative ampere turns, in accordance with the method outlined in the paper. If classical methods are attempted, the calculation is very complicated, the complication increasing with the square of the number of the breaks in the solenoid.

It is noteworthy that Mr. Stephens' method is particularly simple and attractive for numerical work in precisely those cases in which mutual inductance formulas would be most laborious. The converse is also true. Thus, when the cylindrical winding has considerable thickness, mutual inductance calculations for the different portions of the solenoid are extremely laborious, while leakage inductance calculations are relatively simple; whereas, if the cylinder is very thin, mutual inductance formulas would not be so laborious to apply, while accurate leakage inductance calculation would be made difficult.

In order to avoid futile efforts at impossible applications, it may be well to point out that the very heart of the method is the resolution of the magnetic field into 2 mutually perpendicular components. Consequently, the method *in its simple form* is not applicable if it is attempted to obtain 2 concentric components (or 2 interleaved components). The justification of the method in simple terms is that there can be no mutual effect between 2 components whose axes are at right angles to each other. This condition cannot be satisfied unless one component is axial, the other transverse. But if 2 concentric (or 2 interleaved) components are attempted, their axes will be parallel, and there will be mutual reactance between the 2 components, which must be calculated and included in the total reactance.

This method is found particularly useful whenever magnetic materials (like transformer core) are in the neighborhood of the coils; it is so very much easier to take into account such effects on longitudinal and transverse components, than on the unsymmetrical coil arrangement directly.

An interesting and useful academic problem would be to determine the formal limits or conditions of the validity of the method as a broad mathematical method. Another interesting theoretical problem would be to analyze the transverse component of the magnetic field of a simple cylindrical finite solenoid in terms of Mr. Stephens' conceptions, and develop or reformulate appropriate inductance formulas.

E. A. Church: It would be of interest to operating engineers to have a simple formula, even though it may only be approximate, for determining the copper

loss in transformers operating on various tap connections when the copper loss on full winding only is known. Such a formula is suggested as follows:

$$P = X(P_1/X^2) = P_1/X$$

where

P = rated load copper loss in tapped winding
P_1 = rated load copper loss in full winding
X = fraction of winding in operation

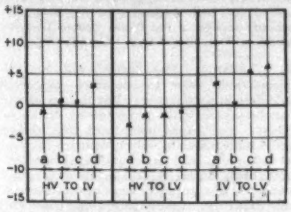
The above formula neglects any eddy current losses in the inactive part of the winding, or any change in eddy current losses in the active part caused by the irregularities of the windings.

It would be of interest to have the author give an opinion as to the maximum error which would be likely to be made by using the above formula or suggest one which would be more accurate and yet could be applied with a reasonable amount of labor.

H. B. Dwight: The "cross-flux" method of H. O. Stephens is a very ingenious and useful way of dealing with transformers. While it is characterized by simplicity, its accuracy has been tested by longer alternative calculations. It improves the calculation of reactance and eddy current loss of practical transformers for which apparatus there is distinct necessity for this type of calculation. It does more than that, for it leads directly to the device of thinning out the turns opposite the tap sections, as illustrated in Fig. 4 of Mr. Stephens' paper, and in this way the cross flux method leads to improved apparatus as well as to improved calculations.

A. N. Garin: In common with many other impedance problems, the problem forming the subject of this paper can be analyzed using 2 fundamentally different methods, the so-called "field" and "circuit" methods. The paper itself and the discussions by A. Boyajian and by Prof. V. Karapetoff employ the "field" method of attack, which is well suited for the purpose of visualizing the physical phenomena responsible for additional reactance and eddy current losses. If, however, a quantitative analysis is desired, the "circuit" method of attack may be found to be preferable. Thus, it can be shown that in addition to the concentric and interleaved components taken into account by H. O. Stephens' method, the total or effective reactance of concentric windings with nonuniform ampere turn distribution contains what may be called a "diagonal" component. While the concentric and the interleaved components are always additive, the diagonal component may be either additive or subtractive. The absolute magnitude of the diagonal component depends on the proportions and configuration of windings and for winding arrangements considered in the paper it is negligibly small. This establishes both the validity of H. O. Stephens' method of reactance calculation when applied to concentric windings with nonuniform ampere turn distribution and its limitations when applied to other groupings of windings.

From a practical standpoint the importance of the method suggested by Mr. Stephens lies in the fact that no matter how unbalanced and nonuniform the distribution of ampere turns in concentric windings, the reactance and the eddy current losses can be calculated with good engineering accuracy using only well-known and very simple formulas developed years ago for uniform concentric and interleaved windings. Only in exceptional cases, when still higher accuracy is desired, recourse must be had to more elaborate methods.



Per cent deviation of tested from calculated reactances showing accuracy of H. O. Stephens' method of reactance calculation as applied to 2-winding reactances of a 3-winding transformer with taps in all windings. Standard N.E.M.A. tolerance for 3-winding transformer = 10 per cent

a. Both windings connected for maximum turns
b. Primary maximum turns; secondary minimum turns
c. Primary minimum turns; secondary maximum turns
d. Both windings connected for minimum turns

The accompanying figure gives an idea of the accuracy of reactance values calculated by H. O. Stephens' method. The deviations of tested from calculated values are seen to be well within the standard N.E.M.A. tolerance for impedance of 3-winding transformers. In any reactance calculation there must be of course a comfortable margin between the accuracy of calculation and the maximum permissible deviation of tested from desired values because neither commercial tests nor the mechanical assembly of transformers are mathematically exact.

H. H. Wagner: The calculation of the leakage flux circuit in transformers and of its effect on the reactance and eddy current loss has been, perhaps, the most elusive problem of transformer designers, and only gradually have the methods of such calculation been developed and improved. In this paper, Mr. Stephens has made one of the most important and practical contributions to transformer literature in recent years. His unique method of resolution of leakage flux into 2 perpendicular components should find wide application among transformer design engineers, since the circular concentric coil construction is used in the majority of modern power transformers and is rapidly coming into favor also in distribution transformers. The paper, appropriately, points out in a concise and clear manner some of the fundamental differences in the concentric and interleaved types of construction, and some of the basic reasons why a concentric transformer is inherently more rugged and simple than an interleaved transformer.

Although the method of reactance calculation is quite comprehensive, I believe that Mr. Stephens might be a little more specific in the application of interleaving reactance calculation, particularly with reference to obtaining the length of leakage path, since the conventional formula for this is usually not so accurate with the long and slender proportions of the "interleaved groups" which would occur in this method applied to the concentric winding. However, it is evident that a considerable per cent of error in the interleaved component would usually result in only a comparatively small error in the total reactance value since the interleaved component will usually be of the order of 10 per cent of the total reactance.

It seems that mention might also be made of what value to assign to the thickness of barrier between the interleaved groups; it would appear to be logical to use a value of zero for this term in the conventional formula.

I believe that there is an error in the ratio given in step 5 of the method originally published; if the interleaved reactance component is calculated by using the total turns in the winding, it should be multiplied by the ratio $\left(\frac{\text{interleaved effective turns}}{\text{total effective turns}}\right)^2$ in order to convert it into percentage of line voltage.

H. O. Stephens: Mr. Boyajian's suggestion that a similar method of calculation might be used to determine the inductance of a solenoid or reactor having nonuniform distribution of turns and with appreciable radial build of windings appears to be sound. With equally accurate formulas for self- and mutual-inductances and for reactance of interleaved windings it appears that the conventional method and the proposed method would yield equally accurate results. In order to check the accuracy of the method suggested by Mr. Boyajian, as applied to inductance I took the simple case of a 3-phase reactor with the phases coaxially mounted but connected in series and considered as one single-phase reactor. The insulation breaks between the middle and end phases constitute the irregularity. The calculated inductance by the conventional method was 1.2 per cent higher than the tested inductance and the calculated inductance by the proposed method was 0.8 per cent below the tested inductance. Either method is sufficiently accurate for all practical purposes and the method to be selected would probably be decided principally by the relative familiarity of the calculator with the 2 methods as well as the degree of irregularity of the winding of the reactor.

Mr. Church suggests a simple formula for determining the impedance loss of a transformer operating with one of its windings connected on a tap when the impedance loss is known only for the full windings.

Any formula which does not take into account the peculiarities of the design, the irregularities of the windings, and the eddy current and stray losses can give only a rough approximation of the true losses. However, where operators desire this information quickly extreme accuracy probably is not required and the following formula will give a rough approximation of the required losses:

$$W_T = \frac{XW + W}{2X}$$

where

W = impedance watts on full windings
W_T = impedance watts on desired tap
X = fraction of tapped winding in operation

This formula assumes that the impedance losses are equally divided between the 2 windings (seldom correct) and that the eddy current and stray losses are the same proportion of the total impedance watts on the tap as on the full winding (also seldom correct).

Mr. Garin's extreme case of the 3-winding transformer reactance shows that the method may be used to give commercially accurate results even for great irregularities, and it is very gratifying to find that this simplified method yields such accurate results for extreme irregularities.

In preparing the paper all reactance formulas have been purposely omitted. There are so many details to cover that the paper otherwise would have been hopelessly involved and probably less valuable. The paper presupposes that the designer has proper formulas for the calculation of interleaved and concentric reactances and that these give proper weight to long slender and short thick coils. In most cases the thickness of the barriers between the groups of the resultant interleaved components will be zero as Mr. Wagner suggests. Step 5 on p. 347 is correct for the conventional formulas that I use, which give the reactance in per cent of the voltage considered. The paper gives the method to be employed in resolving the reactance into the concentric and interleaved components. The designer must rationalize the method to suit his particular reactance formulas.

Professor Karapetoff has suggested that unless one were very familiar with calculating transformer reactances he might be very much at sea in attempting to apply the proposed method. This is absolutely true. The method presupposes a thorough knowledge of the conventional methods of calculating interleaved and concentric transformer reactances so that the designer may use good engineering judgment in applying the proposed method. Professor Karapetoff also has suggested that the method might be used to advantage in determining the reactance between certain unbalanced windings of induction motors. There are so many points of similarity between transformer and induction motor theory that one is tempted to extend the methods employed in calculating one over to the other. In this case I would prefer to leave the answer to this question to the induction motor designer who undoubtedly has short cut methods of his own to solve his particular problems.

Distance Relay Action During Oscillations

Discussion and authors' closure of a paper by E. H. Bancker and E. M. Hunter published in the July 1934 issue, p. 1073–80, and presented for oral discussion at the selected subjects session of the North Eastern District meeting, Worcester, Mass., May 16, 1934.

F. J. Adams: This paper will be of considerable value to operating engineers in determining whether or not their systems can be satisfactorily protected by distance relays. The paper points out that there are conditions under which distance relays, as now used, may cause undesired breaker operations, during system swings or oscillations. It also suggests ways of overcoming this difficulty. One cannot avoid the feeling, however, that distance relays are not the ultimate solution of transmission line protection. The idea of some sort of differential relaying, using pilot wires or carrier current pilot circuits, still seems to offer some hope. Is it not possible that the development of thermionic vacuum tubes may lead to the development of some type of relay not now contemplated? To sum up, it seems that the door of opportunity is still open for the development of a system of protection for transmission lines more satisfactory than any now in use.

G. A. Powell: This paper is a very timely addition to distance relay literature. The curves shown on Figs. 8 to 12 will materially reduce the calculations necessary to determine whether or not distance relays in a given location are liable to cause unnecessary tripping. The relaying of the interconnection between the New York City system and the Niagara-Hudson system involved the study of this problem. A large number of curves almost exactly like the ones shown on Fig. 5 of the paper were drawn. These curves showed conditions for different circuit loads both above and below the transient stability limits for different types of faults. A study of these curves showed that if distance relays were used at all of the stations on the 2-circuit interconnection, unnecessary and undesirable separations would occur under oscillating conditions on the remaining circuit immediately following the tripping of one of the circuits due to a fault.

Various modified schemes of directional relaying were studied including a combination of distance directional and standard power directional relays which limited the phase angle through which the distance relay could trip its switch. In addition, the distance relay was to be designed so that, after a definite time delay, the angle through which it normally operated was automatically changed in an effort to prevent its operation during load swings. This scheme appeared fairly satisfactory except that under some out-of-step conditions, tripping would occur at stations where it was not desired to trip. Furthermore, correct operation of this scheme involved a race between the different relays with small margins of time and phase angle.

From the knowledge gained in the above study, I am not sure that the authors' proposed use of a true power relay as a blocking relay, even if its action is delayed, will make it desirable to use distance relays in all cases. In practical application it will be difficult to obtain a watt and a time setting for the blocking relay which will give the desired results, particularly where relays must be set to give satisfactory protection with single line operation as well as double line operation. I believe it highly desirable to separate at some predetermined point depending upon system connections, and for this reason agree with the authors that for automatically separating under out-of-step conditions the use of an out-of-step relay especially designed for the purpose offers the best solution. Having provided this relay for out-of-step tripping at a predetermined point, it would be highly objectionable to have the distance relays at some other station trip at the same time as the out-of-step relay.

The use of the carrier current pilot relaying scheme appears to offer the most dependable relay scheme for protecting important circuits which are subject to oscillating and out-of-step conditions. The addition of an independent out-of-step relay to the standard directional relays controlled by carrier would make this scheme almost ideal.

G. W. Gerell: Previous to the construction and interconnection of the Osage Hydroelectric plant in 1931, experiences with unstable systems had been rather meager. It was well recognized that we would not be immune to these troubles unless proper remedial measures were taken to eliminate them. All new circuits and equipment were, therefore, provided with high speed relays and oil switches, and all of the existing circuits comprising the major transmission system were similarly equipped. It was believed that high voltage buses and radial feeders should also be provided with high speed protective equipment, but it could not be economically justified at that time.

For reference in the following discussion a one line diagram of the major 60 cycle transmission system is shown (Fig. 1). During the last 3 years of operation of this system there have been 3 cases of trouble resulting in an unstable condition. In all 3 cases the fault occurred on the 66-kv system, one also involving the 13.8-kv system at the Page Ave. station, and under such conditions that the high speed relays did not have an opportunity to function. The faulty circuits in each case were properly isolated, but, in addition, the impedance relays on the Osage-Page lines operated to clear this circuit at both ends. The reactance relays at the Cahokia station on the Rivermines lines also operated in 2 instances.

The results of an a-c calculating board study for one particular case showed that the system actually became unstable. Determination of current and voltage relations at the relay stations explained the operation of the impedance relays on the Osage-Page lines and also the operation of the reactance relays on the Rivermines lines at Cahokia. All instability cases which we have experienced have occurred for faults electrically close to the Venice station, and in each case the distance relay operations have been identical and at relay stations nearest

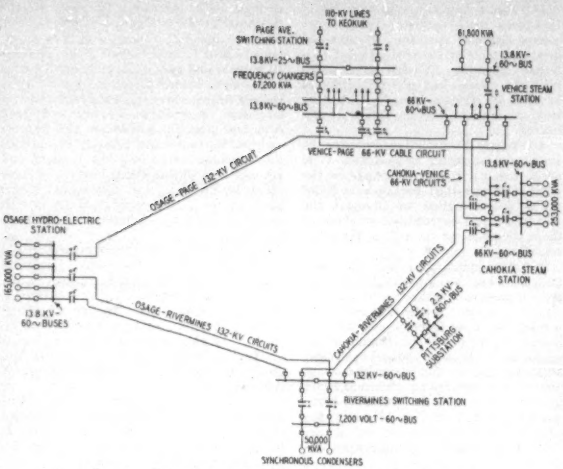


Fig. 1. General plan of the 66- and 132-kv transmission systems

to the fault, although outside of the section upon which the fault occurred.

In order to prevent the recurrence of such troubles on our system, we have endeavored to provide high speed relay equipments at all points which were not previously equipped at the time of the Osage interconnection. This included the installation of differential protection on the 66-kv buses at Cahokia and Venice and the installation of high speed ground relays to a number of radial feeder circuits from these buses. A number of other improvements have been made on the relay system, particularly in regard to the high speed protection of transformer banks.

At the present time, our protective equipment will, with very few exceptions, clear faults on the 66- and 132-kv systems in less than 0.3 second. Most transmission line faults are isolated in 0.15 second with negligible disturbance to the system. Stability studies substantiated by recent experiences indicate that switching times of this order are amply fast to prevent instability of the system during fault conditions. Incidentally, it is of interest to note that several automatic oscillographs located at strategic points have been invaluable in providing us with data concerning instability phenomena and have been the basis upon which several improvements were made to the relay system.

H. R. Stewart: May I call attention to an additional matter which has been experienced on one or 2 systems when an unbalanced fault on a low tension bus or feeder has been delayed in clearing, with the result that the 2 ends of the system reached a 180 deg out-of-phase condition before the fault was cleared. Under this condition the positive sequence voltage at one end of the system is opposite and approximately equal to that at the other end of the system and passes through zero at the electrical center; the negative sequence voltage is zero at the 2 ends, and is a maximum at the point of fault. Therefore, there is a zone where the negative sequence voltage exceeds the positive sequence voltage, giving the effect of reversed phase rotation of the voltage. The result of this is incorrect operation of one or more of the relay directional elements at each line terminal in this zone, with consequent increased undesirable tripping of breakers if the associated distance elements are also in position to trip.

I note that in comparing the action of reactance and impedance relays under out-of-step conditions, the authors use a setting on the impedance relay of equal sensitivity to that of the starting unit of the reactance relay. In view of the fact that in practice the starting unit of the reactance relay is set to reach out over approximately $2^1/_2$ line sections, and is thus set more sensitively than an impedance relay which is set to reach out over 80 per cent of a line section, is the comparison of practical value? Should not the comparison be made on the basis of settings which would be used under operating conditions?

Giuseppe Calabrese: The rapid increase in the number of interconnections which has taken place in the past years has made it evident that protective relays should operate correctly, not only during faults, but during swings and out-of-step conditions as well. Thus it is gratifying that a paper such as the one presented by Messrs. Bancker and Hunter should be submitted before the Institute. The analysis made during the past 10 years of the problem of stability and the factors affecting it has led to operating improvements and increased service continuity. The stability analysis, however, has stopped at the point where the machine either remains in step or loses synchronism. To my knowledge, with the exception of a few sporadic papers, no systematic analysis is available of what happens afterward. I believe, therefore, that its extension to cover the period after synchronism is lost would be useful as it would undoubtedly lead to additional improvements, probably as important as those brought about by the systematic study of the stability problem.

A short time ago, the engineers of the New York Edison and the Niagara-Hudson systems were faced with the same problem as that treated by the authors, in studying the protection of the 132-kv interconnection between these 2 systems. A detailed analysis of a scheme of protection with distance relays of the reactance type was made. It was found that the scheme, though satisfactory during faults, would have given rise under certain conditions to incorrect tripping during swings. Furthermore, during out-of-step conditions, the separation of the 2 systems might have occurred at points other than the desired ones. For these reasons, the scheme was abandoned altogether and the high frequency carrier protection was used. The details of the protection of this interconnection will be described in a paper that is planned for submission before the Institute in the near future.

One point I wish to emphasize concerning the performance of distance relays during swings and out-of-step conditions is the effect of the current transformer connections. The performance of the directional unit and the ohms indicated by the ohm unit depend on the potential and current transformer connections as well as on their ratios and relay location. As an illustration, there may be mentioned the case of a reactance relay used on a pure reactance tie line between 2 systems of equal internal voltage. In such a case, the reactance center and the electrical center coincide. If the current transformers are connected in delta, the ohm indication during swings and out-of-step conditions is equal to the reactance of the tie line between the relay location and the reactance center. This is evident from Fig. 2 in which E is the magnitude of the line to neutral voltages of systems Nos. 1 and 2; θ the angle by which system No. 1 leads No. 2 at the instant considered; I the current flowing from system No. 1 to No. 2; E_r the line to neutral voltage at the relay location; X_r reactance of the tie between the location of the relay and the reactance center; θ_r the angle between E_r and I. With potential and current transformers both connected in delta, the ohms measured by the relay are proportional to $\frac{\sqrt{3}\,E_r}{\sqrt{3}\,I}\sin\theta_r$ that is, to X_r, as seen from the triangle RCO in Fig. 2. If the settings of the relay are smaller than this reactance, the relay will never trip during swings and out-of-step conditions. If the potential transformers are connected in delta and the current transformers in wye, the ohms measured by the relay during swings and out-of-step conditions are proportional to $\frac{\sqrt{3}\,E_r}{I}\sin(\theta_r + 30°)$. With this connection, therefore, the ohms which the relay measures are not constant but vary as the angle be-

tween the 2 systems changes and may become less than the value for which the relay is set, thus resulting in an undesirable tripping operation.

Another point I wish to discuss concerns the use of a true power relay with circuit opening contacts to block out distance relays in order to prevent tripping during swings. It is stated that the setting of the true power relay should be "high enough so that there would be no danger of blocking on high resistance faults." It is assumed that the high resistance faults referred to in the paper are arcing faults, involving 2 or 3 conductors. Of course, arcing faults involving 2 conductors are unbalanced. As to arcing faults involving all 3 phases, it seems highly improbable that such faults will ever be balanced. In those few cases, when they occur, in all probability they are unbalanced. Therefore, as all unbalanced faults produce negative sequence voltages,

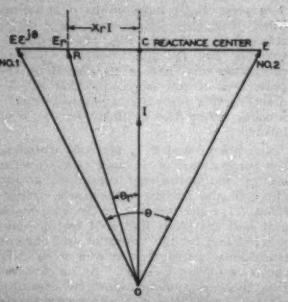


Fig. 2. A reactance relay example assuming a pure reactance tie line between 2 systems of equal internal voltage

it would be entirely feasible to avoid the undesirable high setting of the power relay by paralleling the trip contacts of the latter with those of a sensitively set negative sequence relay with circuit closing contacts, both sets of contacts being connected in series with those of the reactance relay. With this arrangement, the pick-up of the true power relay must be only high enough to prevent the relay from picking up with 3-phase dead short circuits. All unbalanced faults, 2 phase or 3 phase, would be detected by the distance relay through the contacts of the negative sequence relay, irrespective of the action of the true power relay. Three-phase dead short circuits would be detected through the contacts of the true power relay. Power swings above the setting of the true power relay and out-of-step conditions would not cause incorrect trippings regardless of the ohms measured by the distance relay, as the negative sequence relay would be inoperative and the true power relay energized, thus blocking the trip circuit of the distance relay. During power swings below the pick-up of the true power relay, the distance relay would not be blocked out. However, with the power relay pick-up maintained sufficiently low, these swings would be but small and therefore would not cause distance relays to pick up.

The curves showing the performance of impedance and reactance relays under various operating conditions should be of great assistance in the application of protective equipment. It would be very helpful if the authors had given the formulas on which the curves are based in order that their limitations may be more clearly understood.

Referring to the method suggested by the authors for calculating the maximum stable angle, also not specifically stated in the paper, I assume that whenever an initial and a final condition are involved, the calculation must be made on the basis of the final and not on the basis of the initial condition.

Regarding out-of-step relays as applied to interconnections between 2 large systems, it may be mentioned that with the high frequency carrier scheme of protection, it is possible, under favorable conditions, to incorporate the out-of-step feature in the scheme itself without additional equipment other than that required by consideration of protection against faults. This was found to be possible in the case of the interconnection between the New York Edison and the Niagara-Hudson systems and will be described in detail in the paper under preparation.

E. H. Bancker and E. M. Hunter: The authors are entirely in sympathy with the suggestion made by Messrs. Adams, Powell, and Calabrese that the best solution to avoid false operation of distance relays during swings is the use of a pilot system of relaying instead. Some pilot systems would be entirely impervious to either oscillation or out-of-step currents, while others which would not inherently be immune can be rendered so. The suggestion of a change to a more stable form of relaying as a solution was not included in the paper as its purpose was primarily to assist in studies of distance relays already in use and to suggest such remedial measures as might be applied in case they were found to be in any danger of tripping incorrectly.

The authors also subscribe fully to Mr. Gerrell's commendation of the use of automatic oscillographs. Prior to their adoption, any analysis of what actually happened during system disturbances was much more a matter of guesswork and conjecture than of real knowledge. Even the comparatively few automatic oscillographs now in use have been almost invaluable in giving fundamental information from which a real analysis of the events which occur throughout the disturbance might be made.

Mr. Stewart questions the utility of the comparison made in Fig. 7 between impedance relays having equal sensitivity with the starting unit of reactance relays. The purpose of this comparison was chiefly to bring out the effect of relay location upon the 2 types of devices and naturally such effect could be studied much more easily if the relays were brought to a common basis in all other respects. However, the behavior of the starting unit of a reactance relay is a rather difficult matter to describe because its minimum operating amperes are a function of both volts and power factor, both of which change with relay location. The impedance relay is affected only by voltage which, of course, changes with location. Because of the double effect of location upon the reactance relay starting unit, it may under fault conditions be able to cover about 2 line sections (9.6 ohms) and yet be no more sensitive to swings than an impedance relay set for 4.8 ohms, a setting which might be required on a long line. Hence the starting unit will cover 2 or more line sections as Mr. Stewart says and the impedance relay is set only for the impedance of its own line section, and yet under oscillating conditions the 2 have equal sensitivity. For any real study, however, the actual settings of the relays should be used in conjunction with Figs. 8 to 12.

Mr. Calabrese's statement regarding the use of final conditions is correct. The usual cause for a system oscillation is a short circuit and it is presumed that the faulted line will be disconnected by its protective relays. Therefore, the determination of the maximum stable angle must be made with the faulted line out of service, or as Mr. Calabrese says, using the final condition of system set-up.

Curves of the paper were actually calculated from the pickup current vs. voltage curves of the different elements. This is the only convenient way of deriving the curve for the *GAX* type because of its nonlinear potential coil circuit. The linear circuits of the impedance and *GCX* relay starting units make it possible to give an equation for them. For the impedance relay, the minimum operating current expressed as a function of the displacement angle, the relay location with respect to the electrical center, and the setting of the relay is given by the following equation:

$$I = \frac{\sqrt{\left(\cos\frac{\theta}{2}\right)^2 + \left(\frac{x}{X}\sin\frac{\theta}{2}\right)^2}}{Z}$$

where θ is the displacement angle; $\frac{x}{X}$ is the per-unit relay distance from the electrical center, and Z is the maximum impedance for which the element is set.

For the *GCX* starting unit using the same terminology, the minimum operating current is

$$I = \frac{\left(\cos\frac{\theta}{2}\right)^2 + \left(\frac{x}{X}\sin\frac{\theta}{2}\right)^2}{9.6\,\frac{x}{X}\sin\frac{\theta}{2}}$$

It may be of interest to note in connection with this element that the maximum sensitivity is attained by a relay located at such a point that the angle between the relay voltage and the voltage of the electrical center is 45 deg. This figure obtains regardless of the total displacement angle, so that the location of the most sensitive relay during a swing progresses from some imaginary point outside of the generator side of the system down to the electrical center.

As stated in the text of the paper, the curves apply to relays so connected that the maximum torque occurs at the natural angle of lag of the system using either wye volts and amperes or delta volts and amperes. Calculations can be made of the action of relays using delta volts and wye amperes, but they are complicated by the addition of the 30-deg displacement angle mentioned by Mr. Calabrese.

Iron Shielding for Telephone Cables

Discussion and authors' closure of a paper by H. R. Moore published in the February 1934 issue, p. 274–80, and presented for oral discussion at the communication session of the summer convention, Hot Springs, Va., June 27, 1934.

I. C. Forshee and K. L. Maurer: In connection with the electrification of the Philadelphia-Norristown section of the Wilkes-Barre division of the Pennsylvania Railroad in 1930, the railroad's open-wire communication circuits were replaced by an aerial tape-armored lead sheath cable, similar in make-up to the cables described in the paper, in order to secure protection against voltages induced by the electrification. This aerial installation, about 16 miles in length, extends over the greater part of the electrified section. The cable is paper insulated and contains 12 quads of No. 13 AWG conductors. The lead sheath has a nominal thickness of $^1/_8$ in., an outside diameter of $1^9/_{16}$ in., and is covered with a double layer of spirally wound galvanized steel tapes 0.043 in. thick and $1^3/_4$ in. wide. Sheath and armor are bonded together at every splice and both are connected to the electrified tracks through signal impedance bonds at intervals of 1 to 2 miles. On account of the relatively small size of the cable sheath, additional shielding was provided for by placing 2 4/0 copper shield wires on the same pole line about 18 in. above the cable. These shield wires also are connected to the tracks at impedance bonds.

The electrification system consists of an 11,000-volt 25-cycle trolley over each of the 2 tracks and 2 25-cycle 132-kv transmission lines on the same structures that support the trolleys. The communication cable and a braid covered signal cable are each suspended from a steel messenger carried on wood poles just outside the catenary supports.

Before the electrification was placed in operation, a number of tests in which the American Telephone and Telegraph Company coöperated were conducted to determine the merit of this arrangement of shields in limiting voltages induced in the communication circuits. A test section about 1,500 ft long was used, at the ends of which insulating joints were cut into the cable sheath and armor, and insulators in the 2 cable messengers and the 2 shield wires. Inside the test section, with the exception of the tape armored cable and its messenger, all metallic connections between the shields were removed. With one of the trolleys energized to the tracks at low current over most of the electrified section, the 25-cycle induced voltages in the communication conductors were measured with the shields successively in and out of the circuit. These tests showed a shield factor for the entire combination of 0.44 for the induced voltage referred to the tracks and 0.30 for the induced voltage referred to ground connections about 100 ft away from the tracks. This shield factor was observed with a testing current of approximately 30 amp in the trolley, and the figure is thus for the condition of low current in the sheath of the tape armored cable. With sheath currents that would correspond to operating conditions or short circuit conditions on the electrification, the contribution to the total shielding made by the tape armored cable would be considerably larger than under the test conditions so that the combined shield factor would be expected to be smaller than the above test factors. It was not possible under the test conditions available to determine precisely what proportion of the total shielding was contributed by the tape armored cable. Indications are, however, that under the test conditions, the shield factor due to the tape armored cable alone was about 0.6 with voltages referred to the tracks and something less than this with voltages referred to a ground independent of the tracks. From laboratory tests made by Mr. Moore on a sample of this cable (sample No. 11 in Table I of the paper), it is estimated that under normal operating conditions on the electrification the 25-cycle shield factor of the tape armored cable by itself would average about 0.4, and under short-circuit conditions about 0.2.

Under the field test conditions, the shielding was larger for voltages referred to ground connections independent of the track return system than for voltages referred to the track return system. This condition results from the fact that with the shielding system connected to the tracks the shielding current under the test conditions was determined partly by induction along the sheath and partly by the potential difference between track and ground. With the circuit for measuring voltage in the cable conductors completed through the tracks this voltage is the same as that producing the shielding current, but if the circuit is completed through ground connections independent of the tracks the conductor voltage is produced chiefly by the induction along the cable, which in this case was smaller than the voltage imposed on the sheath. In general, the difference in shield factors for the 2 reference points of conductor voltage will depend, among other things, upon factors which control the voltage to ground of the tracks, chief among which are the self-impedance of the tracks, their leakage conductance to ground, and length of energized section. If the energized trolley, the cable sheath, and the conductors are of equal length, the ratio of shield factor for voltages referred to tracks to that for voltages referred to independent grounds ranges from unity for very long feeding distances through a maximum value which may be as much as 4 or 5 under average conditions as to ballast resistance, to a value considerably less than unity for very short feeding distances.

The results obtained with this shielding arrangement during approximately 4 years of service have been very satisfactory from the communication standpoint in the limitation of induced voltages and freedom from service interruptions from this source.

Another installation of aerial, tape-armored cable on the Pennsylvania Railroad was used to replace open-wire conductors on the concrete pole line across the New Jersey meadows between Newark, N. J., and the west end of the Hudson River tunnels to New York. In addition to the tape armored cable, this pole line carries an unarmored lead sheath cable, a braid covered signal cable, and a 4/0 copper shield wire which is carried on pin type insulators on top of the wood crossarm from which the cables are suspended. The tape armored cable has a lead sheath 0.151 in. thick with an outside diameter of $2^7/_{16}$ in., over which is wound a double layer of galvanized steel tape 2 in. wide and 0.044 in. thick. The plain lead sheath cable has a sheath thickness of $^1/_8$ in. and outside diameter of $2^1/_{32}$ in. The features of the electrification system and the exposure of the communication circuits are similar to those described for the Wilkes-Barre division.

Tests conducted jointly as on the Wilkes-Barre division were made over a section of this line about 3 miles long. At the terminals of this section provision was made for connecting the cable sheaths and shield wire to the track return system through impedance bonds. Measurements were made of 25-cycle induced voltage with the previously mentioned shields connected singly or in groups and with one trolley, coterminal with the test conductors and shields, energized with a current of about 35 amp. Shield factors observed under the test conditions were as follows: tape armored cable alone, 0.52; lead sheath cable alone, 0.69; shield wire alone, 0.44 to 0.53; and all shielding conductors in parallel, 0.31 to 0.38. The induced voltages in all cases were referred to ground connections about 200 ft from the tracks. For the length of section used in this test, the shield factors would have been larger had the voltages been referred to the track return system. It will be noticed that the shield factor for the shield wire ranges below the shield factor for the tape armored cable. This is undoubtedly due to the fact that the latter was measured at a low value of sheath current and it would be expected that at values of sheath current obtainable under normal load or short-circuit conditions, the tape armored cable would compare much more favorably with the shield wire.

With regard to the use of the track return system instead of ground connections independent of the tracks for completing the shielding circuit for tape armored cables and shield wires, it is the view of the Pennsylvania Railroad that with the former the effectiveness of the shielding system is, in general, increased. The track return system in most of the electrified sections involves a plurality of heavy, well-bonded rails in parallel, the conductivity of which is augmented by copper ground wires on the catenary structures, conditions which limit voltages imposed on the shielding structures due to potential difference between track and ground. The equivalent of low resistance ground connections is obtained with ease and the necessity and expense of installing and maintaining driven ground connections are avoided.

L. P. Ferris: It is of interest to examine how charts of Moore's paper may be utilized for the rapid solution of specific problems of the kind discussed in the paper by Gilkeson and Hanks.

The inductive exposure discussed in the Gilkeson-Hanks paper is 20 miles long, capable of giving longitudinal induced voltages at the location proposed for the communication conductors of 18,600 volts

for the worst fault condition on the power line and 170 volts for the worst normal operating condition. The corresponding voltages per 1,000 ft are 176 and 1.6. The frequency is 60 cycles. It was desired to reduce the longitudinal voltage on the communication conductors to something less than 900 volts under abnormal conditions and to less than 5 volts under normal conditions. Thus, shield factors of 0.048 for abnormal induction and 0.029 for normal induction are required. The problem is, in essence, to find a practical design of armored cable which will give these or better shield factors.

If it be assumed that a cable of approximately full size would be required to carry the desired number of communication conductors plus auxiliary conductors paralleled with the sheath, and that the sheath is grounded at the ends of the exposure, Fig. 5 of Moore's paper is directly applicable. With a disturbing field of 176 volts per 1,000 ft and the corresponding desired shield factor of 0.048, there is found for the resistance of the sheath, plus grounding resistance $\left(r_{sn} + \frac{R}{l}\right)$, a value of 0.063 ohm per 1,000 ft. For induction under normal operating conditions of 1.6 volts per 1,000 ft and the corresponding required shield factor of 0.029, Fig. 5 gives the resistance as 0.015 ohm per 1,000 ft. Obviously, therefore, the normal induction is the controlling factor in determining the permissible resistance of the cable sheath. If it be assumed that the sheath is grounded through connections of negligibly low resistance, the sheath resistance itself must not exceed 0.015 ohm per 1,000 ft, to obtain which there would be required about 580,000 cir mils of copper in parallel with the normal lead sheath. This is but slightly larger than the value worked out by Gilkeson and Hanks. Returning to Fig. 5 with this sheath resistance of 0.015 ohm per 1,000 ft and the 176 volts per 1,000 ft induced under abnormal conditions, there is found a shield factor of about 0.012, again in good agreement with the figure derived by Gilkeson and Hanks.

From a developmental standpoint, it is to be regretted that the proposed installation has not materialized so as to afford an opportunity for an experimental check on these estimates.

H. R. Moore: Although more than 500 miles of steel tape armored communication cable have been installed in this country, there have been as yet only a few instances in which the choice of this construction was based upon a need for its unique shielding properties. Hence, it has been of considerable interest to study the report of I. C. Forshee and K. L. Maurer on 2 installations of armored cable specifically intended to protect communication circuits from induction due to an electrified railway. Because of the high traction currents the protection of circuits located on the railway right-of-way definitely requires shielding of the order provided by the steel armored cable. Extensive use of this type of cable has been made in Europe also, notably in Germany and in Sweden, under such conditions.

Two errors have been found in the printed text of the paper: The unit applying to the symbol l in the list following eq 3 should be inches rather than mils. In Figs. 7 and 8, the units for the quantity $l\sqrt{G}$ should be (mho ft $\times$ 1,000)$^{1/2}$ rather than (mho per 1,000 ft)$^{1/2}$.

Iron Armored Aerial Communication Cable

Discussion and authors' closure of a paper by C. L. Gilkeson and A. J. Hanks published in the June 1934 issue, p. 890–5, and presented for oral discussion at the communication session of the summer convention, Hot Springs, Va., June 27, 1934.

A. E. Bowen: In the paper by Messrs. Gilkeson and Hanks the authors say that their "problem is to determine the most economical combination of iron armoring and copper shielding capable of providing the desired degree of reduction." While they arrived at a cable design which would yield the desired shielding it is not at all certain that the recommended cable is the most economical one. Looked at critically the problem which the authors set and answered was: "Given a cable sheath of fixed dimensions, armored with iron tapes of fixed dimensions and magnetic characteristics, what amount of copper placed within and connected in parallel with the sheath will supply the desired amount of shielding?" To this restricted problem the authors have supplied an answer, but the more general problem is considerably more difficult and has by no means been solved.

If, in the design of a cable for a given application, the adjustment of the copper-lead-iron balance is given complete latitude, there may be considered as variables:

For the iron tapes. Number, thickness, width, spacing (or angle of lay), permeability, and resistivity.

For the lead sheath. Thickness.

For the copper shield wires. Number, gauge, and angle of lay. (Alternatively, tapes or rectangular wires might be considered.)

A fixed dimensional factor is the inner diameter of the copper as determined by the required group of communication conductors and their insulation, while only those combinations are eligible which yield a specified shield factor for a specified field intensity. The latter condition demands the additional specification of the earth return impedance of the cable sheath and its grounding resistances.

From the purely electrical standpoint, the array of possible variations in design features is formidable. If there are considered at the same time the mechanical consequences of changes in the size and method of spiralling of the copper wires or iron tapes, as is necessary to insure a cable of feasible characteristics, the complications are multiplied. Finally, determination of the most economical design from among all of the possible constructions capable of affording the required shielding would require interrelated studies of costs of materials and manufacture involving a most intricate balance. It may be concluded that, with the information now available, it is not practical to determine what construction is the *most* economical.

Preliminary experimental studies by the Bell Telephone Laboratories of means for improving the shielding other than by paralleling the sheath with copper have indicated that much could be gained by modification of the armoring, which, in the present cables, was designed primarily from mechanical considerations. With the same amount of steel, so wound as to diminish the air gap between turns and annealed to develop greater permeabilities, it is expected that the improvement in the shielding may be such as to substantially reduce the amount of auxiliary copper required. Further benefits are possible by changes in the composition of the steel. Some of these possibilities have also been investigated experimentally by Zastrow and Wild of the Siemens Halske Company (*E.N.T.* 1932, v. 9, p. 10).

K. L. Maurer: The paper by Messrs. Gilkeson and Hanks is an interesting example of inductive coördination planning in advance of construction of one of the facilities involved in an inductive relationship. Field tests on several actual installations of tape armored aerial cable with which I am familiar have indicated the general reliability of the formulas and data upon which the calculations in the paper are based, and there appears to be no reason why the large estimated reduction factor for the cable design worked out by the authors could not have been realized in practice. It is thus a striking illustration of the possibilities in special cable design to incorporate protection against outside disturbing influences.

In the section dealing with direct contacts between a faulted phase conductor and the cable sheath several statements would appear to need a certain amount of qualification. It is mentioned that in the event of such a contact the cable sheath would be raised in potential to earth by an amount equal to the product of the fault current and the impedance of the cable sheath to ground, and that this potential difference would also exist between the sheath and the conductors inside at the point of contact but not along the conductors nor at their terminals. The first of these statements is correct if the faulted phase wire and the cable sheath are so situated in relation to one another that there is no inductive coupling between them. This condition might be realized, for example, by a contact at a right angle crossing of a cable and an a-c power line. Under these circumstances the voltage of the cable sheath above earth would be equal to the product of the total current entering the sheath and the impedance of the sheath to ground at that point. However, this voltage will, in general, not exist between the cable sheath and the internal conductors at the point of contact, the latter also being elevated in potential above earth by reason of the voltage induced in them by the current on the cable sheath. The voltage between the sheath and the conductors at the point of contact will depend on a number of factors among which are the electrical constants of the sheath-earth circuit, the leakage conductance of the sheath to ground, and the length of the cable either way from the point of contact. If the cable sheath and conductors extend for considerable distances beyond the point of contact or if the conduc-

tors are connected to ground through terminal apparatus the potential between sheath and conductor at the point of contact will be the integrated resistance drop in the cable sheath. For the cable described in the paper this quantity would be expected to be a relatively small part of the voltage of sheath to ground so that the voltage of conductor to ground at the point of contact would be expected to be of the same order of magnitude as the voltage of sheath to ground.

If the power line is parallel to and not widely separated from the cable, which is understood to be the arrangement applying to the situation considered in the paper, the potential to ground assumed by the cable sheath in the event of a cross would be influenced by the voltage induced in the cable sheath by residual power line current on either side of the point of contact. For the same total fault current and the same cable sheath conditions as in the right angle crossing case, the voltage to ground at the point of contact would, in general, be expected to be lower. The voltage between cable sheath and conductors at the point of contact also would be influenced by the coupling with the faulted power conductors on each side of the contact. These relationships can readily be formulated in terms of the distributed constants of the cable and the mutual impedance between the power line and the cable. These expressions are rather cumbersome, and as their formulation depends on the physical arrangement of the systems involved with regard to such things as length of power and communication lines, single versus 2-way power feed, location of fault, etc., they are not given here.

With regard to the calculated values of sheath to ground voltage given in the table at the end of the section dealing with this question, it would appear from the above considerations that the voltage figures would not also apply to the potential between sheath and conductors. The large difference in sheath to ground voltage depending upon whether the contact is in the middle of a span or at a tower seems surprising, in view of the relatively short spans (15 towers per mile, or about 350-ft spacing on the average). If these potentials are taken as the product of the fault current and the impedance of the sheath to ground, the earth-return impedance of the sheath apparently would have to be between 11 and 12 ohms per mile to account for the difference in voltage for the 2 points of contact.

C. L. Gilkeson: Mr. Maurer comments on the large difference in the computed voltage to ground for the condition of a contact in midspan and at a tower. The reason for this difference is that these calculations were not based on the average span of 350 ft, but on the maximum span of 600 ft. The longer span, of course, represents the more unfavorable condition.

Throat Liners of the Boulder Dam Penstocks

A RECENT photograph taken as machinists in the shops of the Westinghouse Electric and Manufacturing Company at East Pittsburgh, Pa., prepare to "face off" the throat liners of the huge penstocks to be used at Boulder Dam. The tool in the left background makes the desired cut in the face of the casting, 2 minutes being required for each complete revolution. After being "faced off," 912 holes are drilled through the 2-in. thickness of the steel. Ten days are required for this latter operation on the boring machine, which had to be improvised to accommodate the casting's unusually large size. The steel casting weighs 40 tons, and is 36 ft in outside diameter.

Recent Developments in Power Line Carrier

Discussion of a paper by T. Johnson, Jr., published in the April 1934 issue, p. 542–7, and presented for oral discussion at the communication session of the summer convention, Hot Springs, Va., June 27, 1934.

R. C. Buell: The unit construction employed in the carrier telephone equipment described in Mr. Johnson's paper makes it possible to utilize this apparatus for carrier applications other than telephone. In the operation of power systems, carrier very frequently offers means of supervisory control, remote indication, and relaying which have outstanding advantages in economy and reliability. The most important of these applications of carrier has been pilot relaying of transmission lines. For most power systems pilot relaying surpasses all other forms of protection in the speed with which all line faults can be cleared. Carrier is of particular advantage as a pilot channel, not only because of the economies it offers but because of its inherent reliability; it is in use only when the transmission line is conducting power current to an external short circuit, and under this condition the continuity of the carrier channel is absolutely assured.

The use of power line carrier as a simple solution to remote control problems is illustrated by the instance of an operating company which had a long high-voltage power line tapped by another circuit some distance from the generating station. The usual substation with oil circuit breakers and associated equipment could not be justified and only air break disconnect switches were installed in the circuits. Due to the inaccessible location of these disconnect switches, it often took a patrolman 2 or 3 hours to reach the switches when trouble occurred on this line. In order to facilitate restoration of service, the 2 disconnect switches were motor operated from a battery and a time delay undervoltage relay was installed to open the air break disconnect switches in case of power failure. Carrier current was used to send a tripping impulse over the power line to reclose the disconnect switches one at a time at the discretion of the operator. Now, when the line gets in trouble, the operator tests the line to the disconnect switches, and, if O. K. that far, he closes first one and then the other disconnect switch, locating the section in trouble and restoring service to the good section.

In another case, a load dispatcher wanted to be able to vary the load on an automatic hydroelectric station, so a simple carrier transmitter was installed at his office, and a receiver at the station. When the operator wants to increase the load at the station he pulls a switch in one direction which energizes the carrier current transmitter on each positive half cycle of the 60-cycle power system. The receiver at the station picks up a relay and starts opening the gates as long as the carrier is transmitted. When the operator desires to decrease the load he pulls the switch in the opposite direction, sending out carrier on the negative half cycle which runs the gates toward the closed position.

News

Of Institute and Related Activities

A.I.E.E. Directors Meet at Institute Headquarters

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute headquarters, New York, N. Y., on August 7, 1934.

Present: *President*—J. Allen Johnson, Buffalo, N. Y. *Past Presidents*—J. B. Whitehead, Baltimore, Md.; and H. P. Charlesworth, New York, N. Y. *Vice President*—W. H. Timbie, Cambridge, Mass. *Directors*—F. Malcolm Farmer, New York, N. Y.; N. E. Funk, Philadelphia, Pa.; H. B. Gear, Chicago, Ill.; Everett S. Lee, Schenectady, N. Y.; L. W. W. Morrow, New York, N. Y.; A. C. Stevens, Schenectady, N. Y.; and H. R. Woodrow, Brooklyn, N. Y. *National treasurer*—W. I. Slichter, New York, N. Y. *National secretary*—H. H. Henline, New York, N. Y.

The minutes of the board of directors meeting held June 27, 1934, were approved.

A resolution in memory of Past President Harris J. Ryan, who died on July 3, 1934, was adopted, as appearing elsewhere in this issue.

A report was presented of a meeting of the board of examiners held July 25, 1934, and the actions taken at that meeting were approved. Upon the recommendation of the board of examiners, the following actions were taken: 7 applicants were elected and 16 were transferred to the grade of Member; 57 applicants were elected to the grade of Associate; 75 Students were enrolled.

The finance committee reported monthly expenditures, as follows: July, $18,128.34; August, $13,504.51. Report approved.

Upon recommendation of the committee on Student Branches, authorization was given for the organization of a Student Branch of the Institute at Brown University, Providence, R. I.

Announcement was made of the appointment by the President of committees for the administrative year beginning August 1, 1934; and representatives of the Institute on various bodies were appointed by the board for the new year. (List of committees and representatives appear elsewhere in this issue.)

In accordance with the by-laws of the Edison Medal committee, the board confirmed the appointments to the committee made by the president, as follows: C. E. Stephens as chairman for the year 1934–1935, and H. B. Gear, L. C. Nichols, and J. B. Whitehead, for terms of 5 years each; and the board elected from its own membership, for terms of 2 years each, F. M. Farmer, Everett S. Lee, and A. C. Stevens.

Complying with the by-laws of the Lamme Medal committee, the board confirmed the president's appointment of C. E. Skinner as chairman for the year beginning August 1, 1934, and of L. B. Imlay, F. B. Jewett, A. M. MacCutcheon as members of the committee for terms of 3 years each.

C. O. Bickelhaupt (chairman), F. J. Chesterman, J. Allen Johnson, William McClellan, and C. E. Stephens were reappointed representatives, and H. H. Henline, alternate, of the Institute on the assembly of American Engineering Council for the year 1935.

The following local honorary secretaries were reappointed for the 2-year term beginning August 1, 1934: V. J. F. Brain, for Australia; A. S. Garfield, for France; H. P. Thomas, for India; and W. Elsdon-Dew, for Transvaal.

Report was made of the appointment, upon the nomination of the standards committee, of the following representatives: R. C. VanSickle as a member of the Institute delegation on the Sectional Committee on Power Switchgear, A.S.A. Project No. C-37; and W. C. White as one of the Institute's representatives on the Sectional Committee on Radio, A.S.A. Project C-16.

An invitation was presented to nominate a person for the award of the 1935 Kelvin Medal, and the president was authorized to appoint a committee to recommend nominees to the board of directors.

Decision was made to hold the next meeting of the board of directors on Friday, October 19, 1934.

Other subjects were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

President of A.S.T.M. Dies

William Hastings Bassett, newly elected president of the American Society for Testing Materials, died on July 21, 1934, only 3 weeks after assuming his new office. He was born at New Bedford, Mass., on March 7, 1868. He graduated from Massachusetts Institute of Technology with the degree of B.S. in 1891, and after various chemical work joined the Ohio Brass Company in 1903 as chief chemist, becoming technical superintendent and metallurgist in 1912 and metallurgical manager in 1930.

Mr. Bassett was a pioneer metallurgist in the brass industry, and was among the first in the United States to apply microscopy to the metallography of non-ferrous metals, and likewise the spectroscope to routine work in the industry. He was a past-president of the American Institute of Mining and Metallurgical Engineers and a former director of the American Institute of Chemical Engineers. Other societies in which he held membership included the American Chemical Society, The American Society of Mechanical Engineers, Society of Automotive Engineers, American Electrochemical Society, Mining and Metallurgical Society of America, American Geographical Society, Franklin Institute, Institute of Metals of London, England, and Society of Chemical Industry of London, England. His son, W. H. Bassett, Jr. (M'30) is technical superintendent and metallurgist, Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.

Future AIEE Meetings

Winter Convention,
New York, N. Y., Jan. 22–25, 1935

South West District Meeting,
Oklahoma City, Okla., Apr. 26–28, 1935

Summer Convention,
Ithaca, N. Y., June 24–28, 1935

Pacific Coast Convention,
Los Angeles vicinity, Fall 1935

Great Lakes District Meeting,
Indianapolis—Lafayette Section territory (Date to be determined)

Ford to Install Second 110,000-Kw Generator

A second 110,000-kw turbine generator is to be installed by the Ford Motor Company at its River Rouge power plant at Fordson, Mich., similar to, but even more efficient than the one installed there in 1930. The new machine, like the first, is a vertical compound unit, and the high pressure turbine and generator will be mounted directly on top of the low pressure turbine and generator. Each element has a capacity of 55,000 kw, and rotates at 1,800 rpm. The rating of the combined unit is 110,000 kw, 80 per cent power factor, 13.8 kv, 3 phase, 60 cycles, with steam conditions of 1,200-lb gauge pressure, 900-deg F total temperature, and one inch absolute back pressure. Because of the high initial temperature, it is not necessary to reheat the steam before it goes into the low pressure unit, as had to be done in the case of all 1,200-lb turbines built heretofore.

As a result of the high temperature, less than a pound of coal will be needed to generate the kilowatthour. One of the important features of the vertical design will be the small amount of space taken by the unit,

the general dimensions being 57.5 ft by 23 ft, with 21 ft over-all height from the floor. The weight will be approximately 1,000 tons.

For the same station, a 15,000-kw noncondensing turbine is being obtained to furnish process steam to the Ford factory at 250 lb pressure. Both units are being built by the General Electric Company.

Former Chairman of Boston Section Dies

W. Irving Middleton, who for many years was active in the electrical industry, died at his home in Watertown, Mass., on April 27, 1934. He was a specialist in insulation, and was chief electrical engineer of the Simplex Wire and Cable Company, Boston, Mass., until poor health caused his resignation from his position and from the Institute 2 years ago. Mr. Middleton was born at Lowell, Mass., February 9, 1870. He joined the Simplex organization in 1903, and was instrumental in the development of the sine wave generator. He was elected an Associate in 1909, and a Member in 1914.

Mr. Middleton presented a number of papers before the Institute, and was chairman of the Boston Section in 1920–21. He was one of the founders of the Insulated Power Cable Engineers Association, and a member of the National Electric Light Association, the American Engineering Standards Committee, and the Engineers' Club of Boston.

Major Armstrong Appointed Professor at Columbia University. Major Edwin Howard Armstrong, famed for his discoveries in radio communication, and a central figure in a celebrated patent controversy which after nearly 2 decades still engages the attention of the United States Supreme Court, has been appointed professor of electrical engineering at Columbia University. Major Armstrong will direct instruction in radio communication and high frequency research in the Hartley laboratory, which will be incorporated into the department of electrical engineering, of which Prof. W. I. Slichter (A'00, F'12, and national treasurer) is the head. The Hartley laboratories have been the scene of many of the accomplishments of Prof. M. I. Pupin (A'90, F'15, HM'28, member for life, and past-president), as well as of the early efforts of Armstrong in the development of the vacuum tube oscillator. Professor Pupin will continue his researches in these laboratories. As announced by Dean J. W. Barker (M'26, F'30) of the school of engineering, the appointment of Major Armstrong fills the vacancy created by the death last winter of Prof. J. H. Morecroft.

In Memoriam

THE death, on July 3, 1934, of Dr. Harris J. Ryan removed from the American Institute of Electrical Engineers its thirty-sixth President and a member who had throughout his career, participated enthusiastically in its activities.

Upon beginning his life work as an engineering teacher only 2 years after his graduation, in 1887, from Cornell University, he immediately displayed one of his most notable characteristics, an impelling desire to ascertain through experimental research the basic scientific facts needed to give his students a clear understanding of the fundamental principles involved in the various types of electrical equipment. In 1889, he presented his paper on the transformer, which received wide attention and was the first of a long series of technical papers presenting the results of pioneer research in many divisions of electrical engineering. As head of a department of electrical engineering during nearly the whole of his career, he constantly brought to his administrative duties and to his work in the classroom great enthusiasm and breadth of vision supported by a vast store of technical information developed through his studies and experimental researches.

HARRIS J. RYAN

His ability, his delightful personality, his keen enthusiasm in the advancement of scientific knowledge and in the education of young engineers, his continuing interest in the problems encountered by his graduates, and his outstanding contributions to the development of the electrical industries made him a highly respected leader, and won the affection of all who knew him.

Professor Ryan joined the Institute in 1887, and was transferred in 1895 to the grade of Member and in 1923 to the grade of Fellow. He served on many Institute committees, represented it upon other bodies, and was manager 1893–96, vice president 1896–98, and president 1923–24. He was awarded the Edison Medal in 1925.

RESOLVED: That the board of directors of the American Institute of Electrical Engineers hereby expresses, upon behalf of the membership, its deep sorrow at the death of Dr. Ryan, and its keen appreciation of his many contributions to its activities, and be it further

RESOLVED: That these resolutions be entered in the minutes and copies be transmitted to members of his family.

—A.I.E.E. Board of Directors, August 7, 1934

Annual Science Exhibition of A.A.A.S.

The annual science exhibition of the American Association for the Advancement of Science and associated societies will be held in Pittsburgh, Pa., December 27–30, 1934. The exhibit will be in the new building of the Mellon Institute for Industrial Research. This building is probably one of the finest pieces of architecture in the United States.

The science exhibition is expected to be by far the greatest ever held by this organization, and is the single outstanding feature of the meetings to be held concurrently with the exhibits. Free exhibition space is available for those exhibits or demonstrations which are found acceptable. Some of the special attractions already arranged are demonstrations on cosmic rays, deuterium, neutrons, induced radioactivity, stratosphere flights, and a series of demonstrations of recent advances in physics. Requests for information should be made to F. C. Brown, director of exhibits, American Association for the Advancement of Science, Smithsonian Institution Building, Washington, D. C.

Additional Awards for 1933 Institute Papers

In addition to the national and District prizes for papers presented before the Institute during the calendar year 1933, as announced in ELECTRICAL ENGINEERING for June 1934, p. 1026, and August 1934, p. 1234–5, announcement now has been made of the award of 2 additional prizes. These are:

DISTRICT No. 2

Prize for best paper awarded to Maxwell K. Goldstein (A'33) for his paper "Telemetering in Large Power Stations," presented before the Baltimore Section, May 19, 1933.

DISTRICT No. 8

Prize for best paper awarded to Lloyd F. Hunt (A'21) and Alex A. Kroneberg (A'26) for their paper "Some Recent Relay Developments," presented before the Los Angeles Section, December 12, 1933.

Membership—

The Section membership committees have been continuing their activities during the summer months and the results are as follows:

Applications for membership received during May, June, and July, 1933 71

Applications for membership received during May, June, and July, 1934 135

We need the help of every member of the Institute in our membership work. As a member you can do 2 things:

1. Be appreciative of the program of your Section membership committee and give of your time to it as you can.
2. Send to the Chairman of your Section membership committee the names of those whom you think should be invited to join the Institute.

Chairman National Membership Committee

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Engineering Education for Non-Engineers

To the Editor:

The primary purpose of secondary education is to fit the graduate to live up to the full capacity of his potentialities, adequately adjusted to the environment in which he finds himself. The present civilization in which we are now living is an engineering civilization, the chief landmarks of which are our so-called modern conveniences. Man's present day environment is permeated with engineering achievements in which the forces and materials of nature have truly been yoked for his benefit. It is well-nigh impossible to pick out any detail of man's daily routine that is devoid of dependence upon engineering. From the time he rises from his bed in the morning, until he retires at night, he unknowingly finds himself totally dependent upon the ingeniousness of the engineer. The worst calamity that an Asmodeus could wreck upon humanity would be to remove the past 50 years of engineering progress from our present civilization and leave us with only those conveniences which existed at that time. If a civilization is to exist at all, it must be a progressive civilization; a dormant or retrogressive civilization eventually leads to annihilation. A progressive civilization is one that is dominated by the results of engineering achievements, each achievement based upon former achievements, and each one a little better than those which have gone before. Civilization is thus in a state of flux, with a slowly and constantly progressive trend toward something a little better. Civilization's progress is intimately linked with engineering progress; these 2, in fact, being synonomous. Man's present environment in which he lives, moves, and has his being, is thus an engineering environment, and his secondary education should, therefore, fit him to live in such an environment.

It is putting the matter conservatively to say that a large percentage of all male students in the colleges do not know why they are there, what they are headed for, or what they are interested in. They do not know what they want to do after leaving college, therefore they do not know what course to pursue while in college. The result is that very often they select a hit-or-miss set of courses (outside of the required courses) with enough easy ones to make certain of accumulating an abundance of credit units toward graduation. And that is the way they prepare to meet the problems of life; they feel that the best bet probably is to take a general course which will fit them for anything in general, but nothing in particular.

Since the world in which the graduate must live and earn a living is so pervaded with things engineering, what better selection could he make to adjust himself to his environment than to take an engineering course? A college course in engineering will come nearer to fitting him for our present civilization than any other choice he could make; it is an ideal "general course" and will put him in a better position to strike out for a livelihood than any other general course he could devise. This is true no matter whether he finally becomes a butcher, banker, business man, or what not. Because he takes an engineering course does not necessarily mean that he must practice engineering upon graduation. He can enter any line of business and will find that his rigorous training in analytical thinking based upon facts will stand him in good stead for success in that business.

Too many practicing engineers today advise young men to take any course in college but engineering, with the thought in mind that an engineering course is good for nothing else other than the practice of engineering. The first thought that comes to mind is, "There are already too many engineers, so why encourage more?" and they never stop to consider that an engineering training might possibly be good for something other than the practice of engineering. If more men were encouraged to take engineering with the broad idea in mind of preparing for life and not necessarily for engineering alone, the engineering profession would receive a much greater appreciation for its services and would not be in such a sad plight of non-recognition as it is today. No one appreciates the problems of engineering better than engineers themselves, consequently, if more of our business men had engineering training, the profession of engineering would be much more highly appreciated.

The complaint that an engineering course is too narrow and devoid of the necessary liberalizing subjects to make it a good general course, is groundless. The average engineering curriculum permits a goodly number of elective courses to be selected from the departments of economics, English, history, psychology, sociology, etc., so that by and large the engineer's training becomes fairly liberal. The engineering curriculum requires considerably more credit hours than the general or arts curriculum, and very frequently the number of elective hours almost equals the number of hours required for one year's work in the arts course, making it possible for the engineering student to carry the equivalent of almost a whole year of liberal arts. It is difficult to conceive of a more ideal college course than the engineering curriculum with electives in liberal arts. Such a course not only prepares the student to live in and contribute the most to this present age, but it automatically builds up a greater appreciation for the engineer and the engineering profession.

Very truly yours,
W. J. SEELEY (A'19, M'28)
(Professor of Electrical Engineering, Duke University, Durham, N. C.)

Personal Items

J. B. Fisken (A'03, F'13, and member for life) safety engineer, The Washington Water Power Company, Spokane, was honored by the Institute's Spokane Branch by the presentation of a resolution commemorating his 21 years of activity in the founding and building of the Branch. The presentation was made at a meeting celebrating the 50th anniversary of the Institute and the 21st of the Branch. Mr. Fisken has been intimately connected with power development in Washington since 1887. He was an Institute manager, 1916–19, and a vice president, 1919–20, and has served on the following committees: public policy (now Institute policy), 1916–17; sections, 1917–18, 1920–22; economics of electric service, 1919–20; and membership, 1928–29.

Philander Betts (A'96, F'13, and life member) has resigned as chief engineer of the New Jersey Board of Public Utility Commissioners after 24 years' service, and will engage in private practice. Previous to his connection with the commission he was engaged in the construction of power plants and street railways and as a government engineer at Washington, D. C. During the war he became a lieutenant colonel, later becoming a colonel in the engineers reserve corps. He has served on several Institute committees: board of examiners, 1914–16 and 1921–23; economics of electric service, 1914–19; meetings and papers (now technical program), 1915–17; and safety codes, 1924–30.

L. F. Morehouse (M'16, F'20) equipment development engineer, American Telephone and Telegraph Company, New York, N. Y., has had the degree of doctor of engineering conferred upon him by the University of Michigan in recognition of his contributions to telephone engineering. He has been engaged in communication engineering since 1906. Mr. Morehouse has been very active in Institute affairs, having been a manager 1919–23 and a vice president 1924–26, and has been on 13 committees.

J. C. Damon (A'05, M'13) formerly engineer in the construction department of Jackson and Moreland, Boston, Mass., is now chief engineer with the Public Service Commission of Wisconsin, where he has given special attention to the continuous inventory plan for public utilities. He served on the power transmission and distribution committee of the Institute from 1925 to 1927.

M. M. Samuels (F'24) formerly with the J. G. White Engineering Corporation, New York, N. Y., has been appointed economic analyst of the rate survey being made by the Federal Power Commission. Mr. Samuels was a member of the Institute's power generation committee from 1924 to 1927.

W. A. Hillebrand (A'08, M'13) professor of electrical engineering, University of California, Berkeley, Calif., has been elected secretary of the San Francisco Section of the Institute for 1934–35. He served on the power transmission and distribution committee 1925–26 and 1933–34.

J. B. FISKEN

John Morse (A'09) general superintendent, Shawinigan Water and Power Company, Montreal, Que., Canada, has been elected president of the Canadian Electrical Association for the coming year. Mr. Morse is a member of the general power applications committee of the Institute.

G. T. Shoemaker (M'20) vice president, United Light and Power Engineering and Construction Company, Davenport, Iowa, has been named assistant general manager in the United Light and Power Company, Davenport. He will continue his former duties in the subsidiary company.

E. A. Baldwin (A'07) vice president, International General Electric Company Inc., Paris, France, has been designated by the American government as an official observer to the eighteenth session of the International Labor Conference now in session at Geneva.

C. H. Keel (A'09, M'13), patent attorney specializing in electrical and automotive patents, New York, N. Y., has been elected secretary of The New York Patent Law Association for 1934–5. Mr. Keel is a member of the firm of Bartlett, Eyre, Scott, and Keel.

G. C. Shaad (A'03, F'13) dean, school of engineering and architecture, University of Kansas, Lawrence, was elected a vice president of the Society for the Promotion of Engineering Education at the annual meeting held in June at Ithaca, N. Y. He was a vice president 1930–32.

C. J. Hawkes (M'26) engineer, The Electric Storage Battery Company, Seattle, Wash., has been lecturing on recent developments in storage batteries before each of the 4 Northwest Sections.

C. F. Himes (A'34) electrical department, Stanolind Pipe Line Company, Haven Kans., received the 1933 A.I.E.E. South West District prize for Branch paper and not the North Eastern District prize as announced in the August 1934 issue.

H. S. Lane (A'12, M'30) assistant engineer, Pacific Gas and Electric Company, San Francisco, Calif., has been elected a member-at-large of the Institute's San Francisco Section. He was a member of the communication committee 1933–34.

J. F. Porter (A'87, F'33, and member for life) president, Kansas City Power and Light Company, Kansas City, Mo., has received an honorary degree in electrical engineering from Iowa State College, Ames, of which he is a graduate.

W. J. S. Dormer (A'25, M'31) division toll plant engineer, Bell Telephone Company of Canada, Montreal, Que., for the past 5 years, has been appointed district engineer, Three Rivers and Montreal suburban districts.

H. C. Hamilton (A'23, M'26) superintendent, standardizing and testing department, Edison Electric Illuminating Company of Boston, Mass., has been elected vice chairman of the Boston Section of the Institute.

T. R. Langan (A'13, M'30) northeastern district manager, Westinghouse Electric and Manufacturing Company, New York, N. Y., has been elected a director of the New York Electrical Society.

Donald Rhodes (A'30) division transmission engineer, Bell Telephone Company of Canada, Montreal, Que., for the past 2 years, has been appointed district engineer of the Sherbrooke district of that company.

C. W. Lehy (A'30) publishing director, *Electrical West*, McGraw-Hill Company of California, San Francisco, Calif., has been elected a member-at-large of the Institute's San Francisco Section.

D. D. Smalley (A'20, M'33) distribution superintendent, Midland Counties Public Service Corporation, Santa Maria, Calif., has been elected a member-at-large of the Institute's San Francisco Section.

G. J. Crowdes (A'21, M'32) electrical engineer, Simplex Wire and Cable Company, Cambridge, Mass., has been elected chairman of the Boston section of the Institute.

J. B. Kobrock (A'13, M'26) assistant to the general manager, New England Telephone and Telegraph Company, Boston, Mass., has retired as chairman of the executive committee of the Engineering Societies of New England.

H. I. Finch (A'03, M'13) former president of the Emerson Electric Manufacturing Company, St. Louis, Mo., has become chairman of the board of that company.

C. A. Corney (A'16, M'20) assistant superintendent, electrical engineering department, Edison Electric Illuminating Company of Boston, Mass., is chairman of the executive committee of the Engineering Societies of New England.

P. O. Noble (A'19, M'28) has been appointed engineer of the fractional horsepower motor engineering department, of which he was formerly assistant engineer, of the General Electric Company, Fort Wayne, Ind.

A. F. Welch (A'12, M'27) former engineer of the fractional horsepower motor engineering department of the General Electric Company, Fort Wayne, Ind., has been appointed consulting engineer of that department.

F. W. Bliss (A'30) district manager, sales development department, General Electric Company, Boston, Mass., is a member of the executive committee of the Engineering Societies of New England.

C. E. Wilson (A'16) electrical erecting engineer, General Electric Company, Schenectady, N. Y., has been elected a director of the Electric Household Utilities Corporation.

J. M. Murray (A'29) electrical engineer, Simplex Wire and Cable Company, Cambridge, Mass., has been elected secretary and treasurer of the Boston Section of the Institute.

W. G. Stearns (A'09) formerly with the General Cable Company, is sales representative for The Okonite Company in San Francisco, Calif.

H. A. Smith (A'03) division manager, Wisconsin Power and Light Company, Fond du Lac, Wis., for the past 2 years, is now in charge of special development work for the same company in Madison, Wis.

A. M. Bohnert (A'12, M'26) district engineer, Ohio Brass Company, San Francisco, Calif., has been elected chairman of the Institute's San Francisco Section for 1934–35.

E. M. Wright (A'20, M'31) assistant engineer, Pacific Gas and Electric Company, San Francisco, Calif., has been elected vice chairman of the Institute's San Francisco Section for 1934–35.

R. O. Broshmer (A'31) General Electric Company, San Francisco, Calif., has been elected a member-at-large of the San Francisco Section of the Institute.

G. F. Fowler (A'29) Bell Telephone Laboratories, Inc., New York, N. Y., has been elected treasurer of the New York Electrical Society.

J. B. Bassett (A'13, M'23) assistant district engineer, General Electric Company, New York, N. Y., has been elected a director of the New York Electrical Society.

Obituary

Herbert Aubrey Barre (A'11) chief engineer, Southern California Edison Company, Ltd., died on June 28, 1934, as the result of a cerebral hemorrhage. He was born at Picton, Nova Scotia, Canada, on January 26, 1875. After his graduation from the University of California in 1897 he was employed by several power and transit companies in California until in 1902 he became assistant to a Los Angeles, Calif., consulting engineer. Four years later he was again engaged with power companies, and in 1908 came to New York, N. Y., as engineer with the Electric Operating Construction Company. He returned to California 3 years later as electrical-mechanical engineer for the Pacific Light and Power Corporation, a company later acquired by the Southern California Edison Company. Mr. Barre became executive engineer of the latter company in 1917 and chief engineer in 1929. He was largely responsible for the construction and operation of the first 150,000-volt long-distance transmission line in the world, that between the Big Creek–San Joaquin development and Los Angeles. This line was converted under his supervision for 220,000-volt operation in 1923. He served the Institute on the transmission and distribution committee, 1915–17, and the power generation committee, 1920–27. Mr. Barre was also a member of The American Institute of Mechanical Engineers.

Samuel Groenendyke McMeen (A'95, F'12, and member for life) retired consulting engineer of Pasadena, Calif., died on June 22, 1934. He was born at Eugene, Ind., Nov. 28, 1864. He left Purdue University, Lafayette, Ind., to work for the Central Union Telephone Company in 1884, becoming assistant chief engineer at Chicago, Ill., in 1896. In 1902 he accepted a position as engineer in the central office equipment department of the Western Electric Company, Chicago, Ill. Two years later with the late K. B. Miller he formed the firm of McMeen and Miller in Chicago, consulting engineers in telephone systems, and patent experts. For this firm Mr. McMeen designed and constructed the automatic telephone systems in San Francisco, Oakland, and Berkeley, Calif. In 1912 he entered public utility management, and was president of the Mount Hood Railway and Power Company, Portland, Ore.; Columbus Railway Power and Light Company, Columbus, Ohio, Ohio State Telephone Company; and East St. Louis railway, light, power, and gas properties. He was vice president and director of similar properties in Tennessee, and was also chairman of the board of directors of the North Electric Manufacturing Company, Galion, Ohio, from 1918 to 1922. He was a member of the Naval Consulting Board in 1916. Mr. McMeen was an inventor of many devices used in the telephone and automotive arts. In conjunction with others he wrote "Telephony," "American Archery," and the "American Handbook for Electrical Engineers," and was author of other technical writings. He served on the Edison Medal committee 1912–17, and was also a member of The American Society of Mechanical Engineers, the Western Society of Engineers, and the American Electric Railway Association.

George Alfred Damon (A'98, F'14) consulting engineer, Pasadena, Calif., died June 23, 1934, of cerebral congestion after an illness of only a few hours. He was born at Chesaning, Mich., April 7, 1870. During 1893 he was employed at the World's Fair in Chicago, Ill., and for a short time by the Fisher Electrical Works, Detroit, Mich., after which he returned to the University of Michigan to complete his course and receive his engineering degree in 1895. Following graduation he was associated with B. J. Arnold (A'92, F'12, past president, and member for life) in Chicago, Ill., as draftsman and engineer. From 1900 to 1907 Mr. Damon was managing engineer of The Arnold Company, engineers and constructors in Chicago, and in this position was in responsible charge of the design of power plants and electrical installations for a number of railroads. In 1907 he was again associated with Mr. Arnold on transit appraisals and reports in New York, N. Y., and Pittsburgh, Pa. He went to California in 1910 and the following year became dean of engineering at the California Institute of Technology, Pasadena, Calif., which position he held until 1914. He then engaged in consulting engineering in Los Angeles, San Jose, and Long Beach, Calif. He was a member of the Pasadena Historical Society, and of the Western Society of Engineers, and a past president of the Society for the Promotion of Engineering Education. He was chairman of the Los Angeles Section of the Institute in 1913.

Arthur W. Dawson (A'19) manager, Michigan Northern Power Company, died recently. He was born Sept. 2, 1877 at Sault Ste. Marie, Mich., and worked first as a lineman for the Bell Telephone Co., then in power house work with the Canadian government. In 1900 he became electrician with the Rhodin Chemical Works for 2 years, then entered the Michigan Lake Superior Power Company as chief operator, one year later becoming superintendent, taking charge a few years later of the electrical installation and operation of a station of the Michigan Northern Power Company, in which he eventually became manager.

Donald Cameron Allison (A'26) manufacturer's representative, Mexico, D. F., Mexico, died in January 1933, according to word recently received at Institute headquarters. He was born at Philadelphia, Pa., on April 8, 1889. In 1907 he was employed by the Mexican General Electric Company, and with the exception of a year in the foreign department of the General Electric Company at Schenectady, N. Y., in 1916, remained in Mexico, becoming assistant manager there in 1925.

Membership

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before Sept. 30, 1934, or Nov. 30, 1934, if the applicant resides outside of the United States or Canada.

Anderson, C. H. (Member), Niagara, Lockport & Ontario Pwr. Co., Olean, N. Y.
Anderson, H. A., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Bangs, N. K., The Fox Paper Co., Lockland, Ohio.
Baum, M., N. Y. Water Serv. Corp., N. Y. City.
Brown, M. K. (Member), Niagara, Lockport & Ontario Pwr. Co., Buffalo, N. Y.
Clancy, C. A. (Member), Niagara Falls Pwr. Co., Niagara Falls, N. Y.
Dunning, O. M., Thomas A. Edison Inc., Orange, N. J.
Eley, F. L., Southern California Edison Co. Ltd., Los Angeles.
Frantz, W. P., Curtis Pub. Co., N. Y. City.
Griffin, G. G., Crouse-Hinds Co., Dallas, Tex.
Hackmann, W. K., Natl. Pwr. Survey, Federal Pwr. Comm., Washington, D. C.
Harrington, H. L. (Member), Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Holland, G. E., United Elec. Controls Co., South Boston, Mass.
Jeffe, E. F. (Fellow), N. Y. Edison Co. & United Elec. Lt. & Pwr. Co., N. Y. City.
Johnson, E. M., Gen. Elec. Co., Spokane, Wash.
Johnson, R. L., 12 S. Mulberry St., Hagerstown, Md.
Jones, J. D., c/o M. W. Kellogg Co.; Atlantic Refining Co., Philadelphia, Pa.
Kurtz, J. A., J. Kurtz & Sons, Inc., 773 Broadway, Bklyn., N. Y.
Lacallade, C. J., 515 Scotland St., Williamsburg, Va.
Lai, G. D., R. C. A. Victor Co., Inc., Camden, N. J.
Lamnera, R. S., Jr. (Member), Westinghouse Elec. & Mfg. Co., Atlanta, Ga.
Leather, Maurice P., Boston Woven Hose & Rubber Co., Cambridge, Mass.
Montgomery, L. A., Imperial Irrigation Dist., Andrade, Calif.
Osborn, R. E., Delco Remy Corp., Anderson, Ind.
Otto, G. A. (Member), The Telecegister Corp., N. Y. City.
Robida, R. B. (Member), Niagara Falls Pwr. Co., Niagara Falls, N. Y.
Sawyer, O. E., New England Pwr. Assoc., Providence, R. I.
Sharp, H. M. (Member), Buffalo Gen. Elec. Co., Buffalo, N. Y.
Smith, R. L. (Member), Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Stone, E. W., Central Illinois Light Co., Peoria.
Tice, H. W., So. Calif. Edison Co. Ltd., Los Angeles, Calif.
Ulrey, D., Westinghouse Res. Lab., East Pittsburgh, Pa.
Wagner, E. S. (Member), 205 W. Chocolate Ave., Hershey, Pa.
Wheeler, W. S., P. O. Box 43, Dover, N. H.
Wohlgemuth, A. J., Telautograph Corp., N. Y. City.
Zinter, H. C., Buffalo Gen. Elec. Co., Buffalo, N. Y.

36 Domestic

Foreign

Billingham, R. O., Elec. Industries (Pty.) Ltd. Cape Town, So. Africa.
Dawson, George (Member), McMaster-Jacob Engg. Co., Ltd. Toronto, Ont., Canada.
Fethi, S. I., Pwr. House of Kozlu Komuris, Zonguldak, Turkey.
Gautam, S., Upper India Sugar Mills Ltd., Khatauli, Dist. Muzaffar Nagar, India.
Mildner, R. C., Std. Tel. & Cables, North Woolwich, London, England.
Miller, J. L. (Member), Ferranti Ltd., Hollinwood, Lancashire, England.
Panaotovic, P. Gj. (Member), Amer. Yugoslav Elec. Co., Novisad, Yugoslavia.
Thorn, R. C., Talkoo Sugar Refinery, Hong Kong, China.

8 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Adams, William C., 801 S. Lynn St., Champaign, Ill.
Babloonian, Levon M., 776 N. Cass St., Milwaukee, Wis.
Clark, Merrill C., 161 Madison Ave., New York, N. Y.
Handley, Wilbur H., 4416 Loren Ave., Los Angeles, Calif.
Jordan, Henry, 7408A Christopher Colombus, Montreal, Que., Can.
Losoncy, William A., 14067 Cherrylawn Ave., Detroit, Mich.
Mexal, J. Rene, 86-03 Britton Ave., Elmhurst, L. I., N. Y.
Moellendick, K. F., L. A. Automotive Works, 1010 Towne Ave., Los Angeles, Calif.
Schultz, Carl H., 15 Cook St., Jersey City, N. J.
Stuntz, Hans, 106 Peck Ave., Newark, N. J.
Thompson, B. F., Minas de Matahambre, Matahambre, Pinar Del Rio, Cuba.
Villegas, Lucio P., Tacoma General Hospital, Tacoma, Wash.
Wagoner, K. S., 320 Wisconsin, Oak Park, Ill.

13 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

DESIGN of MACHINE ELEMENTS. By V. M. Faires. N. Y., Macmillan Co., 1934. 468 p., illus., $4.00. Those elements of machines which can be designed without using the more complicated theories of strength of materials are presented at the outset, and the chapters then advance to more difficult work. The subject can be studied before strength of materials, or concurrently with it. The book covers usual college requirements clearly and practically.

EARTH, RADIO, and the STARS. By H. T. Stetson. N. Y., McGraw-Hill Book Co., Whittlesey House, 1934. 336 p., illus., 5 x 6 in., cloth, $3.00. An account of our present understanding of the earth in its relations to its cosmic environment using recent developments in astronomy, geology, and radio engineering; the constitution and movements of the earth, the nature of the sun and its radiation, sunspots, and the relation between solar phenomena and terrestrial magnetism and radio transmission are presented.

ELASTICITY, STRUCTURE, and STRENGTH of MATERIALS USED in ENGINEERING CONSTRUCTION, Developed by the Geometry of Strain and the Energy Function through Thermodynamic and Chemical Equations in Such Wise that Strength May Be Figured from Chemical Composition of Rolled Metals and the Modification of This Resistance by Mechanical Work. By C. A. P. Turner. Privately published by the author at 300 Builders Exchange Bldg., Minneapolis, Minn., 1934. 416 p., illus., 10 x 6 in., cloth, $6.00. Conclusions from many years' study of the theory of resistance. Considerable portions of the author's earlier book, "Elasticity and Strength of Materials," reappear, but the theoretical framework has been further developed.

MACHINE DESIGN. By L. J. Bradford and P. B. Eaton. 3 ed. N. Y., John Wiley & Sons, 1934. 289 p., illus., 9x6 in., cloth, $3.00. Aims to supply a brief course which can be covered in about 25 lessons, and which will emphasize the fundamental facts and processes of machine design. Revised to conform with recent developments, especially in lubrication and welded construction.

MACHINES AUTOMATIQUES, MECANIQUES et ELECTRIQUES. (Collection Armand Colin.) By P. Maurer. Paris, Librairie Armand Colin, 1934. 185 p., illus., 7x5 in., paper, 10, 50 frs.; bound, 12 frs. A concise study of the automatisation of machines. Bases for a classification of automatic machines and of the general theory of mechanisms are discussed, the processes for making machines automatic are considered, and the chief automatic electrical and mechanical devices are considered.

MECHANICS of ENGINEERING. By S. D. Chambers. N. Y., Macmillan Co., 1934. 279 p., diagrs., 9x6 in., cloth, $3.50. A class-room text covering only the essentials of statics and kinetics, intended for students of engineering who are acquainted with the elements of the calculus and college physics. The material is arranged to fit one-hour recitations.

MUNICIPAL INDEX, 10th ed. 1933. N. Y. Am. City Mag. Corp. 491 p., illus., 10x7 in., les. $5.00. An up-to-date list of city managers, mayors, engineers, water-works and street superintendents and police and fire chiefs in cities over 100,000 in population, and of state highway engineers, together with statistical and other information upon highway construction and maintenance street cleaning, water supply, sewage disposal, traffic control, parks, playgrounds, etc. Condensed catalogs of materials and equipment are also included.

MYSTERIES of the ATOM. By H. A. Wilson. N. Y., D. Van Nostrand Co., 1934. 146 p., illus., 9x6 in., cloth, $2.50. Concerned chiefly with theories about the microscopic structure of the universe, but large-scale phenomena are considered in chapters on cosmic rays, relativity and gravitation. By omitting technical details, the story has been told briefly, yet with great clarity.

NOTES on LIGHTNING COMPUTATIONS for Transmission Lines with Overhead Ground Wires. By C. A. Jordan. Privately published by the author at 40 North Spring Garden Ave., Nutley, N. J., 1934. 82 p., illus., paper, $5.00. Discusses the design of transmission lines with overhead ground wires from the point of view of lightning protection. General solutions are developed for the lightning voltages and currents at critical points, the surge impedances of the various parts of the ground-cloud circuit and the interwire couplings are discussed and, finally, the application of the analytical methods is illustrated by working out a typical problem of high-voltage line design. Published in facsimile typescript, in an edition of 100 copies.

OUTLINES of PHYSICAL GEOLOGY. By C. R. Longwell, A. Knopf and R. F. Flint. N. Y., John Wiley & Sons, 1934. 356 p., illus., 9x6 in., cloth, $3.00. This is a less comprehensive and somewhat simpler treatment of its subject than that presented in the text published by these authors in 1932. About 2/3 the size of the larger work, it follows the same general plan of presentation and order of subjects, but is adapted to shorter courses.

PROTECTION by PATENTS of SCIENTIFIC DISCOVERIES. Report of the Committee on Patents, Copyrights and TradeMarks. (Occasional Publications of the Am. Assn. for the Advancement of Science, No. 1, Jan. 1934. Supplement to SCIENCE, v. 79.) By J. Rossman, Chairman, F. G. Cottrell, A. W. Hull and A. F. Woods. N. Y., Science Press. 40 p., 10x8 in., paper, $.50. Discusses very fully the problem of the scientific worker whose researches lead to results of commercial value. Considers the advantages and disadvantages of protecting inventions by patent, and the patent policies of various institutions. Also discusses the desirability of legal protection for scientific discoveries.

Engineering Societies Library

29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Officers and Committees for 1934-35

President

J. ALLEN JOHNSON — Buffalo, N. Y.
(Term expires July 31, 1935)

Junior Past Presidents

H. P. CHARLESWORTH — New York, N. Y.
(Term expires July 31, 1935)

J. B. WHITEHEAD — Baltimore, Md.
(Term expires July 31, 1936)

Vice Presidents

Dist. No.		
(2)	A. M. WILSON	Cincinnati, Ohio
(4)	F. M. CRAFT	Atlanta, Ga.
(6)	R. B. BONNEY	Denver, Colo.
(8)	R. W. SORENSEN	Pasadena, Calif.
(10)	A. H. HULL	Toronto, Canada

(Terms expire July 31, 1935)

(1)	W. H. TIMBIE	Cambridge, Mass.
(3)	R. H. TAPSCOTT	New York, N. Y.
(5)	G. G. POST	Milwaukee, Wis.
(7)	F. J. MEYER	Oklahoma City, Okla.
(9)	F. O. McMILLAN	Corvallis, Ore.

(Terms expire July 31, 1936)

Directors

L. W. CHUBB	East Pittsburgh, Pa.
B. D. HULL	Dallas, Tex.
H. R. WOODROW	Brooklyn, N. Y.

(Terms expire July 31, 1935)

G. A. KOSITZKY	Cleveland, Ohio
A. H. LOVELL	Ann Arbor, Mich.
A. C. STEVENS	Schenectady, N. Y.

(Terms expire July 31, 1936)

P. B. JUHNKE	Chicago, Ill.
EVERETT S. LEE	Schenectady, N. Y.
L. W. W. MORROW	New York, N. Y.

(Terms expire July 31, 1937)

F. M. FARMER	New York, N. Y.
N. E. FUNK	Philadelphia, Pa.
H. B. GEAR	Chicago, Ill.

(Terms expire July 31, 1938)

National Treasurer

W. I. SLICHTER — New York, N. Y.
(Term expires July 31, 1935)

National Secretary

H. H. HENLINE — New York, N. Y.
(Term expires July 31, 1935)

General Counsel

Parker & Aaron
20 Exchange Place, New York, N. Y.

Local Honorary Secretaries

AUSTRALIA—V. J. F. Brain, Department of Public Works, Philip St., Sydney, N. S. W.

BRAZIL—F. M. Servos, Rio de Janeiro Tramway Light & Power Co., Rio de Janeiro.

ENGLAND—A. P. M. Fleming, Metropolitan-Vickers Elec. Co. Ltd., Trafford Park, Manchester.

FRANCE—A. S. Garfield, 173 Boulevard Haussmann, Paris, 8e.

INDIA—H. P. Thomas, 41 The Lower Mall, Lahore.

ITALY—Renzo Norsa, Via Caravaggio 1, Milan 25.

NEW ZEALAND—P. H. Powell, Canterbury College, Christchurch.

SWEDEN—A. F. Enstrom, Ingeniorsvetenskrapsakademien, Stockholm.

TRANSVAAL—W. Eladon-Dew, P. O. Box 4563, Johannesburg, Transvaal, Africa.

GENERAL COMMITTEES

Executive

J. Allen Johnson, Chm., 302 Electric Building, Buffalo, N. Y.

H. P. Charlesworth	W. I. Slichter
F. M. Farmer	R. H. Tapscott
Everett S. Lee	J. B. Whitehead

Code of Principles of Professional Conduct

C. E. Stephens, Chm., Westinghouse Elec. & Mfg. Co., 30 Rockefeller Plaza, New York, N. Y.

A. H. Babcock	L. W. Chubb
H. H. Barnes, Jr.	F. B. Jewett
H. P. Charlesworth	W. E. Mitchell

Board of Examiners

W. R. Smith, Chm., 80 Park Place, Newark, N. J.
H. E. Farrer, Secy., 33 W. 39th St., New York, N. Y.

H. C. Dean	F. V. Magalhaes
H. W. Drake	R. H. Marriott
H. Goodwin, Jr.	L. W. W. Morrow
S. P. Grace	A. L. Powell
H. A. Kidder	A. E. Silver
S. D. Sprong	

Columbia University Scholarships

W. I. Slichter, Chm., Columbia University, New York, N. Y.

Francis Blossom — H. C. Carpenter

Constitution and By-Laws

E. B. Meyer, Chm., 80 Park Place, Newark, N. J.

C. O. Bickelhaupt	H. A. Kidder
W. S. Gorsuch	W. I. Slichter

Coördination of Institute Activities

L. W. W. Morrow, Chm., *Electrical World*, 330 W. 42nd St., New York, N. Y.

C. O. Bickelhaupt	E. B. Meyer
R. N. Conwell	I. M. Stein
H. H. Henline	R. H. Tapscott

Economic Status of the Engineer

C. O. Bickelhaupt, Chm., 195 Broadway, New York, N. Y.

E. W. Rice, Jr.	Charles F. Scott
W. S. Rugg	H. R. Woodrow

Edison Medal

Appointed by the President for term of 5 years.

C. I. Burkholder — F. A. Gaby — R. A. Millikan
(Terms expire July 31, 1935)

H. H. Barnes, Jr. — E. B. Meyer — P. H. Thomas
(Terms expire July 31, 1936)

Gano Dunn — S. P. Grace — C. E. Stephens, Chm.
(Terms expire July 31, 1937)

V. Bush — H. P. Charlesworth — K. S. Wyatt
(Terms expire July 31, 1938)

H. B. Gear — L. C. Nichols — J. B. Whitehead
(Terms expire July 31, 1939)

Appointed by the Board of Directors from its own membership for term of 2 years.

L. W. Chubb — G. A. Kositzky — H. R. Woodrow
(Terms expire July 31, 1935)

F. M. Farmer — Everett S. Lee — A. C. Stevens
(Terms expire July 31, 1936)

Ex-officio

J. Allen Johnson, President
W. I. Slichter, National Treasurer
H. H. Henline, National Secretary
(Terms expire July 31, 1935)

Finance

R. H. Tapscott, Chm., 4 Irving Place, New York, N. Y.

Everett S. Lee — L. W. W. Morrow

Headquarters

W. S. Gorsuch, Chm., 600 W. 59th St., New York, N. Y.

H. H. Henline — R. H. Tapscott

Institute Policy

H. P. Charlesworth, Chm., 195 Broadway, New York, N. Y.

A. W. Berresford	D. C. Jackson
C. C. Chesney	William McClellan
B. Gherardi — J. B. Whitehead	C. E. Skinner

Iwadare Foundation

F. B. Jewett, Chm., 195 Broadway, New York, N. Y.

C. E. Skinner — Gerard Swope

Lamme Medal

P. L. Alger — H. B. Gear — C. E. Skinner, Chm.
(Terms expire July 31, 1935)

C. F. Harding — Malcolm MacLaren — R. W. Sorensen
(Terms expire July 31, 1936)

L. E. Imlay — F. B. Jewett — A. M. MacCutcheon
(Terms expire July 31, 1937)

Legislation Affecting the Engineering Profession

W. I. Slichter, Chm., Columbia University, New York, N. Y.

James P. Alexander	L. W. W. Morrow
T. F. Barton	John R. Price
B. M. Brigman	Lester S. Ready
N. E. Funk	Herbert S. Sands
W. H. Harrison	M. R. Scharff
D. C. Jackson — J. B. Thomas	H. H. Schoolfield

Membership

Everett S. Lee, Chm., General Electric Co., Schenectady, N. Y.

C. A. Cora	C. J. MacDonald
W. M. Dann	J. R. MacGregor
W. O. Helwig	L. W. W. Morrow

District Vice Chairmen

R. W. Adams (1)	L. A. Bingham (6)
E. S. Fields (2)	O. S. Hockaday (7)
J. E. McCormack (3)	H. W. Hitchcock (8)
E. P. Coles (4)	J. Hellenthal (9)
T. G. LeClair (5)	G. D. Floyd (10)

Ex-officio

Chairmen of membership committees of all Sections.

New York Museum of Science and Industry, Advisory Committee to

John Price Jackson, Chm., New York Edison Co., 130 E. 15th St., New York, N. Y.

R. H. Hughes — R. H. Nexsen

Prizes, Award of Institute

R. N. Conwell, Chm., 80 Park Place, Newark, N. J.

C. O. Bickelhaupt — F. M. Farmer

Publication

C. O. Bickelhaupt, Chm., 195 Broadway, New York, N. Y.

F. A. Lewis, Secy., 33 W. 39th St., New York, N. Y.

J. W. Barker	L. F. Hickernell
R. N. Conwell	E. B. Meyer
L. A. Doggett	L. W. W. Morrow
W. S. Gorsuch	I. M. Stein
H. H. Henline	H. R. Woodrow

Safety Codes

F. D. Knight, Chm., Edison Elec. Illuminating Co. of Boston, 39 Boylston St., Boston, Mass.

J. C. Balsbaugh	Wills Maclachlan
A. W. Berresford	F. V. Magalhaes
G. S. Diehl	John D. Noyes
H. B. Gear	F. A. Pattison
I. W. Gross	Frank Thornton, Jr.
W. B. Kouwenhoven	W. C. Wagner
M. G. Lloyd	H. S. Warren

Sections

I. M. Stein, Chm., Leeds & Northrup Co., 4901 Stenton Ave., Philadelphia, Pa.

H. H. Henline, Secy., 33 W. 39th St., New York, N. Y.

L. A. Doggett	F. A. Hamilton, Jr.
Mark Eldredge — W. H. Timbie	A. P. Hill

Ex-officio

Chairmen of all Institute Sections.

Standards

E. L. Moreland, Chm., 31 St. James Ave., Boston, Mass.

H. E. Farrer, Secy., 33 W. 39th St., New York, N. Y.

A. B. Cooper	J. Franklin Meyer
A. L. Harding	V. M. Montsinger
C. R. Harte	F. D. Newbury
A. M. MacCutcheon — W. I. Slichter	E. B. Paxton

Ex-officio

Chairmen of working committees.
Chairmen of A.I.E.E. delegations and representatives on other standardizing bodies.
President of U. S. National Committee of I.E.C.

Student Branches

L. A. Doggett, Chm., Pennsylvania State College, State College, Pa.

R. B. Bonney	Charles F. Scott
F. O. McMillan	W. H. Timbie

Ex-officio

Student Branch Counselors.

Technical Program

R. N. Conwell, Chm., 80 Park Place, Newark, N. J.
C. S. Rich, Secy., 33 W. 30th St., New York, N. Y.
J. W. Barker — W. S. Gorsuch
H. S. Bennion — F. C. Hanker
C. O. Bickelhaupt — W. H. Harrison
O. G. C. Dahl — B. D. Hull
H. B. Gear — W. B. Kouwenhoven — David M. Jones

Ex-officio

Chairmen of technical committees.
Chairman of committee on coördination of Institute activities.

Transfers

H. Goodwin, Jr., Chm., Henry L. Doherty & Co., 60 Wall St., New York, N. Y.
Everett S. Lee — E. B. Meyer
L. R. Mapes — Charles F. Scott

TECHNICAL COMMITTEES

Automatic Stations

M. E. Reagan, Chm., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
F. F. Ambuhl — I. E. Moultrop
A. E. Anderson — J. M. Oliver
L. D. Bale — O. J. Rotty
John Fies — Garland Stamper
A. M. Garrett — D. W. Taylor
Joseph Hellenthal — L. J. Turley
P. B. Juhnke — F. Zogbaum — Chester Wallace

Communication

H. M. Turner, Chm., Yale University, New Haven, Conn.
E. L. Bowles — C. J. Larsen
L. W. Chubb — J. R. MacGregor
A. A. Clokey — John Mills
J. O'R. Coleman — C. W. Mitchell
F. M. Craft — E. J. O'Connell
W. L. Everitt — H. S. Osborne
I. C. Forshee — J. J. Pilliod
G. H. Gray — F. H. Pumphrey
H. H. Haglund — R. R. Shute
H. L. Huber — A. L. Stadermann
B. D. Hull — C. H. Taylor
C. M. Jansky, Jr. — W. M. Vanderslusis
T. Johnson, Jr. — Chester Wallace
G. M. Keenan — R. S. Wishart
M. J. Kelly — F. A. Wolff
H. S. Lane — F. C. Young

Education

L. A. Doggett, Chm., Pennsylvania State College, State College, Pa.
J. W. Barker — D. C. Jackson, Jr.
Edward Bennett — F. E. Johnson
P. S. Biegler — C. L. Kinsloe
R. B. Bonney — A. H. Lovell
E. L. Bowles — T. H. Morgan
H. V. Carpenter — Burke Smith
R. E. Doherty — R. W. Sorensen
A. M. Dudley — A. C. Stevens
O. W. Eshbach — G. B. Thomas
H. H. Henline — W. L. Upson
Alan Howard — Joseph Weil

Electric Welding

H. M. Hobart, Chm., General Electric Co., Schenectady, N. Y.
C. A. Adams — C. J. Holslag
A. M. Candy — J. C. Lincoln
W. E. Crawford — Wm. Spraragen
F. Creedy — A. C. Stevens
K. L. Hansen — H. A. Winne — H. E. Stoddard

Instruments and Measurements

W. B. Kouwenhoven, Chm., Johns Hopkins University, Baltimore, Md.
H. S. Baker — A. E. Knowlton
O. J. Bliss — H. C. Koenig
P. A. Borden — Everett S. Lee
H. B. Brooks — Paul MacGahan
J. S. Cruikshank — R. T. Pierce
R. D. Doyle — R. J. Rutan
Marion Eppley — A. C. Seletzky
W. N. Goodwin, Jr. — W. J. Shackelton
C. H. G. Gray — G. M. L. Sommerman
T. S. Gray — H. L. Thomson
I. F. Kinnard — Joseph Weil — H. M. Turner

Iron and Steel Production, Applications to

R. W. Graham, Chm., Bethlehem Steel Co., Lackawanna, N. Y.
J. J. Booth — O. Needham
F. E. Harrell — A. C. Stevens
G. A. Kaufman — A. J. Whitcomb
L. R. Milburn — H. A. Winne
S. H. Mortensen — R. H. Wright

Electrical Machinery

V. M. Montsinger, Chm., General Electric Company, Pittsfield, Mass.
P. L. Alger — H. C. Louis
B. L. Barns — O. K. Marti
R. S. Bundy — S. H. Mortensen
J. E. Clem — R. W. Owens
A. B. Cooper — H. V. Putman
H. E. Edgerton — K. A. Reed
J. L. Hamilton — O. E. Shirley
S. L. Henderson — W. F. Sims
A. H. Hull — W. I. Slichter
C. M. Laffoon — George Sutherland
J. J. Linebaugh — C. G. Veinott

Electrochemistry and Electrometallurgy

N. R. Stanat, Chm., General Electric Co., Schenectady, N. Y.
W. C. Kalb, Vice-Chm., National Carbon Co., Inc., Cleveland, Ohio.
J. C. Hale, Secy., Research Corp., Bound Brook, N. J.
J. V. Altfriend — W. C. Kalb
L. W. Chubb — H. P. Kirchner
P. H. Brace — A. E. Knowlton
G. H. Clamer — C. C. Levy
F. M. Clark — R. G. Mansfield
C. L. Dudley — Wm. E. Moore
G. W. Elmen — J. L. Woodbridge
A. M. Hamann — C. F. Yodder

Electrophysics

W. F. Davidson, Chm., Brooklyn Edison Co., 55 Johnson St., Brooklyn, N. Y.
S. S. Attwood — C. E. Magnusson
A. Boyajian — R. C. Mason
O. R. Buckley — F. O. McMillan
K. K. Darrow — H. H. Race
C. S. Gordon — Joseph Slepian
L. O. Grondahl — J. B. Whitehead — M. S. Vallarta

Liaison Representatives of American Physical Society

Harvey L. Curtis — Leigh Page

Light, Production and Application of

J. W. Barker, Chm., Columbia University, New York, N. Y.
H. S. Broadbent — R. D. Mailey
C. A. B. Halvorson — G. S. Merrill
L. A. Hawkins — P. S. Millar
J. T. Holmes — L. W. W. Morrow
W. C. Kalb — A. L. Powell

Marine Work, Applications to

H. C. Coleman, Chm., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
E. C. Alger — I. H. Osborne
A. A. Beekman — G. A. Pierce
R. M. Glasgow — W. H. Reed
H. F. Harvey, Jr. — H. M. Southgate
C. J. Henschel — W. E. Thau
Wm. Hetherington, Jr. — A. E. Waller
H. L. Hibbard — O. A. Wilde
A. Kennedy, Jr. — J. L. Wilson
J. B. Lunsford — R. L. Witham
L. W. W. Morrow — W. N. Zippler

Mining Work, Applications to

L. C. Ilsley, Chm., Bureau of Mines Experiment Station, 4800 Forbes Street, Pittsburgh, Pa.
J. E. Boriand — C. W. Parkhurst
Graham Bright — K. A. Pauly
J. H. Edwards — D. E. Renshaw
L. H. James — A. C. Stevens
Carl Lee — E. B. Wagner
C. H. Matthews — C. D. Woodward — J. F. Wiggert

Power Applications, General

Mark R. Woodward, Chm., Babcock & Wilcox Co., 20 North Wacker Drive, Chicago, Ill.

(*Members to be appointed.*)

Power Generation

H. W. Leitch, Chm., New York Edison Company, 4 Irving Place, New York, N. Y.
F. A. Annett — A. H. Lovell
J. R. Baker — I. E. Moultrop
P. H. Chase — A. L. Penniman, Jr.
J. B. Crane — G. G. Post
W. S. Gorsuch — C. A. Powel
F. H. Hollister — F. A. Scheffler
A. H. Hull — A. E. Silver
D. M. Jones — W. F. Sims
A. V. Karpov — Philip Sporn

Power Transmission and Distribution

D. M. Simmons, Chm., General Cable Corp., 420 Lexington Ave., New York, N. Y.
F. E. Andrews — W. A. Hillebrand
G. M. Armbrust — D. C. Jackson, Jr.
Raymond Bailey — J. P. Jollyman
D. K. Blake — F. B. Juhnke
M. O. Bolser — A. H. Lawton
E. S. Bundy — J. B. MacNeill
A. B. Campbell — L. N. McClellan
C. V. Christie — F. J. Meyer
R. N. Conwell — L. L. Perry
W. A. Curry — D. W. Roper
A. E. Davison — H. J. Scholtz
S. M. Dean — G. B. Shanklin
M. Eldredge — A. E. Silver
R. D. Evans — C. T. Sinclair
F. M. Farmer — L. G. Smith
C. L. Fortescue — H. R. Spencer
C. W. Franklin — Philip Sporn
T. H. Haines — Stanley Stokes
Edwin Hansson — W. K. Vanderpoel
C. F. Harding — H. S. Warren
K. A. Hawley — A. M. Wilson
L. F. Hickernell — L. F. Woodruff
C. R. Higson — T. A. Worcester

Protective Devices

H. P. Sleeper, Chm., Public Service Elec. & Gas Co., 80 Park Place, Newark, N. J.
J. C. Balsbaugh — J. P. McKearin
H. W. Collins — H. A. McLaughlin
J. O'R. Coleman — J. R. North
W. S. Edsall — H. V. Nye
F. R. Ford — G. G. Post
S. L. Goldsborough — C. H. Sanderson
S. M. Hamill, Jr. — H. J. Scholz
J. Hellenthal — H. K. Sels
R. T. Henry — L. G. Smith
A. V. Joslin — H. R. Summerhayes
T. G. LeClair — A. H. Sweetnam
W. A. Lewis, Jr. — O. C. Traver
H. J. Lingal — H. M. Trueblood
K. B. McEachron — E. M. Wood — H. E. Turner

Research

F. M. Farmer, Chm., Electrical Testing Laboratories, 80th St. & East End Ave., New York, N. Y.
R. W. Atkinson — W. B. Kouwenhoven
O. E. Buckley — Everett S. Lee
L. W. Chubb — F. O. McMillan
E. H. Colpitts — K. W. Miller
E. C. Crittenden — H. H. Race
O. G. C. Dahl — D. W. Roper
W. F. Davidson — T. Spooner
F. Hamburger, Jr. — Philip Sporn
H. M. Hobart — C. H. Willis
V. Karapetoff — R. J. Wiseman
A. E. Kennelly — K. S. Wyatt

Transportation

C. M. Davis, Chm., General Electric Co., Erie, Pa.
R. Beauwkes — J. J. Linebaugh
A. H. Candee — E. L. Moreland
J. V. B. Duer — John Murphy
N. E. Funk — N. W. Storer
W. A. Giger — W. M. Vanderslusis
W. S. H. Hamilton — Sidney Withington
G. I. Wright

INSTITUTE REPRESENTATIVES

Alfred Noble Prize Committee

R. N. Conwell

Am. Assoc. for the Advt. of Science, Council

C. A. Adams — C. E. Skinner

American Bureau of Welding

H. M. Hobart

American Committee on Marking of Obstructions to Air Navigation

R. N. Conwell — H. L. Huber

American Engg. Council Assembly

C. O. Bickelhaupt — Wm. McClellan
F. J. Chesterman — C. E. Stephens
J. Allen Johnson — H. H. Henline, *Alternate*

American Marine Standards Committee

R. A. Beekman

American Stds. Assoc. Council

A. M. MacCutcheon — F. D. Newbury
Alternates
H. S. Osborne — E. B. Paxton

American Stds. Assoc. Bd. of Directors
Bancroft Gherardi

American Year Book, Advisory Board
H. H. Henline

Charles A. Coffin Fellowship and Research Fund Committee
J. Allen Johnson

Com. of Apparatus Makers and Users, N.R.C.
L. F. Adams

Com. on Heat Transmission, N.R.C.
T. S. Taylor

Coördination Committee of Engineering Societies
C. O. Bickelhaupt W. A. Del Mar L. B. Stillwell

Educ. Research Com., The Engg. Foundation
W. S. Rodman

Electrical Standards Committee, A.S.A.
A. M. MacCutcheon H. S. Osborne
F. D. Newbury E. B. Paxton, *Alternate*

Engineering Foundation Board
C. E. Skinner W. I. Slichter

Engg. Societies Monographs Committee
E. B. Meyer W. I. Slichter

Engineers' Council for Professional Development
C. O. Bickelhaupt L. W. W. Morrow C. F. Scott

Hoover Medal Board of Award
Gano Dunn F. B. Jewett E. W. Rice, Jr.

John Fritz Medal Board of Award
H. P. Charlesworth Bancroft Gherardi
C. E. Skinner J. B. Whitehead

Library Board, United Engg. Trustees, Inc.
W. S. Barstow H. H. Henline
W. A. Del Mar W. I. Slichter W. B. Jackson

National Bureau of Engg. Registration, Advisory Board
W. I. Slichter

Nat. Fire Prot. Assoc. Electrical Committee
F. D. Knight F. V. Magalhaes, *Alternate*

National Fire Waste Council
F. D. Knight F. V. Magalhaes

Nat. Research Council, Division of Engg. and Industrial Research
L. W. Chubb D. C. Jackson Chester W. Rice
Ex-officio H. H. Henline

Nat. Safety Council, A.S.S.E.—Engg. Section, Com. on Low Voltage Hazards F. D. Knight

Radio Advisory Com., Bur. of Standards
A. E. Kennelly

Research Procedure Com., Engg. Foundation
L. W. Chubb

United Engineering Trustees, Inc.
H. P. Charlesworth G. L. Knight H. R. Woodrow

U.S. National Committee of the International Commission on Illumination
A. E. Kennelly C. F. Scott C. H. Sharp

U.S. National Committee of the International Electrotechnical Commission
A. M. MacCutcheon F. D. Newbury H. S. Osborne
E. B. Paxton, *Alternate*

Commission of Washington Award
L. A. Ferguson Wm. B. Jackson

Local Sections of the Institute

Name	District	Chairman	Secretary	Secretary's Address
Akron	2	R. A. Hudson	H. H. Schroder	2429 E. Market St., Akron, Ohio
Alabama	4	H. J. Scholz	H. M. Woodward	Southern Bell Tel. & Tel. Co., Birmingham, Ala.
Atlanta	4	L. M. Shadgett	W. F. Oliver	Box 2211, Atlanta, Ga.
Baltimore	2	J. L. D. Speer, Jr.	J. H. Lampe	Johns Hopkins University, Baltimore, Md.
Boston	1	G. J. Crowdes	J. M. Murray	66 Sidney St., Cambridge, Mass.
Chicago	5	D. L. Smith	B. Smith	Illinois Bell Tel. Co., 212 W. Washington St., Chicago, Ill.
Cincinnati	2	E. J. Jonas	J. T. Bronson	General Elec. Co., 215 W. 3rd St., Cincinnati, Ohio
Cleveland	2	W. H. LaMond	H. T. Killingsworth	American Tel. & Tel. Co., 750 Huron Rd., Cleveland, Ohio
Columbus	2	E. E. Dreese	F. W. Marquette	Columbus Ry. Pwr. & Lt. Co., Columbus, Ohio
Connecticut	1	H. J. Blakeslee	W. B. Hall	Yale University, New Haven, Conn.
Dallas	7	E. T. Gunther	L. C. Starbird	Telephone Bldg., Room 820, Dallas, Texas
Denver	6	G. S. Dring	R. H. Owen	National Broadcasting Co., 1370 Krameria St., Denver, Colo.
Detroit-Ann Arbor	5	J. R. North	H. P. Seelye	Detroit Edison Co., 2000 Second Ave., Detroit, Mich.
Erie	2	A. S. Goodrich	F. B. Moore	18 Hess Ave., Erie, Pa.
Florida	4	R. P. Smith	Joseph Weil	University of Florida, Gainesville, Fla.
Fort Wayne	5	O. Kiltie	D. H. Hanson	General Elec. Co., 1635 Broadway, Fort Wayne, Ind.
Houston	7	P. H. Robinson	L. B. Bricker	P. O. Box 1780, Houston, Texas
Indianapolis-Laf.	5	T. F. Irvine	F. R. Fischout	5690 N. Delaware St., Indianapolis, Ind.
Iowa	5	B. S. Willis	H. H. Brown	3415 First Ave., S. E., Cedar Rapids, Iowa
Ithaca	1	B. K. Northrop	L. A. Burckmyer	Cornell University, Ithaca, N. Y.
Kansas City	7	R. L. Frisby	H. V. Rathbun	P. O. Box 679, Kansas City, Mo.
Lehigh Valley	2	C. J. MacDonald	Edgar Bell	Pennsylvania Pwr. & Lt. Co., Hazleton, Pa.
Los Angeles	8	Fred Garrison	O. W. Holden	Bureau of Pwr. & Lt., 207 So. Broadway, Los Angeles, Calif.
Louisville	4	W. H. Mansfield	G. M. Miller	731 W. Ormsby Ave., Louisville, Ky.
Lynn	1	G. R. Sturtevant	H. A. Hemingway	General Electric Co., West Lynn, Mass.
Madison	5	R. B. Johnson	R. R. Benedict	University of Wisconsin, Madison, Wis.
Memphis	4	P. L. Christenbury	H. B. Hosford	Memphis Pwr. & Lt. Co., Memphis, Tenn.
Mexico	3	C. E. Plumb	L. Castro, Jr.	National Railways of Mexico, Estacion Colonia, Mexico, D. F.
Milwaukee	5	C. D. Brown	E. W. Kane	Marquette Univ., Milwaukee, Wis.
Minnesota	5	R. R. Herrmann	J. H. Kuhlmann	University of Minnesota, Minneapolis, Minn.
Montana	9	J. A. Thaler	H. Dale Cline	312 So. 6th Ave., Bozeman, Montana
Nebraska	6	T. H. Granfield	C. E. Winn	1408 W. O. W. Bldg., 14th and Farnum Sts., Omaha, Nebr.
New Orleans	4	J. M. Todd	P. E. Johnson	317 Baronne St., New Orleans, La.
New York	3	W. R. Smith	W. S. Gorsuch	I.R.T. Co., 600 W. 59th St., New York, N. Y.
Niagara Frontier	1	E. P. Harder	C. E. Gaylord	N. Y. Tel. Co., 63 E. Delavan Ave., Buffalo, N. Y.
North Carolina	4	H. M. Doerschuk	S. L. Coulter	Box 425, Badin, N. C.
Oklahoma City	7	A. Naeter	C. E. Bathe	Oklahoma Gas & Elec. Co., Oklahoma City, Okla.
Philadelphia	2	H. C. Albrecht	J. L. MacBurney	Elec. Storage Battery Co., Philadelphia, Pa.
Pittsburgh	2	H. A. P. Langstaff	C. A. Powel	Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Pittsfield	1	L. H. Burnham	C. A. Read	General Electric Co., Pittsfield, Mass.
Portland	9	Walter Brenton	John Bankus	Portland General Elec. Co., Portland, Ore.
Providence	1	E. B. Curdts	R. J. Underwood	Narragansett Elec. Co., Providence, R. I.
Rochester	1	Wm. M. Young	H. Bunson	General Ry. Signal Co., Rochester, N. Y.
St. Louis	7	E. G. McLagan	C. O. Campbell	1322 Pierce Bldg., St. Louis, Mo.
San Antonio	7	J. W. Farrelly	E. G. Conroy	107½ Magnolia Drive, San Antonio, Texas
San Francisco	8	A. M. Bohnert	W. A. Hillebrand	University of California, Berkeley, Calif.
Saskatchewan	10	J. M. Taylor	F. E. Estlin	Canadian General Elec. Co., Ltd., Regina, Sask., Can.
Schenectady	1	F. A. Hamilton	Alan Howard	General Elec. Co., Schenectady, N. Y.
Seattle	9	C. E. Rogers	G. H. Walker	Great Northern Ry. Co., 810 King St. Station, Seattle, Wash.
Sharon	2	F. J. Vogel	W. A. Sumner	Westinghouse Elec. & Mfg. Co., Sharon, Pa.
Southern Virginia	4	E. L. Lockwood	R. C. Bailey	P. O. Box 112, Richmond, Va.
Spokane	9	R. H. Hull	M. F. Hatch	Washington Water Pwr. Co., Spokane, Wash.
Springfield	1	J. W. Bennett	C. G. Veinott	Westinghouse Elec. & Mfg. Co., Page Bldg., Springfield, Mass.
Syracuse	1	C. H. Bissell	G. E. Tennant	Syracuse Lighting Co. Inc., Syracuse, N. Y.
Toledo	2	E. J. Rommel	W. M. Campbell	Toledo Edison Co., Toledo, Ohio
Toronto	10	C. A. Price	R. E. Jones	Hydro-Elec. Pwr. Comm. of Ontario, 620 University Ave., Toronto, Ont.
Urbana	5	L. L. Smith	H. J. Reich	University of Illinois, Urbana, Ill.
Utah	9	H. T. Plumb	A. C. Keim	Utah Pwr. & Lt. Co., Salt Lake City, Utah
Vancouver	10	F. J. Bartholomew	J. E. Underhill	B. C. Elec. Ry. Co. Ltd., 425 Carrall St., Vancouver, B. C.
Washington	2	H. G. Dorsey	J. E. O'Brien	Catholic University of America, Washington, D. C.
Worcester	1	T. H. Morgan	T. R. Holton	22 Shirley St., Auburn, Mass.

Total 61

Geographical District Executive Committees

District	Chairman (Vice President, A.I.E.E.)	Secretary (District Secretary)
No. 1—North Eastern	W. H. Timbie, Massachusetts Institute of Technology, Cambridge, Mass.	A. C. Stevens, General Electric Co., Schenectady, N. Y.
No. 2—Middle Eastern	A. M. Wilson, University of Cincinnati, Cincinnati, Ohio	L. L. Bosch, Columbia Engg. Corp., 323 Plum St., Cincinnati, Ohio
No. 3—New York City	R. H. Tapscott, 4 Irving Place, New York, N. Y.	C. R. Jones, Westinghouse Elec. & Mfg. Co., 30 Rockefeller Plaza, New York, N. Y.
No. 4—Southern	F. M. Craft, P. O. Box 2211, Atlanta, Ga.	S. A. Flemister, P. O. Box 2211, Atlanta, Ga.
No. 5—Great Lakes	G. G. Post, 314 Public Service Bldg., Milwaukee, Wis.	A. G. Dewars, Northern States Pr. Co., 15 S. 5th St., Minneapolis, Minn.
No. 6—North Central	R. B. Bonney, 1421 Champa St., Denver, Colo.	W. G. Rubel, Mountain States Tel. & Tel. Co., 931 14th St., Denver, Colo.
No. 7—South West	F. J. Meyer, Oklahoma Gas & Electric Co., Oklahoma City, Okla.	C. W. Miser, Southwestern Bell Tel. Co., 405 N. Broadway, Oklahoma City, Okla.
No. 8—Pacific	R. W. Sorensen, California Institute of Technology, Pasadena, Calif.	J. N. Kelman, Kelman Electric & Mfg. Co., 1650 Naud St., Los Angeles, Calif.
No. 9—North West	P. O. McMillan, Oregon State College, Corvallis, Ore.	V. B. Wilfley, 901 Porter Bldg., Portland, Ore.
No. 10—Canada	A. H. Hull, Hydro-Electric Power Commission, 620 University Ave., Toronto, Ont.	J. M. Thomson, Ferranti Electric, Ltd., Mount Dennis, Toronto 9, Ont.

Note: Each District executive committee includes the chairmen and secretaries of all Sections within the District and the chairman of the District committee on student activities.

Student Branches of the Institute

Name and Location	District	Counselor
Akron, Univ. of, Akron, Ohio	2	J. T. Walther
Alabama Poly. Inst., Auburn, Ala	4	W. W. Hill
Alabama, Univ. of, University, Ala	4	Fred R. Maxwell, Jr.
Arizona, Univ. of, Tucson, Ariz	8	J. C. Clark
Arkansas, Univ. of, Fayetteville, Ark	7	W. B. Steiner
Armour Inst. of Tech., Chicago, Ill	5	E. H. Freeman
British Columbia, Univ. of, Vancouver, B. C	10	E. G. Cullwick
Brooklyn, Poly. Inst. of, Brooklyn, N. Y	3	C. C. Whipple
Bucknell Univ., Lewisburg, Pa	2	G. A. Irland
Calif. Inst. of Tech., Pasadena, Calif	8	F. C. Lindvall
Calif., Univ. of, Berkeley, Calif	8	W. A. Hillebrand
Carnegie Inst. of Tech., Pittsburgh, Pa	2	G. McC. Porter
Case Sch. of Ap. Science, Cleveland, Ohio	2	H. B. Dates
Catholic Univ. of America, Washington, D. C	2	T. J. MacKavanagh
Cincinnati, Univ. of, Cincinnati, Ohio	2	L. R. Culver
Clarkson College of Tech., Potsdam, N. Y	1	A. R. Powers
Clemson Agri. Col. Clemson College, So. Car	4	S. R. Rhodes
Colorado State Agri. Col., Fort Collins, Colo	6	H. G. Jordan
Colorado, Univ. of, Boulder, Colo	6	W. C. DuVall
Cooper Union, New York, N. Y	3	A. J. B. Fairburn
Cornell Univ., Ithaca, N. Y	1	R. M. Strong
Denver, Univ. of, Denver, Colo	6	R. B. Nyswander
Detroit, Univ. of, Detroit, Mich	5	H. O. Warner
Drexel Inst., Philadelphia, Pa	2	E. O. Lange
Duke Univ., Durham, N. C	4	W. J. Seeley
Florida, Univ. of, Gainesville, Fla	4	Joseph Weil
George Washington Univ., Washington, D. C	2	A. G. Ennis
Georgia Sch. of Tech., Atlanta, Ga	4	T. W. Fitzgerald
Harvard Univ., Cambridge, Mass	1	C. L. Dawes
Idaho, Univ. of, Moscow, Idaho	9	J. R. Hull
Illinois, Univ. of, Urbana, Ill	5	H. N. Hayward
Iowa State Col., Ames, Iowa	5	B. S. Willis
Iowa, Univ. of, Iowa City, Iowa	5	E. B. Kurtz
Kansas State Col. Manhattan, Kan	7	R. G. Kloeffler
Kansas, Univ. of, Lawrence, Kan	7	R. W. Warner
Kentucky, Univ. of, Lexington, Ky	4	E. A. Bureau
Lafayette Col., Easton, Pa	2	L. J. Conover
Lehigh Univ. Bethlehem, Pa	2	N. S. Hibshman
Lewis Inst., Chicago, Ill	5	F. A. Rogers
Louisiana State Univ., Baton Rouge, La	4	M. B. Voorhies
Louisville, Univ. of, Louisville, Ky	4	J. M. Roberts
Maine, Univ. of, Orono, Me	1	W. H. Bliss
Marquette Univ., Milwaukee, Wis	5	F. A. Kartak
Mass. Inst. of Tech., Cambridge, Mass	1	W. H. Timbie
Michigan Col. of Min. & Tech., Houghton, Mich	5	G. W. Swenson
Michigan State Col., E. Lansing, Mich	5	E. E. Kinney
Michigan, Univ. of, Ann Arbor, Mich	5	S. S. Attwood
Milwaukee Sch. of Engg., Milwaukee, Wis	5	O. Werwath
Minnesota, Univ. of, Minneapolis, Minn	5	J. H. Kuhlmann
Mississippi State Col., State College, Miss	4	L. H. Fox
Missouri Sch. of Mines and Met., Rolla, Mo	7	I. H. Lovett
Missouri, Univ. of, Columbia, Mo	7	A. C. Lanier
Montana State College, Bozeman, Mont	9	J. A. Thaler
Nebraska, Univ. of, Lincoln, Neb	6	F. W. Norris
Nevada, Univ. of, Reno, Nev	8	S. G. Palmer
Newark Col. of Engg., Newark, N. J	3	J. C. Peet
New Hampshire, Univ. of, Durham, N. H	1	L. W. Hitchcock
New Mexico, Univ. of, Albuquerque, New Mexico	7	Chester Russell, Jr.
New York, Col. of the City of, New York, N. Y	3	Harry Baum
New York Univ., New York, N. Y	3	H. N. Walker
North Carolina State Col. Raleigh, N. C	4	R. S. Fouraker
North Carolina, Univ. of, Chapel Hill, N. C	4	W. J. Miller
North Dakota State College, Fargo, No. Dak	6	H. S. Rush
North Dakota, Univ. of, Grand Forks, No. Dak	6	H. F. Rice
Northeastern Univ., Boston, Mass	1	W. L. Smith
Notre Dame, Univ. of, Notre Dame, Ind	5	J. A. Caparo
Ohio Northern Univ., Ada, Ohio	2	I. S. Campbell
Ohio State Univ., Columbus, Ohio	2	F. C. Caldwell
Ohio Univ., Athens, Ohio	2	A. A. Atkinson
Oklahoma A. & M. Col., Stillwater, Okla	7	Albrecht Naeter
Oklahoma, Univ. of, Norman, Okla	7	C. T. Almquist
Oregon State Col., Corvallis, Ore	9	A. L. Albert
Pennsylvania State Col., State College, Pa	2	L. A. Doggett
Pennsylvania, Univ. of, Philadelphia, Pa	2	C. D. Fawcett
Pittsburgh, Univ. of, Pittsburgh, Pa	2	H. E. Dyche
Porto Rico, Univ. of, Mayaguez, P. R	3	Miguel Wiewall, Jr.
Pratt Institute, Brooklyn, N. Y	3	C. C. Carr
Princeton Univ., Princeton, N. J	2	Malcolm Maclaren
Purdue Univ., Lafayette, Ind	5	A. N. Topping
Rensselaer Poly. Inst., Troy, N. Y	1	F. M. Sebast
Rhode Island State Col., Kingston, R. I	1	Wm. Anderson
Rice Institute, Houston, Texas	7	J. S. Waters
Rose Poly. Inst., Terre Haute, Ind	5	C. C. Knipmeyer
Rutgers University, New Brunswick, N. J	3	F. H. Pumphrey
Santa Clara, Univ. of, Santa Clara, Calif	8	E. F. Peterson
South Carolina, Univ. of, Columbia, S. C	4	T. F. Ball
South Dakota State Col., Brookings, So. Dak	6	W. H. Gamble
So. Dak. State Sch. of Mines, Rapid City, S. D	6	J.O. Kammerman
South Dakota, Univ. of, Vermillion, So. Dak	6	C. W. Caldwell
Southern California, Univ. of, Los Angeles, Calif	8	N. C. Clark
Southern Methodist Univ., Dallas, Texas	7	R. H. Flath
Stanford Univ., Stanford University, Calif	8	H. H. Skilling
Stevens Inst. of Tech., Hoboken, N. J	3	H. C. Roters
Swarthmore Col., Swarthmore, Pa	2	Lewis Fussell
Syracuse Univ., Syracuse, N. Y	1	C. W. Henderson
Tennessee, Univ. of, Knoxville, Tenn	4	J. G. Tarboux
Texas A. & M. Col., College Station, Texas	7	R. W. Markle
Texas Technological Col., Lubbock, Texas	7	C. V. Bullen
Texas, Univ. of, Austin, Texas	7	J. A. Correll
Utah, Univ. of, Salt Lake City, Utah	9	J. H. Hamilton
Vermont, Univ. of, Burlington, Vt	1	
Villanova College, Villanova, Pa	2	H. S. Bueche
Virginia Military Inst., Lexington, Va	4	S. W. Andersou
Virginia Poly. Inst., Blacksburg, Va	4	Claudius Lee
Virginia, Univ. of, University, Va	4	J. S. Miller
Washington, State Col. of, Pullman, Wash	9	O. E. Osburn
Washington, Univ. of, Seattle, Wash	9	J. R. Shuck
Washington Univ., St. Louis, Mo	7	W. L. Upson
West Virginia Univ., Morgantown, W. Va	2	A. H. Forman
Wisconsin, Univ. of, Madison, Wis	5	C. M. Jansky
Worcester Poly. Inst., Worcester, Mass	1	C. D. Knight
Wyoming, Univ. of, Laramie, Wyo	6	G. H. Sechrist
Yale Univ., New Haven, Conn	1	W. B. Hall
Total 113		

A Student Branch at Brown University, Providence, R. I., was authorized by the Institute's board of directors, August 7, 1934, but at the time of going to press of this issue, had not yet been organized.

Industrial Notes

Westinghouse Orders Show Large Increase.—For the 2nd quarter of 1934, Westinghouse Electric & Mfg. Co. orders totaled $33,655,022, as compared with $20,237,588 for the previous quarter and $17,557,964 for the second quarter of 1933. Sales billed for the second quarter of 1934 totaled $27,287,545, compared to $17,994,045 for the previous quarter, and $15,926,335 for the corresponding quarter of 1933. Unfilled orders at June 30 were $31,892,155 as compared with $24,705,173 on June 30, 1933. According to President F. A. Merrick, orders received for the first half of 1934 show increase of 77% over a similar period in 1933.

General Radio Co. Opens New York Office.—The General Radio Co., Cambridge, Mass., announces the opening of an engineering office at 90 West Street in New York City. Engineers from the Cambridge staff have been assigned to this office to assist customers in problems pertaining to radio and electrical measurements.

Engineering Services Merged.—Sanderson & Porter, Engineers, with offices in New York, Chicago, and San Francisco, announce the merger of their service for public utility valuation and that of the Cecil F. Elmes organization, to constitute the valuation department of Sanderson & Porter, under the direction of Cecil F. Elmes.

Burgess Appoints E. A. Sipp.—Until recently manager of the lighting division of the Pyle-National Co., E. A. Sipp is now associated with the management of the Burgess Battery Co. and C. F. Burgess Laboratories, Inc., and will maintain his headquarters in the offices of the Burgess organizations at 111 W. Monroe St., Chicago.

Allis-Chalmers Moves Chicago Office.—The new Field Building, 135 S. LaSalle St., now houses the Chicago district office of the Allis-Chalmers Mfg. Co. B. F. Bilsland is manager of the Chicago district. Thus the company returns to its original Chicago location, for the new Field Building stands on the site of the old Home Insurance Building, where the general offices of the Allis-Chalmers Co. were first located after the company was organized, through consolidations, in the year 1901.

Delta-Star to Produce Oil-Blast Circuit Breakers.—The Delta-Star Electric Co., Chicago, reports that it has been granted a patent license by the General Electric Co. to manufacture oil-blast circuit breakers, and has also arranged for the use of the high capacity testing laboratory of the latter company at Schenectady, to conduct tests on these new oil-blast designs. The unit type line of Delta-Star metal-clad switchgear not only includes oil-blast breakers but also the three point balanced circuit breaker mounting, with its single worm gear lifting and lowering mechanism and transfer truck, permitting detanking of breaker for test and inspection without the use of a separate test rack.

New Engineering Service for Manufacturers.—Joseph C. Rah & Co., 5745 West Ohio St., Chicago, has recently been organized to render special services exclusively to manufacturers, along the following lines: materials and process engineering; electrical insulation design; mechanical and electrical design; styling; chemical engineering; research, development, and special problems. The new company reports a very favorable response from manufacturers who wish to keep the development and design of their equipment up to date but at the same time do not wish to add full-time specialists to their staffs.

Electric Locomotives for Penn. R. R.—Work has been started at the Erie, Pa., plant of the General Electric Co. on electric equipment for 11 new type locomotives being obtained by the Pennsylvania Railroad as part of a new building program which will involve the expenditure of more than $6,000,000. Five of the locomotives will be entirely constructed by the General Electric at Erie; the other equipments will be assembled at the railroad's Altoona works. The new engines will be of the same general type as those now in regular passenger service but the cab has been redesigned to give the locomotive more symmetry of line. The engineman's control will be in the center instead of at the ends of the cab. The locomotives will be part of the fleet of 101 electrics for through-electric passenger and freight service between New York and Washington, to be inaugurated next year.

Trade Literature

Sodium-Vapor Lighting.—Bulletin 3010, 4 pp. Describes the sodium lamp for street and highway lighting. General Electric Co., Schenectady, N. Y.

Building Wires and Cables.—Bulletin, 16 pp. Describes Safecote (flame retarding and moisture resistant) braided building wires and cables. General Cable Corp., 420 Lexington Ave., New York.

Electric Instruments.—Catalog GEA-602D, 162 pp. Includes complete data on standard lines of switchboard, portable and laboratory instruments. General Electric Company, Schenectady, N. Y.

Electrically Heated Ladles.—Bulletin P-57. Describes electrically heated funnel and pouring ladles for waxes, compounds, solder, babbitt, etc. Struthers Dunn, Inc., 139 N. Juniper St., Philadelphia, Pa.

Oilproof Portable Cords.—Bulletin, 2 pp. Describes oilproof "Okocord," a Thiokol-sheathed portable cord conductor, insulated with Okonite, particularly designed to meet oily conditions and highly resistant to ozone and corrosive gases and acids. The Okonite Co., Passaic, N. J.

Air Conditioning.—Bulletin, 18 pp., "Air Conditioning Planned and Proved." Outlines the factors to be considered in planning air conditioning projects; lists and describes typical installations. Clyde R. Place, Consulting Engineer, Graybar Building, New York.

Overcurrent Relays.—Bulletin 41–505, 12 pp. Describes types CR and CRA directional overcurrent relays, primarily to sectionalize transmission lines but used also for the protection of generators subject to feed-back from other sources. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Pumps.—Bulletin 221, 16 pp. Describes multi-stage centrifugal pumps, available with as many as six stages in a single casing. Bulletin 223, 12 pp. Describes motor pumping units, single-stage, single-suction, enclosed impeller types, capacities 50 to 750 g.p.m. Pennsylvania Pump & Compressor Co., Easton, Pa.

Ladder Mounts.—Bulletin 376, 24 pp. Describes the Keystone ladder mount and other utility ladders. The ladder mount is a complete extension ladder mounted on a rotating device and arranged to be carried on any small or large truck body. The ladder can be rotated throughout a complete circle and can be rigidly locked in any position. Electric Service Supplies Co., 17th and Cambria Sts., Philadelphia, Pa.

Armored Service Entrance and Drop Cables.—Bulletin 100, 4 pp. Describes concentric armored service entrance and service drop cables which are now offered in a complete line of such types. Photographs and tabulations set forth physical characteristics of the designs available, which may be employed in varying combinations to satisfy specific requirements. American Steel & Wire Co., 208 So. LaSalle St., Chicago.

Brass Die Castings.—Bulletin, 16 pp., entitled "Brass Die Castings with Strength of Steel." According to this bulletin, intricate brass parts which have heretofore presented a difficult or costly production problem can now be produced economically by die castings, and parts which formerly had to be made in separate units and soldered can now be die cast in a single operation. Doehler Die Casting Co., 386 Fourth Ave., New York.

Monel Metal.—Booklet. Describes applications of Monel Metal, nickel, and nickel-clad steel, prepared especially for users of industrial processing equipment. Besides data on the physical and mechanical properties of these materials, the booklet contains considerable miscellaneous information, including instructions on the selection of suitable welding rod and other details on fabrication. The International Nickel Co., Inc., 67 Wall St., New York.

Published Monthly by

American Institute of Electrical Engineers

(Founded May 13, 1884)

Electrical Engineering

Registered U. S. Patent Office

October 1934
Volume 53
No. 10

The Official Monthly Journal and Transactions of the A.I.E.E.

J. Allen Johnson, President
H. H. Henline, National Secretary

Publication Committee
C. O. Bickelhaupt, Chairman
J. W. Barker — L. F. Hickernell
R. N. Conwell — E. B. Meyer
L. A. Doggett — L. W. W. Morrow
W. S. Gorsuch — I. M. Stein
H. H. Henline — H. R. Woodrow

Publication Staff
G. Ross Henninger, Editor
C. A. Gaul, Advertising Manager

PUBLICATION OFFICE, 20th and Northampton Streets, Easton, Pa.

EDITORIAL AND ADVERTISING OFFICES, 33 West 39th Street, New York, N. Y.

ENTERED as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918.

SUBSCRIPTION RATES—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii and the Philippine Islands, Central America, South America, Haiti, Spain and Spanish Colonies; $13 to Canada; $14 to all other countries. Single copy $1.50.

CHANGE OF ADDRESS—requests must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered due to incorrect address cannot be replaced without charge. Be sure to specify both old and new addresses and any change in business affiliation.

ADVERTISING COPY—changes must be received by the fifteenth of the month to be effective for the issue of the month succeeding.

STATEMENTS and opinions given in articles appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters.

REPUBLICATION from "Electrical Engineering" of any Institute article or paper (unless otherwise specifically stated) is hereby authorized provided full credit be given.

COPYRIGHT 1934 by the American Institute of Electrical Engineers.

ELECTRICAL ENGINEERING is indexed in Industrial Arts Index and Engineering Index.

Printed in the United States of America. Number of copies this issue—

16,700

This Month—

Front Cover

Transmission towers in England, showing secondary transmission (33,000-volt) lines in Hampshire supplying electricity from Nursling to Salisbury in southwest England

Educational Series—No. 10

Operational Calculus 1339
By MURRAY F. GARDNER

Special Feature

Another Message From the President to the Institute Membership 1338

A.I.E.E. Papers

"Thyratron" Tubes in Relay Practice 1347
By ROLF WIDERÖE

Overloading of Power Transformers . . 1353
By V. M. MONTSINGER and W. M. DANN

Engineering Education Is Meeting the Challenge 1356
By HAROLD W. BIBBER

Heat Flow in Turbine Generator Rotors 1359
By C. E. PECK

A New Timer for Resistance Welding 1366
By RALPH N. STODDARD

Wide Band Transmission Over Coaxial Lines 1371
By LLOYD ESPENSCHIED and M. E. STRIEBY

A High Power Welding Rectifier . . . 1380
By DANIEL SILVERMAN and J. H. COX

The "Ignitron" Type of Inverter . . . 1384
By C. F. WAGNER and L. R. LUDWIG

Dielectric Properties of Cellulose Paper—I 1389
By J. B. WHITEHEAD and E. W. GREENFIELD

News of Institute and Related Activities 1423

Salt Lake Convention Upholds Coast Reputation 1423
Nomination of A.I.E.E. Officers for 1935 Election; Members Invited to Submit Suggestions for Nov. 15 1425

Letters to the Editor 1427

Membership 1430

Engineering Literature 1431

Industrial Notes 1432

Employment Notes (See Advertising Section)

Officers and Committees (For complete listing see p. 1332–6, September 1934 issue of ELECTRICAL ENGINEERING)

—Turn to Next Page

Discussions of A.I.E.E. Papers

Electrical Machinery

Voltage Control of Vapor Rectifiers—Journeaux 1396

Grid Controlled Rectifiers and Inverters—Herskind 1400

Insulation Coördination of Transformers—II—Bellaschi & Vogel . 1401

Insulation Resistance of Armature Windings—Wieseman . . . 1407

Split Winding Transformers—Chase & Garin 1411

Education

Encouraging Initiative in the Engineering Student—Dawes . 1413, -16

Industry Demands and Engineering Education—Morrow 1413, -18

Engineers of the Next Generation—Hirshfeld 1413

CORRECTION: In the news report of the 1934 A.I.E.E. summer convention held June 25–29 at Hot Springs, Va., which was published on p. 1225–9 of the August issue, White Sulphur Springs, W. Va., was incorrectly stated to be in District No. 4; it is in District No. 2.

Another Message From the President

To the Institute Membership—

IN MY last message I spoke of the desirability of "tidying up" the Institute and the profession and mentioned a number of proposals which seemed to be directed toward that result. Now the cardinal principle of tidiness is "a place for everything and *everything in its place*," and since writing that message I have been thinking about that principle in relation to the A.I.E.E.

In many old New England homes there used to be a piece of furniture called a "what-not." It stood in a corner of the living room and was a depository for all sorts of miscellaneous objects. Somehow, as I look over the names of Institute members listed as "Associates," I cannot help remembering my grandmother's old what-not, and wondering if tidiness like charity, should not begin at home. Would it not be very much in order, as a first step toward tidying up the Institute, for each member to consider his own position therein and, if necessary, take action to put himself in his proper "place."

Specifically, it seems to me very untidy indeed to have a compartment labelled "Associates" all cluttered up, as it is, with people who ought to be in compartments labelled "Juniors," "Members," and "Fellows." In fact, this condition seems to me not only untidy but unfair both to the individuals concerned and to everybody else. It places every Associate in a false position because no one can tell who is which.

Undoubtedly our constitutional organization is partly responsible for this untidy condition. We never have had in the Institute a specific place for the younger engineers in the apprenticeship stage of their development. We have dumped them into the Associate "what-not" where they have found themselves in the company of a heterogeneous throng ranging all the way from novices like themselves to engineers of world-wide reputation. With the Associate grade thus overlapping and blanketing all the others the significance of the successive professional grades of Member and Fellow has been shrouded and largely nullified. The designated pathway of progress in professional standing has been hidden amid this confusion, hence there has been little incentive for orderly advancement from grade to grade and the confusion in the Associate grade has become self-perpetuating and cumulative.

Is it not time to clean house? A "Junior" grade of membership would help, but without waiting for the constitutional changes necessary to add this needed "reception room" to our edifice we can at least put our existing house in order if each of us will find and enter the "compartment" where he belongs. It seems to me we owe this much to our own professional standing as well as to the dignity and prestige of the Institute and the engineering profession. I think we should not forget that to "maintain a high professional standing among its members" is 1 of the 2 constitutional objects of the Institute.

If you have thoughtlessly allowed yourself to drift into the false and anomalous position above described, especially if you are a responsible engineer to whom younger men look for inspiration and guidance, I earnestly commend the above thoughts to your consideration and appropriate action. Let's start tidying up the profession by putting our own house in order.

Faithfully yours,

J. Allen Johnson

President A.I.E.E.

P.S. Transfer application blanks can be obtained from the national secretary or from your Section committee on transfers.

Operational Calculus

By MURRAY F. GARDNER, Member A.I.E.E.
Massachusetts Institute of Technology, Cambridge

Operational calculus is useful in both the formulation and solution of the differential equations involved in engineering problems, and because of its power and directness it is finding increasing favor in engineering analysis. It is especially helpful to the electrical engineer because many of his problems involve transients, the analysis of which requires the solution of differential equations. In this article is presented not a popular treatment of operational calculus (several of which already have been published), but rather a brief survey of the historical development, an introduction to the background, and a summary of the threads of rigorous analysis that bind the many processes into a rational and systematic whole. This is the tenth in a series of special articles developed under the sponsorship of the A.I.E.E. committee on education.

WHILE, in general, transients in physical systems represent undesirable disturbances which must be allowed for with suitable factors of safety in engineering design and operation, today they are being intentionally produced and usefully applied in numerous fields. For examples where they appear in the latter aspect, consider the sweep circuit for the cathode ray oscillograph beam, the high voltage or high current surge generators, and the inverter with its operation a continuous series of transients. The analysis of transients, in whichever aspect they may appear, constitutes a problem of growing practical importance in progressive engineering. In the encouraging progress being made in this field operational calculus is playing a steadily increasing part.

Transient analysis involves the solution of differential equations. In his formal training the engineer has studied ordinary differential equations, particularly the linear type with constant coefficients, and often simple partial differential equations. Operational calculus can helpfully supplement this training. It can help both in the formulation and in the solution of the differential equations of engineering problems. Through the aid to thinking given by the directness of its notation and the powerfulness of its concepts, expression in mathematical language of the physical relations more readily is effected; through its systematic procedure and well-organized summaries of previous experience, solution more easily is accomplished.

Popular treatments of operational calculus are available in technical literature, so this article aims to do something different. It presents a brief survey of the historical development, an introduction to the background, and a summary of the threads of rigorous analysis that bind the many processes into a rational and systematic whole. Any discussion of these aspects must involve functional reasoning in somewhat unfamiliar terms. From this, however, it is not to be gathered that operational calculus is composed of an assortment of bizarre mathematics. On the contrary it embodies an exceedingly compact symbolic substitute for much difficult mathematics. One can appreciate this only from some acquaintance with the mathematics for which it serves, from which it derives its limitations, and from which it gathers guidance in its further development. These aspects, rather than the technique of its application, are the ones discussed here.

Operational calculus applies to systems or situations where cause and effect stand in linear relation. Since in general for practical engineering purposes only first-order effects need be considered, a great range of physical systems can be treated as linear, and their differential relationships lead to equations within the scope of operational methods.

As operational calculus still is evolving, it should not be characterized too closely; but, in general, in its application to differential equations it embodies features such as outlined here. To be explicit, time will be considered the independent variable. The time differentiators in the differential equations are replaced by a simple symbol (the use of p for $\frac{d}{dt}$ is almost universal). The resulting supplementary equations are treated as equations in algebra, and solved algebraically. The disturbing forces may be of general form, but the most common ones are the unit constant force $\mathbf{1}$, the unit exponential $e^{\omega t}\mathbf{1}$, and the unit sinusoid $\sin \omega t\mathbf{1}$. The symbol $\mathbf{1}$ represents a time function which is zero for $t<0$, and unity for $t>0$. Its product with any other time function is likewise zero for $t<0$. The initial conditions of the physical system are generally those of rest, or of equilibrium; if not, these conditions are included in the supplementary equations, each being responsible for certain added terms.

Taking for example a case expressible by a system of ordinary differential equations in which there is a single unit disturbing force $\mathbf{1}$, and the initial conditions are those of rest, the algebraic solution of the supplementary equations for the unknown $h(t)$ is

$$h(t) = \frac{1}{H(p)}\mathbf{1} \tag{1}$$

where $\frac{1}{H(p)}$ is the operator, and $\mathbf{1}$ the operand. The operator embodies all pertinent information about the physical system, such as its interconnections, parameters, and initial conditions. The operand, however, while termed the disturbing "force," need

not have the dimensions of a force. For instance, it may be a suddenly applied electromotive force, current, charge, torque, velocity, displacement, temperature, rate of heat flow, or other independently variable quantity. The requirement is that its entire history and future variation be known, and appear in functional form in this part of the equation. For the simple case considered here, its past was zero; its present and future are unity. Solving eq 1 consists in applying any of them any possible processes for converting the right member into functions of time and the system parameters. A survey of these processes constitutes a large part of the study of operational calculus, and cannot be reproduced here.

A distinctive feature of operational calculus, when used in this manner to solve differential equations, is that it gives directly as its result the *complete* solution of the problem set, with all initial and boundary conditions satisfied. Also, unless it is a convergent series solution, the steady-state and transient portions (i. e., the particular integral and the complementary function with all its constants of integration evaluated) are readily distinguishable. The patchwork process of the ordinary calculus in which a general solution, consisting of particular integral and complementary function, is obtained first and revised afterward to suit the initial conditions, is replaced by a symbolic process involving complete mathematical expression of the problem at the outset, and a systematic conversion of resulting operator and operand into functions of the independent variable and system parameters. Because of this surprising power and directness, operational calculus is finding increasing favor in engineering analysis.

Fields in which the electrical engineer finds use for operational calculus are many and varied, and only a few can be enumerated. It finds application in the analysis of:

1. Traveling wave transients on transmission lines and cables, including reflections at junction points and terminal apparatus.
2. Surge protection of transformers and rotating machinery.
3. Short-circuit transients in a-c machines.
4. Transient voltage regulation of d-c generators.
5. Circuits of high voltage and high current surge generators.
6. Transients in relay and control circuits.
7. Propagation of communication signals.
8. Transients in filter circuits and artificial lines.
9. Transient interference between a grounded transmission line under fault conditions and an adjacent communication line.
10. Cathode ray oscillograph potential-divider, time-delay, and sweep circuits.
11. Transients in vacuum tube amplifier and oscillator circuits.
12. Transients in measurement circuits.
13. Field transients in iron cores partially laminated and partially solid, influencing design of field circuits for quick-response excitation of large a-c generators, and for rapid-reversing d-c rolling-mill motors.
14. Transient heat flow in machinery, cables, and rectifier seals.
15. Transient sound propagation.
16. Transient mechanical vibrations.

Historical Development

Operational methods of solving linear differential equations as met in formal courses in differential equations are largely from the work of Boole (1865) a mathematician of Queen's University, Ireland. He treated the differentiator $\frac{d}{dx}$ as an operator D, showed that the latter obeyed the fundamental laws of algebra as though it were a symbol of quantity rather than operation, and gave theorems for its use in solving both ordinary and partial differential equations. In particular, he was responsible for the partial-fraction expansion scheme of solving the constant-coefficient type of linear equations.

The operational calculus considered here, however, has reference more particularly to the operator processes of Heaviside, who, while not the originator of the symbolic method of treating differential equations, did devise for it those remarkable features of directness and power that make it appeal so strongly to one with a practical interest in mathematics. Operational symbolism first appeared in Heaviside's papers in 1881. Not until 5 years later did he begin to improve upon conventional procedure in the evaluation of integration constants—still a burdensome after-adjustment even with the operational processes of Boole.

In 1886 Heaviside employed his "conjugate" theorem as an aid in evaluating the coefficients of normal function solutions of distributed-system transients. Vallarta (1926) has pointed out that this undoubtedly marked the beginning of Heaviside's normal function expansion theorem. In a paper published a month later in 1886, Heaviside presented this expansion theorem in completed form—casually, in a footnote. The basis here was not his conjugate theorem, but an algebraic expansion in partial fractions such as Boole had employed. As a result of this advance, integration constants became expressible directly by formula provided the initial conditions were those of rest and the disturbing cause a simple unit force.

Within the next 3 years, Heaviside had introduced in his papers the majority of the features associated with his operational methods, such as "resistance" and "conductance" operators for formulation of operational solutions, irrational operators, the unit function, expansions in normal functions, expansions in series, expansions in waves, the transfer operator, and the shifting operation. These features appear in Volume II of his "Electrical Papers" (1892). In Volume II (1899) of his "Electromagnetic Theory" he enlarges greatly upon these processes in connection with the solution of the transient behavior of cables, lines, and networks. In Volume III (1912) is a section devoted to the solution of definite integrals by differential transformation, which will be of interest later in this article. These and his papers "On Operators in Physical Mathematics" in 1893 and 1894 constitute the principal sources of information on his contributions. Nowhere in these, however, does he give any real systematic discussion of his operational processes, correlating them, and establishing their relationship to more formal mathematics. His use of novel methods without introduction, and with small explanation, was bewildering indeed. He was pioneering in the difficult field of diffusion and wave propagation; new mathematical procedures seemed necessary, and he did not hesitate to devise them. It was typical of him with his ec-

centric ways that he should verify carefully all that he did, but leave proof and justification of his processes to others. As a consequence of an unsystematic presentation of his methods, and their difficult and sometimes unorthodox nature, some 30 years elapsed before they received anything like formal substantiation.

Bromwich, a Cambridge mathematician, appears to have been the first to supply formal justification of Heaviside's methods. A paper he presented in 1914, but which was not published until 1916, interpreted these methods in terms of complex function theory. Unit function was expressed as a line integral in the complex plane, and the interpretation of the operational equation (eq 1) was given as

$$h(t) = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} \frac{e^{ut}}{uH(u)}\,du \tag{2}$$

Interpretation of this will appear later.

Wagner in Germany apparently was working simultaneously along lines similar to those followed by Bromwich, seeking to correlate Heaviside's processes with function theory, for he published in 1916 a justification likewise employing line integration in the complex plane. He gave as his interpretation of eq 1 the complex line integral

$$h(t) = \frac{1}{2\pi j}\int_L \frac{e^{ut}}{uH(u)}\,du \tag{3}$$

where L designates the path of integration in the complex plane. The difference in these 2 line integrals rests solely in the path of integration chosen.

Carson, working along independent lines in 1925 evolved an entirely different interpretation of Heaviside's processes. He expressed the relation between $h(t)$ and $\frac{1}{H(p)}$ of eq 1 as an equation of the form

$$\frac{1}{uH(u)} = \int_0^\infty h(t)e^{-ut}\,dt \tag{4}$$

where u may be complex, but its real part must be positive. With $h(t)$ the unknown, eq 4 is an integral equation. It gives $h(t)$ implicitly. Limited to this relationship alone, the determination of $h(t)$ to satisfy the equation would be exceedingly difficult in general were it not for the fact that integrals of this form have been much studied and their evaluations tabulated in complete tables of integrals. However, Carson did not stress it so much as a means of evaluating operational equations as of providing guidance to rules of operational transformations, and substantiation of results obtained operationally.

Like previous writers, Carson considered the solution resulting from unit function with initial rest conditions the fundamental one; but for more general disturbing forces he utilized the Boltzmann-Hopkinson superposition theorem. Thus the solution of the general operational equation

$$h(t) = \frac{1}{H(p)} f(t)\,1 \tag{5}$$

proceeded in 2 steps: first

$$h_1(t) = \frac{1}{H(p)}\,1 \tag{6}$$

with interpretation guided by eq 4, then by the superposition theorem

$$h(t) = \frac{d}{dt}\int_0^t h_1(\lambda)f(t-\lambda)\,d\lambda \tag{7}$$

Interpretations of Heaviside's processes by complex line integral and by integral equation were naturally not without relation, for each expressed a connection between the operator $\frac{1}{H(p)}$ and its equivalent $h(t)$. They were joined when Lévy (1926) and March (1927) pointed out that they constitute the complementary parts of a generalized Fourier integral. That is, if $h(t)$ is the unknown, eq 4 is an integral equation, and eq 2 is its solution; however, if $\frac{1}{H(p)}$ is the unknown, the rôles of the equations are interchanged.

One unskilled in formal mathematics finds Bromwich's papers difficult reading. It is fortunate therefore that Jeffreys (1927), also of Cambridge, has supplied an interpretation; but in his tract on operational methods he has done more than just this. Starting with an operational method, introduced by Caqué (1864), for solving an ordinary linear first-order differential equation (by repeated substitutions resulting in a series for interpretation by repeated integrations), Jeffreys builds up a complete treatment of simultaneous ordinary linear differential equations with constant coefficients. Whereas this supplementary approach could be used for ordinary differential equations, for partial differential equations substantiation still had to rest entirely upon the line integral treatment.

Jeffreys includes in his development a scheme for handling operationally initial conditions other than those of rest. Of course, the systems subject to analysis by operational methods must be linear, and a linear system having such arbitrary initial conditions can be brought within the scope of the conventional operational method by artifices; but at best these are usually awkward to handle, and a straightforward operational formulation of the entire problem at the outset is much to be preferred.

Campbell and Foster published in 1931 a table of Fourier transforms, based upon an earlier paper of Cambell's (1928), which makes available in convenient form to the engineer those solutions of the Fourier integral that the professional mathematician has made. By alliance of the operational calculus with the Fourier integral, this table of transforms can be interpreted conveniently as one of operational formulas, and, as such, is the most complete table of the latter available.

In 1929 van der Pol began a series of papers that has influenced materially recent developments in the operational method. The basis of his treatment is the same integral equation used by Carson, but written

$$\frac{1}{H(u)} = u\int_0^\infty h(t)e^{-ut}\,dt \tag{8}$$

and is the definition of his symbolic relation

$$\frac{1}{H(u)} \doteqdot h(t) \tag{9}$$

in which the unit function is not used. His method is one of transforms. The differential equation is replaced by a supplementary equation as before, but its terms are the transforms, term for term, of the original equation—a new approach entirely in operational calculus. With previous methods, the supplementary equation has been expressed in operational notation, there has been an idea of operator and operand, and the rules for interpreting its solution have been derived from study of either a complex line integral or an integral equation, each involving a complex variable. In this newer method, the supplementary equation is expressed directly in functions of a complex variable. The concept of operator and operand is discarded. Its unknowns are the transforms of the unknowns in the original equation. The problem becomes one of solving the supplementary equation to determine the actual form of the desired transform, and then converting this by retransformation or by operational methods into its equivalent original. Because van der Pol uses $\frac{1}{H(u)}$ as symbolically equivalent to $h(t)$ (rather than using $\frac{1}{uH(u)}$ which would be its actual Laplace transform), and because he uses p as the symbol for his complex variable, his supplementary equations for linear differential equations with constant coefficients appear similar to those found with the older method; but their true significance is different.

This has proved a fruitful process. By means of it van der Pol has been able to do all that was done formerly, including the treatment directly of arbitary initial values. In addition he has extended the operational method to the solution of linear differential equations with variable coefficients; and, amplifying Heaviside's methods of solving definite integrals by differential transformations, he has developed a system of simultaneous operational calculus, and a symbolic treatment of definite integrals.

Some recent work of Lowan (1934) is related to operational developments. Using the processes of van der Pol he has shown the use of the transform in the solution of certain partial differential equations having arbitrary initial and boundary conditions to be satisfied. He has used the actual Laplace transform, rather than its modified form employed by van der Pol. As with the latter's work, when solution of the supplementary equation has been secured it can be retransformed, or else treated operationally, to gain the solution of the original problem. The displacement of operational processes by the transformation scheme is here almost complete.

Many others have contributed to the gradual substantiation, development, and promotion of operational calculus, and it is regrettable that this brief survey cannot include some mention of the work of Berg, Bush, Fry, Georgi, Pennell, Pleijel, Stachó, Sumpner, Volterra, Wiener, and others.

Fourier Integral Background

The most satisfactory substantiations of Heaviside's work are based upon one aspect or another of the Fourier integral. Against the background supplied by this, his methods become well understood as the shorthand expressions for rigorous mathematical relationships. There has been a distinct gain in power for the operational calculus from this association. The Fourier integral is an old and highly developed tool for the treatment of transient phenomena. The parallel between its transform theory and operational processes has been well utilized, and, in recent developments there is evidence of a trend in operational calculus away from rather constraining concepts of "operator" and "operand" toward the more flexible and more powerful processes of the transform.

One familiar with only the conventional features of the operational calculus and unacquainted with the associated Fourier integral background would find the recent developments a rather bewildering interchange of functions and operators in equations, integrals, and summations. There are in use such expressions of relationship as

$\frac{1}{H(u)}$ "is symbolically equivalent to" $h(t)$

$\frac{1}{H(u)}$ is the "image," and $h(t)$ is its "original"

$\frac{1}{uH(u)}$ "is the transform of" $h(t)$

$\frac{1}{uH(u)}$ "is the mate of" $h(t)$

$\frac{1}{uH(u)}$ is the "convert," and $h(t)$ is its "revert"

The unit function seldom is expressed. Heaviside himself did not always express an operand, but his unit function was implied. He departed furthest from this in his treatment of definite integrals by differential transformation, where he replaced functions with operator equivalents, and conversely, quite independent of functional arrangement. It was distinctly a transform process. It is this aspect of Heaviside's work that van der Pol and his co-authors have revived and extended in their "simultaneous operational" and "symbolic" calculus. They have found the operator-operand concepts difficult to reconcile with this freedom of manipulation, and accordingly have frankly discarded them in favor of the transform concept.

Because of this trend in operational calculus toward the use of transforms rather than operators, and because of the many rules for manipulation and interpretation of transforms, and the large collection of transform pairs available as a result of the mathematicians study of the Fourier integral, it is most desirable for one utilizing operational calculus to have some acquaintance with the Fourier method of dealing with transients. The rules for its transforms will guide him in the interpretation and use of his operational processes, and its transform pairs will provide him with a host of operational formulas.

As the engineer is well acquainted with the Fourier series, it will be taken as the introduction to its more powerful ally, the Fourier integral. The form of the integral can be determined quickly from the series by rather nonrigorous steps. This, however, will not be shown here, but rather the correspondence

between their expressions. The argument will be clothed with a certain amount of familiar electrical engineering terminology.

Consider a linear, stable, dissipative, nonimpulsive, 2-terminal network available for which the input impedance $Z(j\omega)$ is known as a function of frequency f, with $\omega = 2\pi f$. If a periodic but nonharmonic emf be applied to this network, it is known from experience that the resulting steady state input current likewise will be periodic and nonharmonic, and in general of wave form different from that of the emf. The computation of this case involves the use of the Fourier series. The emf, presumed to be physically realizable and satisfying all the requirements for Fourier analysis, can be expressed as a summation of sinusoidal emf's of fundamental and harmonic frequencies. The network being linear, the principle of superposition applies. The current resulting from each emf component can be computed separately, and these component currents superposed in proper phase relation to determine the total resulting steady state current. In brief, the process consists of 3 steps: (1) analysis of the emf to determine its components, (2) solution for steady state current component corresponding to each, and (3) synthesis of these components to obtain the total steady state current.

The Fourier series commonly is expressed in trigonometric functions, but a more compact and convenient expression can be made with their equivalent exponential oscillating functions. The period of the fundamental is taken as $2S$. Then, except at any points of discontinuity,

$$e(t) = \frac{1}{2}\sum_{n=-\infty}^{\infty} E\left(jn\frac{\pi}{S}\right) \epsilon^{jn\frac{\pi}{S}t} \tag{10}$$

where

$$E\left(jn\frac{\pi}{S}\right) = \frac{1}{S}\int_{-S}^{S} e(\lambda)\,\epsilon^{-jn\frac{\pi}{S}\lambda}\,d\lambda. \tag{11}$$

Equation 11 constitutes the analysis of $e(t)$, and 10 a synthesis to regain $e(t)$. The nth component of current associated with the nth component of emf is

$$\frac{E\left(jn\frac{\pi}{S}\right)}{Z\left(jn\frac{\pi}{S}\right)}\,\epsilon^{jn\frac{\pi}{S}t}$$

and the total steady state current is

$$i(t) = \frac{1}{2}\sum_{n=-\infty}^{\infty} \frac{E\left(jn\frac{\pi}{S}\right)}{Z\left(jn\frac{\pi}{S}\right)}\,\epsilon^{jn\frac{\pi}{S}t} \tag{12}$$

Equation 12 constitutes the synthesis to obtain $i(t)$. It is to be emphasized that this has dealt only with the steady state, and that both emf and current are periodic.

The sudden application at $t = 0$ of an emf to the network will produce, in general, not only the steady state current, but also a certain amount of transient distortion, finally disappearing since the circuit is dissipative. To express this entire result requires the Fourier integral.

Whereas before, it was sufficient to consider only one complete cycle of emf and current, it is necessary now to express their entire history. For this case an emf will be considered that is zero for $t<0$, nonperiodic for $t>0$ but never becomes infinite, and damps out at least exponentially for t very great. Such an emf has an infinite period. The Fourier integral, by which it can be expressed, appears like a limiting form of the series in which $2S$ has been allowed to increase indefinitely, and $\frac{n\pi}{S}$ has become the general radian frequency ω. It is

$$e(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} E(j\omega)\,\epsilon^{j\omega t}\,d\omega \tag{13}$$

where

$$E(j\omega) = \int_{-\infty}^{\infty} e(\lambda)\,\epsilon^{-j\omega\lambda}\,d\lambda \tag{14}$$

and again there are reservations about points where $e(t)$ is discontinuous. Equation 14 constitutes the analysis of $e(t)$, and 13 a synthesis to regain $e(t)$. These 2 expressions can be combined by substitution to form the double Fourier integral

$$e(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \epsilon^{j\omega t}\int_{-\infty}^{\infty} e(\lambda)\,\epsilon^{-j\omega\lambda}\,d\lambda\,d\omega \tag{15}$$

integration with respect to λ being carried out first.

The component of current associated with the differential component of emf of radian frequency ω is

$$\frac{E(j\omega)\,d\omega}{Z(j\omega)}\,\epsilon^{j\omega t}$$

The expression for the input current resulting from the application of the emf to the above network, initially without currents or charges, is the Fourier integral

$$i(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{E(j\omega)}{Z(j\omega)}\,\epsilon^{j\omega t}\,d\omega \tag{16}$$

Equation 16 constitutes the synthesis to obtain $i(t)$. It is the *total* current at any time t. While evidently from physical reasoning $i(t)$ must be zero for $t<0$, and must vanish for large positive values of t, yet it is expressed as an infinite sum of differentially small, oscillating, *undamped* currents. The emf is not applied until $t = 0$, and there is actually no current in the circuit until this instant. The integral states these facts in a surprising way. According to it, the emf components all were applied to the network in the remote past, and have been actively energizing it ever since. Each of the component currents corresponding to them may have had transient distortion in the beginning, but at least it disappeared in the great past leaving only a system of oscillating undamped components to come down through time. Until time $t = 0$ is reached, these components have had the proper amplitude and phase exactly to annul one another. Beyond this point, without the slightest change in amplitude or phase, they give as their sum the actual current existent in the circuit. One may protest against the artificiality of this concept, but must concede its great power in reducing all transient phenomena to terms of the steady state—which is so well understood, and easily calculated.

Replacing $e(t)$ by $g(t)$ and $E(j\omega)$ by $F\left(\frac{\omega}{2\pi}\right)$ in eqs 13 and 14, and putting $\omega = 2\pi f$, there is obtained

$$g(t) = \int_{-\infty}^{\infty} F(f)\epsilon^{j2\pi ft}\,df \tag{17}$$

where

$$F(f) = \int_{-\infty}^{\infty} g(\lambda)\epsilon^{-j2\pi f\lambda}d\lambda \tag{18}$$

These are the symmetrical forms of the Fourier integral used in the Campbell and Foster table of "Fourier Integrals for Practical Applications." The expression $F(f)$ is the Fourier transform of $g(t)$, and conversely. As with eqs 13 and 14, these integrals are limited to functions $g(t)$ which vanish, at least exponentially, as t approaches either $\pm\infty$.

Among the disturbing forces most commonly used are constant d-c emf's and constant a-c emf's applied at $t = 0$. Since neither of these is representable by the Fourier integral just given, because of their failure to subside to zero as t increases, a more general form of the Fourier integral is required. Thus, if $e(t)$ never becomes infinite, is zero for $t<0$, and meets all other requirements for the Fourier integral except that $\int_{-\infty}^{\infty} |e(t)|dt$ is not finite, it is possible to form the double integral (eq 15) for $\epsilon^{-ct}e(t)$, where c is a positive real constant, since this product function is within the requirements. When the substitution $u = c + j\omega$ is made, and the lower limit for the integration with respect to λ is taken as 0, since $e(-\lambda) = 0$, there is obtained

$$e(t) = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} \epsilon^{ut}\int_0^{\infty} e(\lambda)\epsilon^{-u\lambda}d\lambda\,du \tag{19}$$

This likewise can be written in 2 parts, so as to disclose clearly the steps of analysis and synthesis

$$e(t) = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} E(u)\epsilon^{ut}\,du \tag{20}$$

where

$$E(u) = \int_0^{\infty} e(\lambda)\epsilon^{-u\lambda}\,d\lambda \qquad Re\ u = c > 0 \tag{21}$$

This is a generalized form of the Fourier integral. The function $E(u)$ of the complex variable u is called the Laplace transform of $e(t)$; it is a generalized type of Fourier transform. This integral and transform have been much used in recent developments of operational calculus.

The standard disturbing force in operational calculus is the unit function. It is zero for $t<0$, and unity for $t>0$—the simplest kind of discontinuous time function, consisting of a unit step at the origin.

In terms of emf's, the unit function represents an ideal battery of unvarying unit voltage connected to the circuit at $t = 0$. It requires, however, the generalized integral (eq 20) for its expression. Thus

$$1 = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} \frac{\epsilon^{ut}}{u}\,du \tag{22}$$

since by eq 21

$$\frac{1}{u} = \int_0^{\infty} 1\epsilon^{-u\lambda}\,d\lambda \qquad Re\ u > 0 \tag{23}$$

Equation 22 expresses unit function as an infinite sum of differentially small complex exponentials of the form $\frac{du}{u}\epsilon^{ut}$. Each of these exponential components of emf produces a differentially small complex exponential current of the form $\frac{du}{uZ(u)}\epsilon^{ut}$, and the actual current consists of the synthesis of these components as expressed by

$$i(t) = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} \frac{\epsilon^{ut}}{uZ(u)}\,du \tag{24}$$

From analogy with eqs 20 and 21 it is evident that

$$\frac{1}{uZ(u)} = \int_0^{\infty} i(\lambda)\epsilon^{-u\lambda}d\lambda \qquad Re\ u > 0 \tag{25}$$

Equation 24 gives the solution for $i(t)$ *explicitly*, but as a line integral in the complex plane. The path of integration is a line extending from $c - j\infty$ to $c + j\infty$ parallel to the imaginary axis and in the right-half plane. It is offset from this axis by an amount c sufficiently great so that all values of u that make $\frac{1}{uZ(u)}$ infinite (i. e., all the poles) lie to the left of the path. With $t<0$ the result of the integration is zero. With $t>0$ and $Z(u)$ a rational function, the result of the integration is equal to the sum of the residues at each of the poles—as though the path were actually a closed contour such as a circle about the origin of radius sufficiently great to include within it all these poles. Some knowledge of residue theory is necessary to use this integral.

A variation of the line integral of eq 22 which appears frequently for the unit function is

$$1 = \frac{1}{2\pi j}\int_L \frac{\epsilon^{ut}}{u}\,du \tag{26}$$

and correspondingly for the current resulting from unit function

$$i(t) = \frac{1}{2\pi j}\int_L \frac{\epsilon^{ut}}{uZ(u)}\,du \tag{27}$$

Symbol L designates a path from $-j\infty$ to $+j\infty$ along the imaginary axis, except at singular points on this axis. Here it passes around the point by a small half circle extending out into the right-half plane. For example, in eq 26 $u = 0$ is a pole at the origin, and L passes around the origin by a small hook to the right. In eq 27, if any values of u making $\frac{1}{uZ(u)}$ infinite are pure imaginaries or zero, they lie on the imaginary axis and must be avoided, each individually by small hooks to the right in the path L. These integrals are occasionally referred to as "hook" integrals. Equation 27 gives the same result as eq 24 except for integrals where poles of $\frac{1}{uZ(u)}$ fall to the right of the imaginary axis, but such cases are not of common occurrence.

Equation 25 gives $i(t)$ *implicitly*. With the unknown appearing as a function under the integral sign, it is an integral equation of the Laplace type. Equation 24 is a formal expression of its solution.

The 2 eqs 2 and 4 given earlier in surveying the

history of operational calculus are structurally the same as eqs 24 and 25. To show that they express relations of greater generality than might appear were the symbols for current, voltage, and impedance retained, the general functions $h(t)$ for the real variable t, and $\frac{1}{H(u)}$ for the complex variable u, were used. It may be seen that while Carson based his treatment of operational calculus on an integral equation, and Bromwich and Wagner based theirs on a complex line integral, these 2 defining equations stand in complementary relation to each other as the 2 aspects of analysis and synthesis of the generalized Fourier integral.

Summary of Operator Transformations

With the aid of the Fourier integral it is possible to establish operational calculus upon a strictly rational basis. The interpretation of operational processes, and permissible transformations of operators all can be determined from the corresponding treatment of transforms. These rules governing the use of operators constitute a summary of the subject. While the user must supply the imagination for their application, they can provide him with assurance that his course is sound. They are more fundamental than a table of operational formulas, since by applying them to a few cardinal equations the entire content of such a table can be built up.

While either the complex line integral or the integral equation can be used as a medium for developing the rules of operational calculus, the integral equation serves better because it involves mathematics more familiar to the engineer. Of the relationships given later, all except Nos. 4 and 5 can be derived from this equation by performing on it simple operations of ordinary calculus. These 2 exceptions are derived from the double Fourier integral.

In Table I are summarized the fundamental operator transformations. They are based particularly upon the works of Carson, van der Pol, and Campbell and Foster. The defining equation is given at the head of the table, and upon restoring the parts of the integral that are omitted thereafter each entry becomes of exactly this form. The expression $\frac{1}{H(u)}$ is the generating function corresponding to the operator $\frac{1}{H(p)}$. In the left-hand column are listed 17 transformations of $\frac{1}{H(u)}$. To each corresponds a new operator which, when applied to the unit function, gives the associated time function of the right-hand column. At the end are listed 3 useful equalities applying to operational equations.

The relations are written in terms of the complex variable u, and not the operator p, in order to avoid a dual interpretation of the symbol p. Symbol t stands for any real variable, but usually it represents time; a restriction to $t \geq 0$ is understood for each entry. The symbol a is either a constant or some additional independent variable.

In the following comments, the numeral references are to the entries in Table I:

Item 1 is applied in the most common processes, such as expansion in series and partial fractions, where the object is to break up the operator into a sum or difference of more easily recognized terms.

Item 2 states that factors independent of p or t participate as coefficients.

Item 3 governs a change of time scale.

Item 4 is known in the literature as Borel's theorem, and is the basis of Carson's development; it is another way of expressing the Boltzmann-Hopkinson superposition theorem, also Duhamel's integral. It interprets the product of 2 operational factors when the time equivalent of each taken separately is known. Note that the result is *not* the simple product of the 2 time equivalents, also that factors of operators are commutative.

Item 5 states that the operator equivalent to the product of 2 time factors can be formed if the operator equivalent of each taken separately is known. Note that the result is *not* the simple product of the 2 operator equivalents, but requires a line integration in the complex plane. An operator corresponding to instantaneous power could be derived in this way, letting $h_1(t)$ and $h_2(t)$ represent potential and current.

Item 5a is an alternative to 5, but is limited to cases where $h_1(t)$ can be expanded in a series of positive powers of t.

Item 6 interprets p^{-1} acting singly, showing it means integration with limits 0 and t. It is obtained from item 4 with $h_2(t) = 1$. If the complex line integral is used for developing these rules, p^{-1} is found to mean integration with limits $-\infty$ and t. This is immaterial in actual application provided $h(-t) = 0$, as it generally does in physical problems.

Item 7 is obtained by integrating once by parts. It interprets p acting singly, showing it means more than simple differentiation; if $h(0) \neq 0$, an impulse term $h(0)p1$ must be appended, and not discarded until the final result is reached. Operational calculus deals with functions involving discontinuities in magnitude and slope, and its operators apply to these functions *in entirety*. If interpretation is derived from the complex line integral, p appears to mean simply differentiation. However, there is no disagreement actually, for if $h(0) \neq 0$ and the complex line integral for $\frac{d}{dt}h(t)$ is formed this integral must be broken up into 2 integrals for evaluation. One gives the impulse at the origin; the other gives the derivative of the continuous portion.

Items 6 and 7 disclose fundamental differences between operational calculus and ordinary calculus. In the latter the operation $\frac{d}{dt}$ and $\int_0^t dt$ applied to $h(t)$ are not commutative unless $h(0) = 0$. In the former, by adopting item 7, p and p^{-1} are inverse operators, and commutative. This means $p.p^{-1}h(t)1 = p^{-1}.ph(t)1 = h(t)1$. A distinctive feature of operational calculus is its conversion of a problem of calculus to one largely of algebra. Its operators can be interpreted, as here, so as to obey the commutative, distributive, and associative laws, and the law of exponents. Not all writers adopt the interpretation given in item 7. Consistency is maintained then by some supplementary rule. For example, Jeffreys states that when p and p^{-1} both occur in an operator, the p^{-1} operation must be carried out before the differentiations.

The important difference between the operator p and $D = \frac{d}{dt}$ of ordinary calculus is presented by Sumpner as follows (1 is added here for uniformity):

$$D(at + b) = a \qquad p(at + b)1 = (a + bp)1$$
$$D^{-1}a = at + b \qquad p^{-1}a1 = at\,1 \tag{28}$$

In operational calculus, p operating on a constant times unit function is an impulse, and not zero. Impulse terms are not discarded without supplementary analysis. This troublesome point arises in fractional-order asymptotic series expansions, where integration in the complex plane provides the justification.

Item 8 substantiates transformations involving exponential time factors which Heaviside called "shifting." It is obtained by change of parameter u to $(u + a)$. Many variations can be made of item 8 giving convenient rules for inserting in, or extracting from, operators time factors of exponential form, and for shifting such time factors

between operand and coefficient. These rules are convenient since operators are not commutative with time functions. Four transformations based on item 8 are:

If

$$\frac{1}{H(p)}\,1 = h(t) \tag{29}$$

then

$$\frac{1}{H(p-a)}\cdot\frac{p}{p-a}\,1 = e^{-at}\,h(t), \tag{30}$$

$$e^{-at}\frac{1}{H(p)}\,1 = \frac{1}{H(p+a)}\,e^{-at}\,1 \tag{31}$$

$$\frac{1}{H(p)}\,1 = e^{-at}\left[e^{at}\,h(t)\right] = e^{-at}\,\frac{1}{H(p-a)}\cdot\frac{p}{p-a}\,1 \tag{32}$$

$$\frac{1}{H(p)}\,e^{-at}f(t)1 = e^{-at}\,\frac{1}{H(p-a)}\,f(t)1 \tag{33}$$

These are useful in the treatment of traveling waves and their reflections. They are the basis of the operational treatment of rotating a-c machinery transients whereby rotational effects are eliminated and the case reduced to one of static coupled circuits.

Items 9 and 10 are variations of 8.

Item 11 defines Heaviside's "transfer" operator e^{-ap}. It is obtained by change of variable from t to $(t-a)$ with attendant change in lower limit from 0 to a. The transfer operator is powerful in dealing with transients in distributed systems. It can produce time delay, or shift of reference coördinates. It can convert stationary functions to traveling waves, and conversely. Heaviside used it with an impulse, giving a function $e^{-ap}p1$ which is a unit impulse condensed at $t = a$, and zero elsewhere. With it he treated many problems of subsidence in distributed systems, evaluated difficult definite integrals, and established a connection between his operational processes and the work of Fourier.

Item 12 is established by differentiating with respect to a.

Item 13 is the complement of 12, and is established by integrating with respect to a. Items 12 and 13 state that differentiation or integration with respect to some variable in the operator other than p or t can be carried out freely. This is the basis of the operational solution of partial differential equations. Solution including fulfillment of boundary conditions is made first with respect to x. The result is an operator in p and x. Conversion into a function of t and x follows.

Item 14 is obtained by dividing by u, then differentiating with respect to u. In this and following cases is seen further advantage from using a complex variable u, instead of the operator p, in the statement of these rules. Differentiation or integration of an operator $\frac{1}{H(p)}$ with respect to p would be meaningless.

Item 15 is obtained by integrating once by parts, then differentiating with respect to u. Items 14 and 15 play important parts in recent developments; van der Pol applies them in extending operational processes to the variable coefficient class of linear differential equations, and Lowan employs their equivalent in solving partial differential equations with complicated initial and boundary conditions. As the transformations in items 14 and 15 can be repeated indefinitely, the operator equivalents of very general terms having powers of t for coefficients can be established. Values at the origin of $h(t)$ and its derivatives must be known for these more complicated cases.

Items 16 and 17 are complementary to 14 and 15; 16 involves the upper range of frequencies, while 17 involves the lower range. Each is obtained by dividing by u, integrating with respect to u, then applying 6. These have been used effectively by van der Pol in deriving operators for integral sine, cosine, and exponential.

Items 18, 19, and 20 are equalities provided the integrals exist; 18 and 19 are proved by integrating once by parts before passing to the limit. For 18 the integral $\int_0^\infty h'(t)dt$ must exist. Stated another way, $\frac{1}{H(u)}$ must have no poles on the imaginary axis, or in the right half-plane. Cases barred would be undamped trigonometric

Table I—Summary of Operator Transformations

$$\frac{1}{H(u)} = u\int_0^\infty h(t)e^{-ut}dt \qquad Re\ u>0$$

1.	$\frac{1}{H_1(u)} \doteq \frac{1}{H_2(u)}$	$h_1(t) \doteq h_2(t)$	
2.	$a\,\frac{1}{H(u)}$	$ah(t)$	
3.	$\frac{1}{H\left(\frac{u}{a}\right)}$	$h(at)$	
4.	$\begin{cases}\frac{1}{u}\cdot\frac{1}{H_1(u)}\ \frac{1}{H_2(u)} \\ \frac{1}{u}\cdot\frac{1}{H_2(u)}\cdot\frac{1}{H_1(u)}\end{cases}$	$\int_0^t h_1(\lambda)h_2(t-\lambda)d\lambda$	
5.	$\frac{u}{2\pi j}\int_{c-j\infty}^{c+j\infty} F_1(v)\cdot F_2(u-v)dv$	$h_1(t)\cdot h_2(t)$	Where $\begin{cases}F_1(u) = \frac{1}{uH_1(u)} \\ F_2(u) = \frac{1}{uH_2(u)}\end{cases}$
5a.	$uh_1\left(-\frac{d}{du}\right)\cdot\frac{1}{uH_2(u)}$	$h_1(t)\cdot h_2(t)$	Provided $h_1(t)$ can be expanded in a series of positive powers of t
6.	$\frac{1}{u}\,\frac{1}{H(u)}$	$\int_0^t h(t)dt$	
7.	$u\,\frac{1}{H(u)}$	$\frac{d}{dt}h(t) + h(0)u$	
8.	$\frac{u}{u+a}\cdot\frac{1}{H(u+a)}$	$e^{-at}\,h(t)$	
9.	$\frac{u}{u+a}\cdot\frac{1}{H(u)}$	$h(t) - ae^{-at}\int_0^t e^{at}\,h(t)dt$	
10.	$\frac{1}{H(u+a)}$	$e^{-at}\,h(t) + a\int_0^t e^{-at}\,h(t)dt$	
11.	$e^{-au}\,\frac{1}{H(u)}$	$\begin{cases}0 & t<a \\ h(t-a) & t>a\end{cases}$	$a>0$
12.	$\frac{d}{da}\,\frac{1}{H(u)}$	$\frac{d}{da}\,h(t)$	
13.	$\int_{\infty}^{a}\frac{1}{H(u)}\,da$	$\int_{\infty}^{a} h(t)da$	
14.	$-u\,\frac{d}{du}\,\frac{1}{uH(u)}$	$th(t)$	
15.	$-u\,\frac{d}{du}\,\frac{1}{H(u)}$	$t\,\frac{d}{dt}\,h(t)$	
16.	$\int_u^\infty\frac{1}{uH(u)}\,du$	$\int_0^t\frac{h(t)}{t}\,dt$	Provided the integrals exist
17.	$\int_0^u\frac{1}{uH(u)}\,du$	$\int_t^\infty\frac{h(t)}{t}\,dt$	Provided the integrals exist
18.	$\lim_{u\to 0}\frac{1}{H(u)} = \lim_{t\to\infty} h(t)$		Provided $\int_0^\infty h'(t)dt$ exists
19.	$\lim_{u\to\infty}\frac{1}{H(u)} = \lim_{t\to 0} h(t)$		
20.	$\int_0^\infty\frac{1}{uH(u)}\,du = \int_0^\infty\frac{h(t)}{t}\,dt$		Provided the integrals exist

or cisoidal oscillations. Item 18 shows that the low-frequency content of $\frac{1}{H(u)}$ determines the result at large values of t. This is applied in Heaviside's expansion theorem where the steady state term is written $\frac{1}{H(0)}$ by inspection. Item 19 shows that the high-frequency content of $\frac{1}{H(u)}$ determines the result at small values of t. This is applied in finding from the operator of a problem, initial values of the result and its derivatives.

Item 20 is the result of applying 18 to 16, or 19 to 17; van der Pol uses 20 to evaluate a variety of definite integrals.

Concluding Remarks

As many examples, fully worked out, showing the application of operational methods now can be found in textbooks and technical literature, such have been omitted here in order that attention might be concentrated upon the more fundamental aspects of the subject which give it rationality and cohesiveness. It has been necessary also to omit any discussion of asymptotic series expansions, as argument in terms of the integral in the complex plane is essential for their treatment.

Some helpful references are:

1. Electrical Papers, v. 2, O. Heaviside, 1892.
2. Electromagnetic Theory, v. 2 and 3, O. Heaviside, 1899, 1912.
3. Operational Circuit Analysis, V. Bush, John Wiley & Sons, 1929.
4. Electric Circuit Theory and Operational Calculus, J. R. Carson, McGraw-Hill Book Co., 1926.
5. Operational Methods in Mathematical Physics, H. Jeffreys, Cambridge University Press, London, second ed., 1931.
6. On the Operational Solution of Linear Differential Equations, and an Investigation of the Properties of These Equations, Balth. van der Pol. *Phil. Mag.*, v. 8, 1929, p. 861.
7. The Heaviside Operational Calculus, H. W. March. *Bulletin* Am. Math. Soc., v. 33, 1927, p. 311.
8. Heaviside's Operational Calculus, E. J. Berg, McGraw-Hill Book Co., 1929.
9. Heaviside's Electric Circuit Theory, L. Cohen, McGraw-Hill Book Co., 1928.
10. Fourier Integrals for Practical Applications, G. A. Campbell and R. M. Foster, Bell System *Monograph B-584*, 1931; or The Practical Application of the Fourier Integral, G. A. Campbell, *Bell System Tech. Jl.*, Oct. 1923, p. 639.
11. Theory of Functions, R. Rothe, F. Ollendorff, and K. Pohlhausen, Technical Press, Mass. Inst. of Tech., 1933.

"Thyratron" Tubes in Relay Practice

The application of the grid-controlled gas-filled, or "thyratron," electronic tube to relay practice, principally for the protection of transmission lines, is considered in this paper. Several different types of these relays are discussed under the 2 principal classifications of "normal" design and high speed relays. This paper by Doctor Wideröe, based upon European practice, should be of considerable interest in this country.

By
ROLF WIDERÖE

N. Jacobsen's Elektriske,
Oslo, Norway

As soon as the grid-controlled gas-filled (or mercury-vapor-filled) hot-cathode electronic tube was developed, it became evident that the tube would play an important part in the amplification of electrical impulses, where small quantities of energy are to be applied for controlling a comparatively large amount of energy for electrical apparatus of various kinds. In the majority of cases, however, this tube (designated "thyratron" tube by the General Electric Company, and "grid glow" tube by the Westinghouse Electric and Manufacturing Company) is not capable of controlling the energy continuously. That is, in contradistinction to the grid-controlled high-vacuum tube, the plate current of the grid-controlled gas-filled tube is not some continuous function of the grid bias, but immediately rises from zero to a maximum when the grid potential with respect to the cathode becomes more positive than a critical value which is termed the "firing potential" of the tube. Once the tube has been "fired," the plate current continues to flow as long as the plate potential is maintained, irrespective of any subsequent change in the grid potential. This discontinuous amplification characteristic is admirably suited for the application of this tube to relay practice. All of the grid-controlled gas-filled tube relays herein described have been developed and tested by the author at the A.E.G. relay factory, Berlin, Germany and are protected by patents in several countries.

The relay is an automatic sentinel at all times watching some electric value, for example, the magnitude of an electric current. When the current exceeds a definite, predetermined value, it is the duty of the sentinel to make this fact known by permitting a current to flow in a circuit which sounds an alarm or trips a circuit breaker. The function of the relay, therefore, is a double one; the first part consisting of measuring the current, and the second part to act as a discontinuous amplifier when called upon to do so. This second part of its function corresponds perfectly to the action of the grid-con-

Full text of a paper recommended for publication by the A.I.E.E. technical program committee. Manuscript submitted March 28, 1933; released for publication July 10, 1934. Manuscript revised and put in final form by J. H. Neher (A'24), Philadelphia (Pa.) Electric Company. *Not published in pamphlet form.*

trolled gas-filled tube; and, furthermore, as the "firing potential" of the tube can be kept sufficiently constant, the grid circuit of the tube may be made to perform the first, or measuring function of the relay as well. It will be seen therefore, that the tube inherently possesses the fundamental properties required of a relay. In addition, this

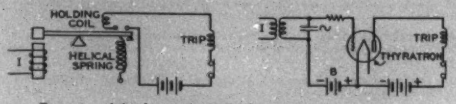


Fig. 1. Mechanical and thyratron instantaneous overcurrent relays

Symbol ~ indicates that voltage across capacitor is alternating

relay possesses the following principal advantages as compared to "mechanical relays."

1. Quick action.
2. Small consumption of energy.
3. Absence of contacts or moving parts.

In the following, the counterparts in this tube relay of the more common forms of mechanical relays will be described together with a brief discussion of some of the limiting features and advantages.

Thyratron Relays of Normal Design, With Electrically Fixed Grid

The overcurrent and undervoltage relays in various forms and combinations, constitute the basis of all of the normal "thyratron" relays.

Overcurrent Relay

One design of a mechanical instantaneous overcurrent relay and the corresponding thyratron relay is shown in Fig. 1. While there are other forms of the mechanical relay, the one shown has been chosen because its several parts have their equivalents in the electronic relay. As shown, this mechanical relay consists of a double balance lever with a set of contacts and a fixed stop. A helical spring holds the lever against the stop and keeps the contacts open. At the other end of the lever is placed an armature which is attracted by an electromagnet, energized by the current to be measured. When the current rises to a predetermined limit, the force of the magnet overcomes the tension of the spring, and the lever turns on its pivot, closing the contacts.

Considering the thyratron counterpart, the thyratron tube is placed in the tripping circuit, and consequently a constant voltage is maintained between its anode and cathode. The tube will therefore "fire" and the tripping current flow when the voltage between the grid and cathode exceeds a certain value. This voltage between the grid and cathode corresponds to the balance lever in the mechanical relay. The battery B is connected in the grid circuit, so that the grid potential is negative and lies under the "firing potential." This battery, therefore, corresponds in its action to the helical spring, or restraining force, of the mechanical relay.

The current I to be measured is arranged to produce an alternating voltage in the grid circuit through a current-voltage transformer (a transformer designed to produce a secondary voltage proportional to the current flowing in the primary). This transformer corresponds to the electromagnet of the mechanical relay. In its positive half cycle, the alternating voltage brings the grid potential nearer to the firing point. When the strength of the current exceeds a certain value, therefore, the grid potential will reach the firing point at the maximum value of the alternating voltage, and the relay will operate.

The action of the overcurrent relay has been described in considerable detail because it is typical of the operation of the majority of thyratron relays. The balance lever is always represented by the grid potential. As long as this potential lies below the firing point, the relay remains inactive, but when the firing point is reached, even for only a short time, the relay will operate. The operation of this relay, therefore, depends only upon the instantaneous relationship between the various voltages appearing

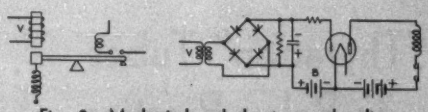


Fig. 2. Mechanical and thyratron undervoltage relays

in the grid circuit, and in this circuit will be found the vital design of the relay.

Undervoltage Relay

In Fig. 2 is illustrated an undervoltage relay, a relay which is brought into action when the voltage falls below a certain value. Contrary to the arrangement of the overcurrent relay just described, the counter force is now arranged so that it tends to close the tripping contacts or to fire the tube. The voltage to be measured acts as the restraining force.

It is evident that in the case of the thyratron relay the alternating voltage to be measured must be rectified (by rectifiers of the copper oxide or selenium type) and filtered since it must be introduced as a direct voltage into the grid circuit of the tube. The mechanical relay does not require voltage rectification since the restraining force is a function of V^2 which is the equivalent as far as the operation of the relay is concerned. As a rule the filtering effect is cared for by the inertia of the balanced beam.

A principal difference between the mechanical and thyratron relays will be noted:

The mechanical relay operates on the effective values of current or voltage and the counter force must be adjusted for the square of the current or voltage.

The thyratron relay operates on the maximum value or some function of the arithmetical mean value of the current or voltage (de-

pending upon the performance of the filter) and the counter voltage must be adjusted for the linear value of the current or voltage.

A considerably distorted current or voltage wave, therefore, may act unfavorably on the tube relay. On the other hand, this relay offers advantages over the mechanical relay when it is necessary to be able to adjust the tripping values of the relay over a wide range.

Under-Impedance Relay

By combining the 2 types of relays just described, the result is a "quotient" relay. The mechanical relay as shown in Fig. 3 compares the mechanical forces of the currents or voltages constituting the quotient. In the tube relay, the different voltages are connected in series and the comparison takes place in the grid circuit of the tube. The action of the relay is evident from the illustration and the descriptions given previously.

The under-impedance relay shown in Fig. 3 compares a current I and a voltage V. It will operate, therefore, when the impedance $\frac{V}{I}$ decreases below a fixed, adjusted value. The voltage V is rectified and operates as the restraining force while the current I furnishes a voltage tending toward operation. In the mechanical system a helical spring has been added to counteract the weight of the armature so as to bring the beam into balance with no magnetic forces applied. In the tube relay the battery B

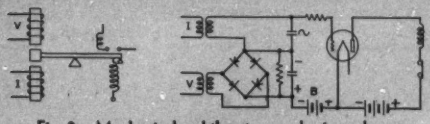


Fig. 3. Mechanical and thyratron under-impedance relays

Symbol ~ indicates alternating voltage

serves the same purpose, causing the firing point to coincide with zero resultant voltage in the applied circuits.

Percentage Differential Relay

Such a quotient relay can be used as a "percentage differential" relay to measure the quotient $\frac{I_1 - I_2}{I_1 + I_2}$ where I_1 and I_2 are the currents measured at the terminals of the apparatus protected. This is illustrated in Fig. 4. A rectified restraining voltage proportional to the restraining current $(I_1 + I_2)$ is applied to the grid circuit of the tube. The tripping voltage is proportional to the differential current $(I_1 - I_2)$. This voltage is also rectified and the resistors and condensers used in the circuit must be selected to obtain a time constant for the tripping voltage greater than that for the restraining voltage.

A modification of the thyratron differential relay described is admirably suited to differential protection of transmission lines by the use of a-c pilot wires, in which case the energy consumption of the differential relay must be reduced to a minimum. The energy consumption of the thyratron relay is very small and depends entirely upon the design and form of the grid circuit. It is not difficult to keep the energy consumption as low as 0.0001 va or $\frac{1}{1{,}000}$ of what a very sensitive mechanical relay requires. This fact indicates the possibilities offered by the relay in the field of differential protection.

Distance Relay

The thyratron tube is readily adapted to distance relay work. Distance relays as a rule are very complicated, consisting of a number of moving parts;

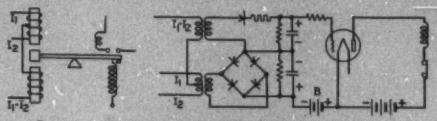
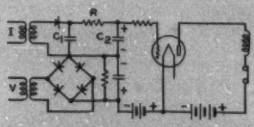


Fig. 4. Mechanical and thyratron percentage current-differential relays

and as a result leave something to be desired in the way of technical perfection and the absolutely reliable operation which should be required for devices of such importance. A thyratron distance relay operating on impedance is illustrated in Fig. 5. It differs from the under-impedance relay of Fig. 3 in that the tripping voltage is rectified as well as the restraining voltage. The rectified tripping voltage appearing across the condenser c_1 charges the condenser c_2 through the resistance R, so that the time

Fig. 5. Thyratron distance relay



constant for the effective tripping voltage appearing in the grid circuit across condenser c_2 is comparatively large. The relay will release when:

$$\frac{V}{I\left(1 - e^{-\frac{t}{T}}\right)} \leq k$$

where $T = Rc_2$, the time constant of the circuit. For values of $t < T$, the expression $1 - e^{-\frac{t}{T}}$ varies substantially as $\frac{t}{T}$ so that the tripping time is proportional to the impedance.

$$t = \frac{T}{k} \cdot \frac{V}{I} = \frac{T}{k} \cdot Z$$

The very low energy consumption of the thyratron distance relay offers the great advantage that

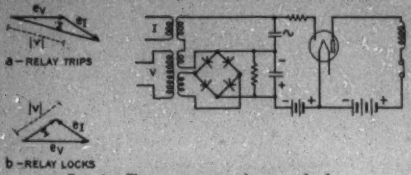


Fig. 6. Thyratron power directional relay

Symbol ~ indicates alternating voltage
e_v indicates voltage derived from V
e_I indicates voltage derived from I
|v| indicates scalar quantity

capacity potentiometers or condenser bushings can be employed in place of potential transformers as the source of secondary potential applied to the relay. This advantage may in many cases determine the selection of the protective system, especially in the case of very high line voltages.

The quotient relays so far described are all independent of the phase angle between the values compared. In many cases, however, relays dependent upon phase angles are required. This can be obtained by the suitable vectorial addition of the voltages in the grid circuit.

Power Directional Relay

A power-directional thyratron relay, a relay which operates when the power flow in a circuit is reversed, is illustrated in Fig. 6. The vectorial addition of a voltage derived from the current I and the voltage V works to trip the relay. The restraining voltage is obtained by rectifying the voltage V. When the current and voltage act in the same direction, the alternating voltage in the grid circuit becomes greater than the restraining voltage and the relay will operate. When the current flows in the opposite direction, the alternating voltage becomes smaller than the restraining voltage and the relay will not trip.

It should be noted that this relay may loose its directional discriminating ability under short-circuit conditions. If the ratio of the current to the voltage becomes sufficiently large, the alternating voltage in the grid circuit will always exceed the restraining voltage and the relay will release.

Reactance Relay

In Fig. 7 is illustrated a thyratron reactance relay which is approximately correct. Its action is much the same as that of the power-directional relay just described.

In order to obtain dependency upon reactance, the voltage V must be rotated 90 deg by means of a resonance circuit. The voltage rotated to this angle is connected in series with another voltage (designated k_1I) derived from the current, and the sum of these 2 voltages is rectified. The figure shows that the restraining voltage thus obtained, within certain limits for the phase angle θ, will be nearly equal to $k_1I + V \sin \theta$. An alternating voltage (designated k_2I) also derived from the current serves to release the relay. The relay will release when:

$$k_1I + V \sin \theta \leq k_2I \text{ or } \frac{V \sin \theta}{I} = X \leq k_2 - k_1$$

Therefore, the relay (within certain phase angles) will trip when the reactance falls below a certain value (under-reactance relay).

Relays of this type can be used for distance protection when a step-by-step characteristic is desired. A more perfect arrangement for this application, however, will be mentioned later.

Effect of Disturbances on Relays of Normal Design

The relays so far described all possess a number of common properties. They form a complete analogy to the common mechanical relays with balance levers and may therefore be designated as "normal relays." The principal properties of these normal relays is that they are comparatively little influenced by electrostatic disturbances. This property is of great importance in the correct functioning of the grid-controlled gas-filled tube (thyratron) relay.

Electrical disturbances, such as line surges, high frequency oscillations (radio waves) and transients in the d-c circuit may easily force themselves into the lines connecting the tube with other equipment and ultimately reach the grid of the tube. If they are able to change the grid potential appreciably, incorrect tripping may result. These electrical disturbances in the tube relay correspond to knocks or blows in the mechanical relay. In order to make the mechanical relay insensitive to disturbance of this nature, the balance lever must possess a comparatively large mass which tends to make the relay sluggish and slow.

In the tube relay of normal design, the same effect is secured by arranging a condenser of sufficient capacity between the grid and the cathode. In the majority of cases the filtering condensers used in the restraining elements can be arranged so that they prevent electrostatic disturbances. One might say that the grid potential is "tied" to the cathode by means of condensers. The relay will, of course, become correspondingly sluggish and slow but as the tripping time of most of these relays is governed by the speed of response of the restraining voltage, which, as a rule will be greater than one cycle, a tendency toward sluggishness in the tripping voltage is of no consequence.

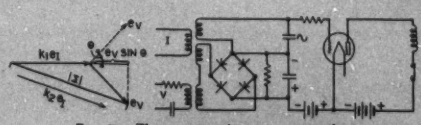


Fig. 7. Thyratron under-reactance relay

Symbol ~ indicates alternating voltage
e_v indicates voltage derived from V
e_I indicates voltage derived from I
|Z| indicates scalar quantity

High Speed Thyratron Relays With Instantaneously Acting Grid

High speed thyratron relays can be built as well as high speed mechanical relays. High speed thyratron relays are characterized by a grid which instantly follows the momentary values of alternating voltages applying to it, and which releases without delay at the right moment.

The fundamental basis for these high speed relays involves an entirely new principle in relay operation, but which bears a certain similarity to the so-called Joubert principle for point to point measurement of a-c waves. This method consists of the use of a rotating contact for connecting a voltmeter for a very short time at the point of the a-c wave which is to be determined. By the successive displacement of the rotating contacts to other points on the wave, the form of the whole wave can be determined.

In the case of the high speed relay, a restraining voltage is introduced into the grid circuit, sufficiently high to prevent, beyond question, the relay from releasing. This counter voltage, however, is made to disappear periodically for a moment, and during this short time interval the relay is given an opportunity to measure the momentary value of an alternating voltage also applied to the grid circuit. By displacement of the phase of this periodically disappearing counter voltage or "test voltage," the relay can be made to measure the alternating voltage at any point on the wave.

High Speed Power Directional Relay

A high speed power directional thyratron relay which acts according to this principle is shown in Fig. 8. The test voltage is derived from the current circuit through a full wave rectifier. It produces a restraining force which disappears twice during each complete cycle. By using a current-dependent resistance such as "thyrite," the moment during which the voltage disappears—the testing moment—will be very short, and the testing voltage rises immediately thereafter to such a magnitude that the tube is unable to release under any circumstances.

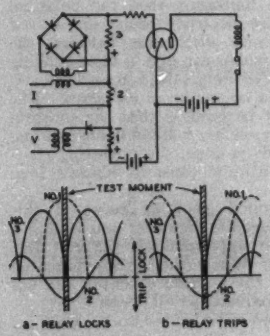
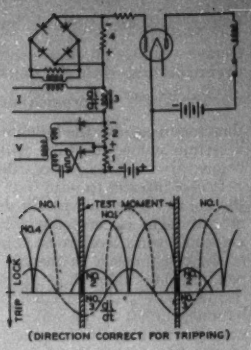


Fig. 8. High speed power directional thyratron relay

Fig. 9. High speed thyratron under-reactance relay with directional control



In addition to the test voltage, there are also acting in the grid circuit of the tube, a voltage proportional to the current I and a directed voltage (by half-wave rectification) proportional to the voltage V. As shown in the figure, the test moment is displaced 90 deg in relation to the current. The test consequently takes place when the current is at its maximum value, and the grid voltage due to the current will in one test moment act in the tripping direction, and in the next test moment, in the direction to lock. Whether or not the relay releases depends upon the directed counter voltage. If this is in action at the test moment when the current tends to release the relay, the release will be prevented. If it is action at the other test moment, however, the relay will release.

It will be found that the relay will lock from nearly +90-deg to −90-deg phase displacement between the current and voltage, provided the test moment is very brief and the directed counter voltage is sufficiently great.

This directional relay is well adapted to carrier-current pilot protection of transmission lines.

High Speed Reactance Relay

A high speed reactance relay especially designed for distance protection according to the step-by-step principle is illustrated in Fig. 9. Contrary to the relay just described, the test voltage here works in phase with the current I. The testing moment will always occur, therefore, when the current is zero. An induced voltage $\left(\text{designated } \frac{di}{dt}\right)$ produced by the current flowing through an unsaturated iron core reactor acts in the direction of release. The directed voltage V acts as the counter voltage. Assuming that the circuit which the relay is to control consists of a resistance R and an inductance L, the instantaneous voltage across the circuit v will amount to:

$$v = i\,R + L\,\frac{di}{dt}$$

Since, in the testing moment, i is zero, the counter

voltage v is consequently equal to $L \frac{di}{dt}$, and this counter voltage is now compared directly by the thyratron tube with the voltage built up across the reactor which is proportional to $\frac{di}{dt}$. The relay therefore measures the inductance L. If L lies above a certain value, the tube will lock. If L decreases below this value, however, the tube will release.

It is of interest to note that in contradistinction to the normal relay previously described, the inductive measurement is correct within wide limits of phase angle and will therefore be substantially independent of the resistance R in the circuit under control (depending only upon how brief the testing moment can be made). Furthermore, the measurement will be independent of the wave form of the current and voltage and also the frequency. It is even possible to measure current-dependent inductances by giving the iron in the reactor the same characteristic as the inductances which are under control.

Directional control may be applied to this reactance relay by simply adding another directed counter voltage proportional to the voltage V which has a phase displacement such that it cannot prevent the measurement of the inductance when the energy flows in the tripping direction. If, however, the direction is reversed, this counter voltage (the directional voltage) will act in the determining test moment and prevent release.

It is important to note that the correct directional action of both of the high speed relays described is conditional upon the presence of line voltage in sufficient magnitude. While this is true of all directional relays, nevertheless the conventional directional relays are slow or inoperative when the line voltage falls to a very low value due to the proximity of a fault, whereas the thyratron relays will operate irrespective of the fault direction and with no loss of speed. This means that particular care must be exercised in applying this tube type of directional relays and it will often be necessary to step up the directional voltage.

Effect of Disturbances on High Speed Relays

As previously indicated, difficulties may arise from surge voltages entering the grid circuits of the high speed tube relays and thereby causing false tripping. In the tube relays of normal design, this difficulty has been overcome by placing a condenser between the grid and the cathode, but in the case of high speed relays, it is impossible to "tie down" the grid in this manner. It is, therefore, necessary to protect the relay against surges with filters, blocks, and by-pass condensers.

To study this very important phase of the problem, the author built an extremely sensitive resonance relay with a freely acting grid. This relay was of the quotient type and was designed to protect the windings of a generator against ground faults. The tripping element of the grid circuit was tuned to resonance at the generator frequency (50 cycles) and the relay operated on approximately 10^{-8} va.

Due to the usual disturbances from the factory supply, the tripping of the relay was very unstable and the surges introduced potentials of nearly 100 volts in the grid circuit. By using high and low frequency blocks between the supply and the relay, the necessary grid biasing to compensate for surges was brought down to approximately one volt.

Conclusion

The grid-controlled gas-filled tube relays which have been described all work with a constant (within ± 10 per cent) anode potential, in which case the firing potential of the grid has a constant value. It may be of advantage sometimes to use an alternating voltage between the anode and cathode of the tube. In this way a very simple phase-dependent relay (such as a directional relay) can be built by letting the current produce the anode potential while the voltage acts on the grid. Such a relay operates in a manner similar to the ordinary Toulon control. It will release or lock depending upon the phase displacement between the current and the voltage. This relay operates satisfactorily, only when the anode potential can be kept fairly constant and not varying within too wide limits.

The principal requirement which must be fulfilled by the thyratron tube when acting as a relay is that the operating characteristics remain constant, even during varying external conditions.

These tubes must thus be independent of temperature variations. This means difficulties for the tubes filled with mercury vapor. As a rule they will not work at temperatures below $+20$ deg C. It is therefore necessary to provide them with a thermal protection, or to maintain the temperature in the vicinity of the relay comparatively constant by means of a thermostat or a similar device.

The grid-controlled tubes filled with argon gas seem to offer several advantages. The pressure of the vapor in these tubes is essentially higher than in the mercury-vapor tubes. Further, the pressure changes very little within the temperature limits usually occurring in practice. The characteristic of the argon-gas thyratron is therefore practically independent of the temperature variations likely to be encountered in practice. The argon-gas thyratron tubes have the limitation that the potential difference between the electrodes must not exceed 500 volts, as otherwise discharges between the electrodes will occur which can give a false tripping of the relay. This is entirely satisfactory, however, when the tubes are to be employed as relays. The thyratron tubes must be built so that the emission centers on the cathode surface will not change during the operation. If this is done, the operating characteristics remain entirely constant during long periods of time.

Various grid-controlled gas-filled tubes of this type were proved to keep the ignition potential at a constant value within approximately 0.2 volt during several months. When the anode potential varies ± 10 per cent, the ignition potential will not vary more than approximately ± 0.5 volt.

The life of the tubes is estimated to be 5,000 hr,

provided the tubes carry the maximum rated anode current. This is of importance for regulating relays. The anode current of the protecting relays is practically always zero, and the cathode only is heated in these relays. Under such circumstances the life will no doubt be considerably longer and should satisfy all reasonable demands.

The tubes which have been discussed are designed for a cathode current of 0.1 amp continuously, but are able to carry 0.2 amp for short time intervals. Larger tubes are available which may be used to handle the tripping current of a circuit breaker directly, and which in turn are controlled by a smaller but correspondingly exact measuring tube of the grid-controlled gas-filled (or mercury-vapor-filled) type.

Overloading of Power Transformers

The A.I.E.E. transformer subcommittee* has planned an extension of the scope of the Institute publication relating to the operation of transformers to include recommendations for the short-time overloading of oil-immersed transformers in service. These recommendations take advantage of the heat storage capacities of the materials of the transformer to supplement present recommendations relating to the continuous overloading that is possible when the ambient temperature is lower than the standard ambient temperature. This report gives a brief review of the considerations upon which the proposed changes are based and includes the new material in the form in which the subcommittee has prepared it. It is submitted to the Institute for constructive criticism.

By
V. M. MONTSINGER
FELLOW A.I.E.E.
General Elec. Co.
Schenectady, N. Y.

W. M. DANN
FELLOW A.I.E.E.
Westinghouse Elec. and
Mfg. Co., Sharon, Pa.

UNTIL recent years, A.I.E.E. standards for transformers have been limited in scope to the establishment of a standard rated output under definite assumed conditions, with the temperature rise under continuous rated load limited to 55 deg C. The sole purpose of these standards is to establish a standardization of design and of test. Experience in actual operation has shown that with these rating standards in force transformers in general have had reasonably long, useful life.

Recognizing that extra output is available from a transformer in service when the ambient temperature is low, the Institute in 1930 established recommendations for loading transformers in service when ambient temperatures differed from those of the rating standards. These recommendations (A.I.E.E. Standards No. 100) do not establish standards of operating performance subject to guarantee and demonstration by acceptance test, but rather they are intended solely as a guide for the safe continuous overloading of transformers under specified conditions.

Within the past year the transformer subcommittee has planned to extend the scope of the standards still further and has prepared a schedule of overloads permissible for short periods of time. This report includes a review of the considerations that have formed the basis for the proposed schedule, and a proposed revision of A.I.E.E. Standards No. 100 to include them.

Temperature Considerations

Deterioration of the insulation used in a transformer is the fundamental consideration that must be taken into account in establishing permissible overloadings. Since deterioration is a function of both *temperature* and *time*, it is essential first to establish a safe and reasonable schedule of limiting temperatures for various periods of time. Having established these temperatures, it is a relatively simple matter to set up overload values.

For some time, 3 limits of winding temperature, corresponding to 3 different time-periods, have been established in A.I.E.E. Standards No. 13. These temperature limits are as follows:

95 deg C for continuous operation. This is the average temperature of the winding resulting from 55-deg rise above an ambient temperature of 40 deg C (A.I.E.E. Standard 13-200).

Full text of a report prepared under sponsorship of the transformer subcommittee of the A.I.E.E. committee on electrical machinery, recommended for publication by the A.I.E.E. committee on electrical machinery, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted June 21, 1934; released for publication July 10, 1934. *Not published in pamphlet form.*

* Personnel of transformer subcommittee: H. V. Putman, *chairman;* G. M. Armbrust, E. S. Bundy, J. E. Clem, B. Lanphier, H. C. Louis, A. C. Monteith, V. M. Montsinger, L. C. Nichols, E. D. Treanor, and F. J. Vogel.

100 deg C for the one-minute operation of grounding transformers (A.I.E.E. Standard 13-250 *c*).

250 deg C for 5 seconds and less. This is the maximum temperature limit permitted during short circuit (A.I.E.E. Standard 13-250).

Having these 3 established temperature limits, all of them verified by years of successful operating experience, it was possible to set up the following temperature limits for the short-time overloading of power transformers:

Time	Winding Temperature Limit, Degrees C by Resistance
Less than 5 sec	250
30 sec	180
60 sec	160
5 min	140
30 min	120
2 hr	105
Continuous	95

It has been found in laboratory research that the rate of mechanical deterioration of fibrous insulating materials doubles approximately for each 8-deg C increase of temperature, and conversely is halved approximately for each 8-deg C decrease of temperature. (See "Loading Transformers by Temperature," by V. M. Montsinger, A.I.E.E. TRANS., v. 49, 1930, p. 776; and "Operating Transformers by Temperature," by W. M. Dann, A.I.E.E. TRANS., v. 49, 1930, p. 793.) When starting with 250 deg for 5 sec, it is realized that the 8-deg rule results in a temperature in excess of 160 deg for 60 sec. At the same time, it is realized that emergency overloads of 1-min operation may occur more often than dead short circuits at the terminals of a transformer. For these reasons the limits appearing in the table have been chosen to give a wholesome degree of conservatism which is warranted when establishing general rules for overloading transformers. Based upon the limiting temperatures that have been established for some time by the Institute, it is thought that this schedule presents a logical and satisfactory basis for the emergency short-time overloading of power transformers.

Classes of Short-Time Overloads

In establishing the limitations for short-time overloading, the transformer subcommittee recognized that circumstances affect the character of the overload and that overloads accordingly should be classified with regard for such circumstances. For instance, emergencies resulting from disturbances on the system may give rise to overloads that are unexpected and unpremeditated; on the other hand, it is desirable or necessary occasionally to undertake overloads for short periods of time in accordance with some considered plan. With these considerations in mind, the subcommittee has set up 2 classes of short-time overloads, namely:

Emergency Short-Time Overload. An emergency short-time overload is an unexpected overload of limited duration caused by some unpremeditated disturbance of normal operation; it is to be regarded as an infrequent occurrence.

Recurrent Short-Time Overload. A recurrent short-time overload is one of limited duration that is undertaken in accordance with a premeditated plan; it is regarded as an occasional occurrence with steady-state temperature conditions restored before repetition.

Emergency short-time overloads, according to the plan of the transformer subcommittee, are considered to be infrequent and not recurrent at relatively short intervals. With this interpretation, the full value of limiting temperatures referred to in previous paragraphs may be used for this class of overloads without restriction. On this basis, emergency short-time overloads have been determined for various periods of time that are thought to be the maximum consistent with safety and conservatism.

Since recurrent short-time overloads may occur more frequently than emergency overloads, it is logical that the level of limiting temperatures should be lower. There are few established levels of limiting temperature for overloads of this character. However, a limit of 100 deg C for 2 hr has been established for some time for railway transformers (60 deg rise above 40 deg ambient A.I.E.E. Standard 13-200). Limiting temperatures for this class of overload finally were set in the form of a curve passing through the following points:

Time	Winding Temperature Limit, Degrees C by Resistance
Less than 4 min	110
20 min	105
2 hrs	100
8 hr or more	95

Determination of Permissible Overload

In order to make the use and application of the foregoing considerations as simple and practicable as possible, overloads that are permissible within the limiting temperatures were calculated for a wide range of time periods and arranged in tabular form. The permissible overload for a given time then may be read directly from the table. If one is interested in the permissible overload for some intermediate time period not given in the table, it may be obtained by plotting a curve through a few points on either side of the desired time period.

Steady state temperature conditions at the beginning of the overload naturally have an important bearing on the value of the permissible overload. For this reason, 2 different steady state temperature conditions have been recognized, one for operation at full load and the other for no-load operation with excitation applied. A method of interpolation to determine the permissible overload for intermediate initial steady state temperature conditions also is provided.

Ambient temperature conditions also affect permissible values of short-time overloads because they affect the ultimate winding temperatures. A method is provided to adjust the permissible overload to an ambient temperature that differs from the standard.

The plan of the subcommittee is to incorporate this new short-time overload information in A.I.E.E. Standards No. 100, which originally was provided for approved operating practice.

Verification of the Proposed Permissible Overloads

Calculations made by transformer designers with a great many transformers of various ratings have given reasonable assurance that standard self-cooled power transformers that conform with the requirements of A.I.E.E. Standards No. 13 will carry safely the short-time overloads included in the revision of A.I.E.E. Standards No. 100 without undue deterioration of the insulation.

In verifying the temperatures for the various permissible overloads, final temperatures were calculated with the formula given in paragraph 13-250, A.I.E.E. Standards No. 13, when periods of overload were of such short duration that the heat developed by the overload current could be assumed to be completely stored within the copper. For longer periods of time, when the dissipation of heat from the copper becomes appreciable, final temperatures were checked by calculating both the temperature rise of the oil and the temperature rise of the winding above that of the oil, with formulas of the following form:

$$\theta = \theta_f\,(1-e^{-Bt}) \qquad B = \frac{W}{C\,\theta_f}$$

where

θ = temperature rise at end of time "t"
W = loss in watts
C = thermal capacity of the material that absorbs the dissipated heat
θ_f = temperature rise that would be attained with loss W continuously maintained
e = base of Naperian logarithms

Recommendations for the Operation of Transformers—A.I.E.E. Standards No. 100

According to the plans of the transformer subcommittee, A.I.E.E. Standards No. 100 will be revised and expanded to include the new material for short-time overloading as follows:

100-3. Continuous Operation at Rated Load.

This paragraph is to be used as it appears in Standards No. 100 but the word "continuous" is to be added to the heading to differentiate it from short-time operation.

100-4. Continuous Operation With Cooling Air and Water Exceeding 40 Deg C and 25 Deg C, respectively.

The word "continuous" is also to be added to the heading of this paragraph.

100-5. Continuous Operation at Loads Greater Than the Rated Load.

The word "continuous" is also to be added to the heading of this paragraph, which through typographical error is called 100-4 in Standards 100.

100-6. Short-Time Operation at Loads Greater Than Rated Load.

(*a*) It is recognized that power transformers of the oil-immersed type, having continuous ratings that conform with the standards for rating, may be loaded in excess of their rated loads for limited periods of time. For the purpose of defining permissible overloads of this kind, two classes of short-time overloads are recognized, as follows:

1. *Emergency Short-Time Overload.* An emergency short-time overload is an unexpected overload of limited duration caused by some unpremeditated disturbance of normal operation; it is to be regarded as an infrequent occurrence.

2. *Recurrent Short-Time Overload.* A recurrent short-time overload is one of limited duration undertaken in accordance with a premeditated plan; it is regarded as an occasional occurrence with steady state temperature conditions restored before repetition.

(*b*) Self-cooled oil-immersed power transformers may be operated at specified overloads for limited periods of time in accordance with the values given in Table I.

Table I—Permissible Short-Time Loads for Self-Cooled Oil-Immersed Power Transformers at an Ambient Temperature of 40 Deg C

Duration of Load	Emergency Loads*		Recurrent Loads*	
	Following Full Load**	Following No Load†	Following Full Load**	Following No Load†
2 sec	25	25	6.5	13
5 sec	14	16	4	8
10 sec	9	10.5	3	6
30 sec	5	6	2.2	4
60 sec	3.7	4.7	1.6	3.25
5 min	2.3	3	1.25	2.1
30 min	1.6	1.9	1.1	1.45
2 hr	1.25	1.4	1.0	1.2

* The overload values contained in the table are expressed in multiples of the continuous rating of the transformers; *e. g.*, the figure 25 indicates a load of 25 times the continuous rating.

** For the permitted loads in the columns headed "Following Full Load," it is understood that, prior to the overload, the transformer has been operating at continuous rated load and at an ambient temperature of 40 deg C for a period long enough to have established steady temperature conditions.

† For the permitted loads in the columns headed "Following No Load," it is understood that, prior to the overload, the transformer has been under normal excitation with an ambient temperature of 40 deg C, but without load current, for a period long enough to have established steady temperature conditions.

1. The permissible short-time load for an intermediate period of time not given in the tabulation may be obtained by plotting a curve through a few points on either side of the desired point.

2. If the steady-state load preceding a short-time overload, either emergency or recurrent, is less than full load, it is possible to increase the permissible short-time loads given in the columns headed "Following Full Load," because of lower initial temperature. Interpolation to determine permissible overloads corresponding to initial loads between "no load" and "full load" may be made on the basis of the square of the initial load, as follows:

$$\left\{\begin{matrix}\text{Permissible}\\ \text{overload}\\ \text{with } X\\ \text{initial load}\end{matrix}\right\} = \left\{\begin{matrix}\text{Permissible}\\ \text{overload}\\ \text{following}\\ \text{no load}\end{matrix}\right\} - \left\{\begin{matrix}\text{Difference between overloads}\\ \text{following no load and full load}\\ \text{multiplied by the square of}\\ \text{the } X \text{ initial load expressed as}\\ \text{a fraction of full load}\end{matrix}\right\}$$

For example, if the steady state load preceding an emergency overload is 70 per cent of full load, permissible load for 30 sec will be: $6 - [(6 - 5) \times 0.7^2] = 5.51$ times continuous rating.

3. *Effect of Ambient Temperature on Short-Time Overloads.* The short-time loads of Table I should be reduced 2 per cent of continuous self-cooled rating below the recommended load for each degree that the temperature of the cooling air exceeds 40 deg C. The use of self-cooled oil-immersed transformers in cooling air exceeding 50 deg C shall be considered as special.

The short-time loads of Table I may be increased 1 per cent of continuous self-cooled rating for each degree that the ambient air is below 30 deg C, except that no further increases are to be made for ambient air temperatures lower than 0 deg C.

(*c*) Permissible short-time overloads for oil-immersed transformers of types other than self-cooled are not yet available.

Engineering Education

Is Meeting the Challenge

By introducing new courses and new methods of instruction, engineering education is meeting the challenge of industry to teach engineers how to solve problems involving economic and social as well as engineering aspects. A few of the steps already taken or contemplated in this direction by several leading engineering colleges are outlined in this paper.

By
HAROLD W. BIBBER
MEMBER A.I.E.E.

The Ohio State Univ., Columbus

DURING the past year there has been much discussion of the demands of present day industry and the ways in which these demands may be met by the engineering colleges, both in the A.I.E.E. ("Industry Demands and Engineering Education" by L. W. W. Morrow, ELECTRICAL ENGINEERING, April 1934, p. 518–22, and discussion, Oct. 1934, p. 1418–22) and outside (papers and discussion at the Ithaca, N. Y., meeting of the Society for the Promotion of Engineering Education, June 1934). This article has been written to state a general solution of the problem as it now exists, and to describe briefly a few of the steps already taken or contemplated by institutions with which the writer is familiar, to achieve some of the objectives.

NEED FOR DEFINITIONS OF ENGINEERING AND ENGINEER

To avoid misunderstanding, it may be well to state at the outset the definition of engineering to which the writer subscribes. While there have been many restatements and elaborations, it is his belief that the simplest and most comprehensive definition of engineering is that contained in the charter of the Institution of Civil Engineers (London) dated 1828, in which what was then termed "civil" engineering—in contrast to "military" engineering—was defined as the "*art of directing the great sources of power in nature for the use and convenience of man.*" It is evident that this definition covers a knowledge of physical science, and at the same time includes the economic and social, or human, aspects of applying physical science for the benefit of human society.

The definition of an engineer in terms of what he does would obviously be "one who practices engineering." For a more descriptive definition, particularly with regard to the broader aspects of an engineer's function or duty, one may refer to the definition of "professional engineer" in the Encyclopaedia Britannica. This states that "*the engineer is under obligation to consider the sociological, economic, and spiritual effects of engineering operations and to aid his fellowmen to adjust wisely their modes of living, their industrial, governmental, and commercial procedures.*"

Recently the Engineers' Council for Professional Development (E.C.P.D.) has found it advisable to proceed to define an engineer for legal purposes in terms of his preparation, experience, and knowledge as determined by examination. No doubt this was necessary not only because of the quacks who had assumed the title, but also because of the fact that engineering graduates often have been referred to as engineers. There may have been a time in the past when it was possible to give a student the broad general training in fundamental physical and social science, and the specialized knowledge of a particular field that justified giving him the title of "engineer" on graduation. If this were ever true, the time long since has passed.

It seems rather important today to distinguish, both in industry and in educational circles, between an engineering graduate, an engineer, and a person who uses engineering methods in other fields such as business.

WHY A NEW EMPHASIS ON SOCIAL ASPECTS?

From earliest times up to about the last 10 years, engineers always have been concerned primarily with production, transportation, or communication. There has never been a sufficient supply of manufactured goods or raw materials in the places they were wanted, and the engineer's work of directing the great sources of power in nature has been primarily that of providing more goods or services, such as transportation or electric power. There always has been a demand for a greater capacity to produce than existed at the time. Usually this has been because the technical means of production were inadequate. Up to very recent years, therefore, the engineer has devoted himself largely to the conquest of the physical difficulties associated with the application of natural science. The part of his work dealing with "the use and convenience of man" in many cases has been minor. Nevertheless, the social aspects of the application of power always have been within the engineer's domain!

As many of the technical problems that years ago confronted engineers have been approaching a complete solution, more of their work has concerned itself with the economic and social aspects of power application or communication. The results of this trend are shown in the opinions of practicing engineers as to what the nature of engineering education should be, as embodied in the report of the Society for the Promotion of Engineering Education on its investigation of engineering education. Other

Full text of a paper recommended for publication by the A.I.E.E. committee on education, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted July 31, 1934; released for publication Sept. 6, 1934. *Not published in pamphlet form.*

studies of similar character have been made by individual colleges and universities. All of these indicate that more and more attention should be given in the schools to the social sciences, such as economics, business organization, history, psychology, and sociology.

Is Engineering Dominance Undesirable?

What interest should be dominant in a course, broadened as previously indicated, to train men for the staff and operating positions of industry? The writer believes it should be the engineering group, not because industry in the past has chosen men for these positions largely from engineering graduates, but because of the unique intermediate position of the engineering group when the engineering function is conceived in accordance with the initial definition of this paper.

An engineer, by that definition, is one who stands between the pure scientist on the one hand and the economist, sociologist, or business man on the other hand. If there should be "pure science dominance" of a course, it is probable that economics, business organization, psychology, and sociology would not have their proper places in the curriculum. They would be overbalanced by higher mathematics, theoretical physics, and technical specialities. If, however, there is "business dominance," too much of the curriculum is likely to be given over to descriptive courses dealing with economic or industrial organization as it now exists, and too little time will be spent on courses of a rigorous character that develop the student's ability to solve problems. Properly qualified engineering teachers, the selection of which men is a very important point in this program, are the ones to determine a reasonable compromise between these 2 points of view.

Problem Solving Ability—The Key

In answer to the question why trained men for staff and operating positions of importance in technological industry are best educated under the dominance of an engineering group, a simple answer can be given: *because engineering training develops the ability to solve problems.* Ask any university student how the engineering courses differ from those of other colleges, and he will reply "you have to solve a lot of problems." This does not mean, of course, that problems are not given in other fields, or that there is not a growing tendency in other fields to recognize the advantages of problems for instructional purposes. At the present time it is, and for some years to come will continue to be, a rather unique attribute of engineering courses.

In order to train young men to tackle problems effectively it would seem advisable to have the subject matter of the problems as simple, straightforward, and definite as possible, so that the attention of both student and instructor could be concentrated on the method of attack, rather than to have it divided between the attack and a discussion of the nature of the data, the possible variations in conditions, doubtful validity of assumptions, etc. Obviously the physical sciences present the most ideal material on which to start.

After the ability to solve physical problems has been developed, the student then may turn his attention with more profit to problems in the social sciences where the variables are much more numerous, the reliability of data are frequently in question, and more than one correct solution is not uncommon. This seems to be the easiest way of education for responsibility in a mechanized industry. It is not the only way, of course, for many able administrators and executives in technical industry never have received an engineering training.

It is likewise true that without alterations the methods of tackling engineering problems cannot be applied to social problems. It is a manifest error to simplify or twist social problems around so that simple engineering solutions can be obtained. The engineering student must be trained to realize the difference and exercise judgment in the application of detailed techniques of solution.

Another benefit derived from starting the training of the staff and operators of mechanized industry in the engineering field is that executives in business need as much of the investigatory attitude in dealing with industrial problems, as the engineer does in dealing with more scientific subject matter. In all of the leading engineering schools research activities are so prominent that this influence is bound to be felt by the students.

"Honors Courses" to Develop Professional Engineers

So far nothing has been said as to how future professional engineers, whose concern will be as much with physical science as with social matters, are to be developed. It would seem that the most promising way of doing this is by the use of "honors courses" such as have been operating successfully at the Massachusetts Institute of Technology and other schools. Under this plan those students showing particular aptitude are given the opportunity to pursue individual study at whatever rate they are capable, and in the direction that gives promise of developing their innate abilities to the greatest extent. The professional engineer more than any other, must have great initiative and the ability to work out problems by himself.

The "honors course" plan appears to offer an admirable way of selecting and educating men who will have these qualities. The results obtained seem remarkable compared with what usually is accomplished in regular classroom work. This plan, of course, is applicable as well to outstanding students whose interests are more economic or social than technical.

In the scheme proposed here there would be no differentiation of department between the training of the men to staff and operate industry, and those, who as professional engineers, would design machines or products of that industry. This single administration is believed to have a very definite value.

If the staff and operating members of an industrial organization have passed through the same basic

educational processes as the professional engineers in that organization, it is possible to hope for a degree of coöperation and mutual understanding of the other's point of view that could not be hoped for in any other way. Those engaged in the sale and application of a technical product cannot be expected to have, and it would not be desirable from the point of industry that they should have, the same point of view as the designer or as the production engineer. Each function must have its own "guiding star," but this does not mean that each can go its own way unrestrained. Organizations can make those compromises that are necessary for the best conduct of business when they are so staffed that the point of view of one department can be understood and accepted as reasonable by another. A great deal often can be accomplished if one group will grant that another group can hold a set of ideas different from that held by the first group regarding a business topic, without being a "bunch of half-wits." Much useless pulling at cross purposes could be avoided in technological industries if better understanding existed between different parts of their organizations.

Make-Up of a Modern Engineering Course

The question "What is the make-up of the course that will accomplish these results?" now will be answered. It will consist of a fundamental training in mathematics, chemistry, physics, the arts of expression, economics, business organization, psychology, history, and sociology. Depending on the field of engineering, there will be basic engineering courses dealing with electrical, mechanical, civil, or other branches. Options in advanced engineering courses will be provided. No required specialized application courses will be included in the 4-yr program. A considerable portion of the student's time will be available for elective courses, subject to reasonable advice and consultation with competent faculty members. In these elective courses the individual characteristics of the student will be amply recognized. Students show many different degrees of interest in the technical and social aspects of engineering. To be successful, any course must enlist their interest and abounding enthusiasm. The "honors course" will provide the method within each engineering department for the development of the relatively few individuals who have some hope of success as professional engineers.

School a Part of Real Life

In the elementary and secondary schools, it is being found that one of the surest ways to awaken the student to creative activity is to reorganize the way in which the school is conducted, so that it becomes a part of real life, and not an area of artificial experience, where people sit with folded hands and do not whisper to each other.

Not all the secondary schools by any means have accomplished this liberalization, so that it is now the job of the college to bridge the gap, if any, between the youth's previous school experience and real life in technological industry, and in a machine age generally. Particularly in the later years of the course, an effort should be made to have the work of the college correspond to real life. Individuals or groups of students would be assigned projects to be completed at specified dates. There would be very few formal lectures, but many round table conferences of committees assigned to related projects. A promising idea, tried out in a few places already, is to provide each senior student with a desk in the manner of large engineering offices, and even with stenographic service. The student is expected to spend a full day on the job, with a night or 2 of study at home each week—just the sort of thing he will do if he makes a success of his early professional career.

With this point of view, the transition from college to industry will be less painful to the individual, and less costly to industry. It will be but a step in progress, and not a revolutionary change. Much of the complaint that is heard of the attitude of young engineering graduates in industry thus will be eliminated.

It may be objected that the success of this program depends entirely upon the caliber of men in the engineering faculty who teach and administer it. The answer to this is that the value of any engineering course, past, present, or future, depends upon the caliber of the men teaching and administering the work.

Type of Faculty Required

To give the type of engineering course here described, the faculty members of the engineering departments must realize clearly the intermediate position in which the engineer stands between the pure scientist on the one hand and the economist, social scientist, or business man on the other. They must realize that it is not the function of an engineering course to train pure scientists, though some graduates may engage later in work of a purely scientific character. However, they must maintain the engineering character of the course, typified by problem solving, as against the necessarily descriptive character of many subjects in social science. At the same time they must have the ability to utilize the student's preparation in these other subjects so that in their own engineering courses the application, either through analysis or synthesis, of fundamental technical and social principles, which really constitute engineering, may be clearly brought out.

Teachers most likely to have properly balanced points of view are those who have had practical experience of some years in industry and who endeavor to maintain that contact during their teaching careers. This means that the criteria adopted in some educational institutions of hiring only those men who have obtained a series of academic degrees will have to be reconsidered, and worth while experience in industry rated the full equivalent of an academic Ph.D. degree.

A man who has done real engineering work in any large industry has unavoidably been impressed by

the necessity of coöperation between the different departments of the corporation. In fact he has seen that unless people coöperate, they are "fired." Such a man is, therefore, one who readily can appreciate the necessity of the coöperation that is essential between the pure science and the social science divisions and the engineering department. Experience usually will have taught him how to go about securing this coöperation.

The New Program Well Worth Its Higher Cost

A college that carries out the modern program of engineering education here proposed will educate young men first in the analysis of physical problems, accompanied by as much practice as possible in the synthesis or devising of new solutions. After some skill in problem solving technique has been acquired, students will attack engineering problems that embrace both technical and social fields.

A knowledge of those few principles of the physical and social sciences that are truly fundamental will be gained through a well balanced curriculum. The whole aim will be to make the college work an integral part of life. To teach the engineering subjects and administer the courses, particularly well qualified teachers will be needed. This new program may cost more per student than the conventional one, but the present demands for improvement are so insistent, and the product sure to be so much better, that they will amply justify the increased expenditure.

Heat Flow in Turbine Generator Rotors

The various factors which enter into a determination of the temperatures in turbine generator rotors are discussed in this paper, and a method of calculating temperatures is given. It is shown that a large number of variables can be taken into account in a relatively simple manner and that the method can be applied with accuracy to all sizes and types of turbine generator rotors.

By
C. E. PECK*

Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.

ACCURATE predetermination of turbine generator rotor temperatures is important from the standpoint of differential expansion of the coil and coil strands, and safe operating temperatures of the field coil insulation.

A reasonably complete and accurate analysis of temperatures in any electrical machine presumes a knowledge of the following factors:

1. An accurate method of calculation based upon an analysis which does not neglect the importance of the several fundamental variables involved.
2. The interaction of the separate parts, such as effect of end winding temperatures on the temperatures in the main body of the machine.
3. The magnitude and distribution of the various losses generated.
4. The ventilation characteristics of the machine, such as the distribution of velocities and amounts of air circulating through the numerous cooling paths.
5. An accurate knowledge based upon research and test experience of the physical constants used in the calculations, such as thermal resistivity of the insulation, contact resistances, and surface dissipation rates corresponding to the various velocities of the cooling medium.

The purpose of this paper is to combine the above factors into a reasonably complete analysis. The method of calculation for the temperature rises in the slot region of the rotor is based upon equivalent thermal circuits which have been worked out by C. R. Soderberg in his paper,[1] "Steady Flow of Heat in Large Turbine Generators." The circuits devised by Mr. Soderberg are based upon a complete theoretical analysis of the fundamental thermal paths in the slot region of a turbine generator. The circuits which are described later in the paper are based solely upon his work and a discussion of the basis of the circuits used is, therefore, omitted.

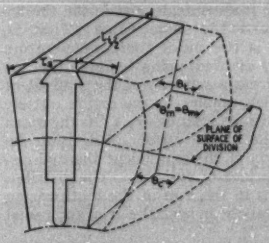


Fig. 1. Detail of slot region considered with surface of division and iron temperature distribution

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 29–25, 1935. Manuscript submitted March 5, 1934; released for publication Aug. 27, 1934. *Not published in pamphlet form.*

* The author has applied for Associate membership in the Institute.

1. For all numbered references see list at end of paper.

The main body of the paper outlines the general method of calculation and discusses the applications. The appendixes give a detailed picture of the calculation methods.

Method of Calculation

The complete steady state temperature analysis involves 3 principal steps, namely, the determination of the following:

I. Temperature rises in rotor body assuming no longitudinal heat flow along the conductors to the end windings or *vice versa*.

II. Temperature rises in the end windings assuming no longitudinal heat flow along the conductors to the rotor body or *vice versa*.

III. Longitudinal distribution of temperatures in the conductors along the complete length of the end windings and rotor body. I and II must be calculated in order to complete the calculation of III.

I. Temperature Rises in the Rotor Body

A detailed oblique sketch of the region considered in the calculations is shown in Fig. 1. This region is bounded on the rotor surface by an area equal to

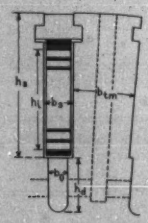


Fig. 2. Detail of slot region showing dimensions used in Figs. 3 and 4

$\tau_s l_s/2$. τ_s = distance between corresponding points on adjacent slots at the air gap (slot pitch) and l_s is the distance between radial ventilating ducts in the axial direction. The region is bounded on the sides by 2 radial planes intersecting at the center of the rotor. The type of ventilation considered is that containing an axial slot under the coil which leads to radial discharge vents.

The radial heat flow in the tooth region divides at an imaginary cylindrical surface, called the "surface of division," which denotes the radial location of the maximum iron temperature. Referring to Fig. 1, the surface of division is located correctly when the mean iron temperatures at the surface of division, calculated from outside and inside the assumed location, have the same value. That is, $\theta_m = \theta_m'$, where θ_m is the mean tooth temperature rise *at the surface of division*, using temperature rise constants derived from a solution of the equivalent thermal circuit which applies to the region outside of the surface of division. Similarly, θ_m' is the mean iron temperature rise at the surface of division derived from a solution of the equivalent thermal circuit inside of the surface of division. The distribution of temperatures in the iron of the tooth region is assumed to be parabolic in both the axial and radial directions. θ_t is the mean tooth temperature as represented by the mean height of the paraboloid of temperature distribution in Fig. 1 above the surface of division.

A detailed sketch of the slot region and diagrams of the equivalent thermal circuits outside and inside of the surface of division are shown in Figs. 2, 3, and 4.

The calculation of the mean temperature rises in the region being considered consists of combining the various thermal resistances in the circuits into "temperature rise constants." These constants when multiplied by the loss give the temperature rise. This is the thermal equivalent of Ohm's law.

The equivalent circuits are based upon the following assumptions:

1. All heat generated in the region defined in Fig. 1 flows through axial and radial paths to the vent ducts and air gap. This assumes that there is no longitudinal heat flow along the copper to the ends. The longitudinal flow will be discussed later in the paper.

2. Losses are generated uniformly.

3. Since the rotor is only partially slotted around its periphery, there is some heat flow in a tangential direction to the pole centers. This effect is approximated by distributing the cooling surface on the pole uniformly over the tooth tips in the slotted portion, thus restricting the problem to heat flow in 2 dimensions (axial and radial).

Symbols and Units of Figs. 3 and 4. In general, ρ with a descriptive subscript is the thermal resistivity in degree(Centigrade)-inches per watt, which is the inverse of thermal conductivity. C with a descriptive subscript is the surface resistance in degree(Centigrade)-inches^2 per watt, which is the inverse of surface dissipation. Each thermal resistance in Figs. 3 and 4 has the units of degrees Centigrade per watt. The losses generated in the region defined in Fig. 1 are expressed in watts. Hence, the product of loss and resistance gives the various temperatures in degrees Centigrade. Other systems of units may be applied without altering the form of the resistances dealt with in this discussion. A complete list of symbols for the circuits is given in Appendix I.

There are various methods of solving the circuits of Figs. 3 and 4, and the method outlined in this discussion is made consistent with Mr. Soderberg's treatment[1] in that the various resistances are combined and expressed as an over-all resistance called a "temperature rise constant," which has the units of surface resistance in degree(Centigrade)-inches^2

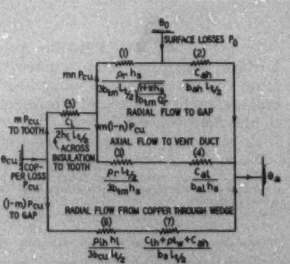


Fig. 3. Equivalent thermal circuit above surface of division

per watt. The various losses are expressed as watts per square inch of rotor surface at the air gap. If P_{cu} is the total copper loss in the region outside of the surface of division as defined in Fig. 1, then the loss in watts per square inch of rotor surface p_{cu} is obtained by the relation

$$p_{cu} = \frac{P_{cu}}{\pi d_r l/2} \tag{1}$$

Solution of the Thermal Circuits. For the region outside of the surface of division, the mean temperature rises of the copper and tooth above ambient are:

$$\begin{aligned} \theta_{cu} &= \theta_a + p_{cu} \cdot C_{cu} + p_0 C_0 \\ \theta_t &= \theta_a + p_{cu} C_t + p_0 C_0 \end{aligned} \tag{2}$$

C_{cu}, C_t, and C_0 are temperature rise constants derived from a solution of the equivalent thermal circuit of Fig. 3 in Appendix I. p_{cu} and p_0 are the copper and surface losses. θ_a is the mean temperature rise of the cooling medium as it absorbs the losses while passing through the ventilating passages.

It is usually more convenient to evaluate the copper loss at a given temperature and apply a correction for the change in resistance. If the copper loss p_{cu} is based upon a temperature of 75 deg C, the mean temperature rises of eq 2 become

$$\begin{aligned} \theta_{cu} &= \frac{310}{310 - p_{cu} C_{cu}} \left[\theta_a + p_{cu} C_{cu} \left(\frac{235 + \theta_0}{310} \right) + p_0 C_0 \right] \\ \theta_t &= \theta_a + p_{cu} C_t + p_0 C_0 \end{aligned} \tag{3}$$

where $p_{cu'} = p_{cu} \dfrac{235 + \theta_0 + \theta_{cu}}{310}$ and θ_0 is the ambient temperature.

Similarly for the region inside of the surface of division, the mean temperature rises of the copper in the slot, the iron in the tooth region, and the iron in the core above ambient are:

$$\begin{aligned} \theta_{cu} &= \theta_a + p_{cu} C_{cu} \\ \theta_t &= \theta_a + p_{cu} C_{cut} \\ \theta_c &= \theta_a + p_{cu} C_{cuc} \end{aligned} \tag{4}$$

C_{cu}, C_{cut}, and C_{cuc} are the temperature rise constants derived from a solution of the equivalent thermal circuit of Fig. 4 in Appendix I. p_{cu} is the copper loss inside of the surface of division, and corrections for change in resistance are carried out as indicated for eq 3.

It is sometimes of interest to know the loss distribution through the various parallel paths. In Fig. 3, the copper loss divides so that m parts flow across the slot insulation to the tooth and $(1-m)$ parts flow from the copper radially to the air gap. In the tooth, the m parts divide into n and $(1-n)$ parts to follow the parallel paths radially and axially to the air gap and vent duct. Expressions for m and n are given in Appendix I.

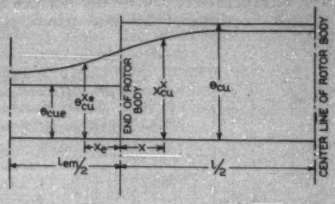


Fig. 5. Diagram of longitudinal temperature distribution

Relative thermal drops in various parts of the circuits can be obtained by the product of the thermal resistance and the loss component as given by the expressions for m and n.

Extent to Which Calculations Should Be Carried. If $\theta_m = \theta_m'$, the surface of division has been located exactly by "matching" the mean iron temperatures. The expressions for θ_m and θ_m' as defined in Fig. 1 are given in Appendix I. The copper temperature rise for the complete radial depth of coil is the weighted average of the value calculated for the outside and inside of the surface of division. In most calculations about the same accuracy is obtained by assuming the location of the surface of division at the midpoint of the radial tooth height and obtaining an average of the copper temperatures outside and inside the surface of division, even though the mean tooth temperatures at the surface of division are not exactly matched.

It is sometimes convenient to obtain an over-all temperature rise constant for the total radial depth of tooth. This can be obtained from the relation

$$C_{cu} = \frac{310(\theta^*_{cu} - \theta_a)}{p_{cu}(235 + \theta^*_{cu} + \theta_a)} \tag{5}$$

where θ^*_{cu} is the average copper temperature obtained from calculation of the copper temperatures outside and inside the surface of division. p_{cu} is copper loss at 75 deg C for the total slot depth.

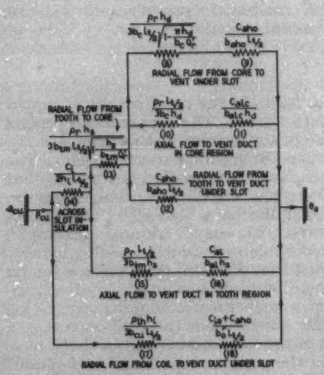


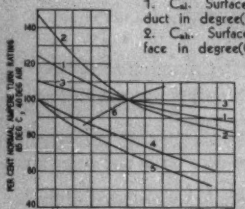
Fig. 4. Thermal circuit below surface of division

II. Temperature Rises in the Rotor End Windings

Rotors of modern construction are usually ventilated in the end turns by means of holes in the retaining rings and with or without special blocks between turns which increase the velocity of the cooling medium relative to the coil. In some cases, the sides of the coil on the ends are not insulated over their

total area so that bare copper is exposed to the cooling medium. A larger part of the coil sides not located near the ventilating passages is surrounded either by dead air space or filler material, which greatly increases the heat resistivity in these parts.

The temperature rises in the ventilated and nonventilated portions are calculated and the interaction of one on the other is accounted for in the same manner, as will be described under III, in which the longitudinal heat flow effects of the end windings and rotor body are considered. In this discussion, the interaction effects of the nonventilated and ventilated portions of the end windings are evaluated



1. C_{al}. Surface resistance of radial vent duct in degree(Centigrade)-inches² per watt
2. C_{ah}. Surface resistance at rotor gap surface in degree(Centigrade)-inches² per watt for nonventilated rotor
3. C_{ah}. Same as 2 except rotor is ventilated
4. P_b. Surface loss in watts per inches² of rotor surface, ventilated rotor, expressed as per cent of copper loss for 85 deg rise
5. P_b. Same as 4 except rotor is not ventilated
6. Peripheral speed based upon 26,000 ft per minute as 100 per cent

Fig. 6. Variation of ampere turn rating

and put in curve form. The method consists of calculating the temperature of the ventilated portion and altering the result by a factor F from the curves of Fig. 10, which allows for the heat flow from nonventilated portions. This greatly shortens the calculation of the end winding temperatures. The method of calculating end winding temperatures is given in Appendix II.

III. Longitudinal Temperature Distribution

Thus far the temperature rises of the rotor body and end windings have been considered neglecting the heat interchange between them. In many cases, there is considerable heat flow longitudinally in the field winding because of the difference in temperature between the ends and the rotor body. The fundamental equations upon which the following equations are based have been discussed before,[3] and therefore are not repeated here.

The mean copper temperatures at the points X and X_e are, respectively (see Fig. 5):

$$\theta_{cu}^{X} = \theta_{cu} - \frac{\theta_{cu} - \theta_{cue}}{1 + \dfrac{C \tanh Cl/2}{C_e \tanh C_e \dfrac{l_{em}}{2}}} \frac{\cosh C(l/2 - X)}{\cosh Cl/2} \tag{6}$$

$$\theta_{cu}^{X_e} = \theta_{cue} + \frac{\theta_{cu} - \theta_{cue}}{1 + \dfrac{C_e \tanh C_e \dfrac{l_{em}}{2}}{C \tanh Cl/2}} \frac{\cosh C_e\left(\dfrac{l_{em}}{2} - X_e\right)}{\cosh C_e \dfrac{l_{em}}{2}} \tag{7}$$

in which θ_{cu} and θ_{cue} are the body and end winding temperatures neglecting longitudinal flow as given earlier in the paper under headings I and II.

$$C = \sqrt{\frac{\rho_{cu} \gamma_s}{C_{cu} \cdot a_{cu}} \left(1 - \frac{\rho_{cu} C_{cu}}{310}\right)}$$

$$C_e = \sqrt{\frac{\rho_{cu} \gamma_s}{C_{cue} \cdot a_{cu}} \left(1 - \frac{\rho_{cue} C_{cue}}{310}\right)}$$

The factor in parenthesis allows for change in temperature coefficient of resistance, on basis of 75 deg C

ρ_{cu} = thermal resistivity of copper, degree(Centigrade)-inches per watt
a_{cu} = cross section area of copper in slot (square inches)
l = axial length of rotor body in inches
l_{em} = length of mean turn on one end of rotor (inches)
= ½ (total mean turn of winding − 2l)
X = distance along coil measured from end of rotor body
X_e = distance along coil on end windings measured from end of rotor body toward extremity of end winding

It is important to note[4] that θ_{cu} and θ_{cue} enter into the equations for longitudinal heat flow. Thus, the accuracy of determination of the longitudinal heat flow depends directly upon the accuracy of the temperatures θ_{cu} and θ_{cue} which neglect the longitudinal heat exchange. It is important to determine θ_{cu} more accurately than θ_{cue} since the body temperatures influence a much larger proportion of the total coil length than the end winding. Usually the rotor temperatures are measured by means of change in resistance of the winding, the measurement corresponding to the mean temperature rise of the winding over its total length. This temperature can be obtained by integration of eqs 15 and 16 over the length of rotor body and end winding, which gives:

$$\theta_{cum} = \frac{l}{l + l_{em}} \theta_{cu} + \frac{l_{em}}{l + l_{em}} \theta_{cue} + \frac{2(\theta_{cu} - \theta_{cue})}{l + l_{em}} \cdot \frac{\dfrac{C}{C_e} - \dfrac{C_e}{C}}{\dfrac{C}{\tanh C_e \dfrac{l_{em}}{2}} + \dfrac{C_e}{\tanh Cl/2}} \tag{8}$$

The method of calculation allows a complete study of the several variables involved, and which should be considered to arrive at an accurate determination of temperature for a large range of size and rating. In addition, the accuracy of determination depends upon the magnitude and distribution of the losses, knowledge of ventilation characteristics, and a knowledge of surface dissipation rates and conductivity constants which are based upon research and test experience on actual machines.

Losses

The electrical losses in the rotor consist of copper losses and surface losses. The copper losses depend upon the square of the current and resistance of the winding, and can be calculated accurately. The surface losses cannot be estimated accurately, but in the normal modern rotor, the surface losses are usually very small and have little effect on the copper temperatures. In single winding generators with unbalanced loads and double winding generators with unequal load division, the surface losses on the rotor may be of large magnitude, and will increase the copper temperatures considerably. This condition usually exists when the field current is a fractional part of the full load current, and the temperature rise in the copper due to surface loss plus

copper loss is no greater than the full load temperature rise.

Ventilation

A complete discussion of the ventilation characteristics of the rotor is beyond the scope of the present paper, but a brief note concerning the determination of the various vent duct velocities may be of interest. A complete study of the pressure drops through the ventilating circuit has been made on a rotating model of a turbine generator rotor. Additional tests on full size rotors were made to determine the ventilation effect by measuring the temperature rises and windage with and without ventilation in the rotor. From these investigations, data on average velocities in the various ducts were obtained.

Dissipation Rates

In addition to the determination of the magnitude of the velocities, the average dissipation rates corresponding to these velocities should be known. The rate of heat dissipation from the axial and radial vent ducts depends not only upon the magnitude of the velocity but also upon the length of the duct and the size and shape of its cross section. Some work of this nature with especial reference to the ducts in electrical machines has already been published.[4]

The dissipation rate from the rotor gap surface is practically constant for the range of high peripheral speeds at which turbine generators operate (22,000 to 28,000 ft per minute). At these speeds, the film of air rotating with the rotor is effective in preventing the heat transfer from increasing beyond a certain value. Other tests, though not conclusive, indicate that grooving the rotor surface increases the effective dissipation area only by a small amount.

The contact resistance between the coil insulation and the slot when it is assembled and has current flowing is decreased below the value that might be expected from the clearances indicated by the difference in dimensions between the slot width and coil width. Tests made on a full size coil indicated that the equivalent air layer was about $^1/_4$ to $^1/_3$ as thick as the clearance dimensions indicate, due to the effect of filler between the coil and slot and also to the swelling of the coil when heated.

Effect of Several Variables on Rating

Curves on Figs. 6 and 7 show the change in ampere turn rating of a representative large turbine generator rotor as the several variables enumerated below are changed over a large range of values. The 100 per cent value indicates the values of the variables for normal ampere turn rating. The effect of changes in the mean air temperature rise as the ventilation and losses are varied is taken into account in the calculation. The ampere turn rating is expressed for 85 deg C rise above 40 deg C air according to present A.I.E.E. standard.

Variation in Vent Duct Velocity. This affects the surface resistance to heat flow at the vent duct (C_{ai}, Fig. 6). If the surface resistance is $^1/_2$ the value at 100 per cent rating, the ampere turn rating is increased 10 per cent. If the surface resistance is twice the value at 100 per cent rating, the ampere turns decrease 10 per cent.

Variation in Gap Surface Dissipation (C_{ai}, Fig. 6). The change in ampere turn rating is considerably greater with a nonventilated rotor than with a ventilated rotor. If the surface resistance is $^1/_2$ the value at 100 per cent rating for a nonventilated rotor, the ampere turns are increased 23 per cent. However, if the surface resistance is $^1/_2$ for the ventilated rotor, the ampere turns are increased 5 per cent. The resistance to radial heat flow to the gap is obviously much larger than the resistance to axial heat flow to the ventilating ducts.

Surface Losses (p_0, Fig. 6). In this case, also, the ampere turn rating decreases at a faster rate with a nonventilated rotor than with a ventilated rotor. Obviously surface losses must be limited to reasonably small values if affects on ampere turn rating are to be neglected.

Effect of Speed (Fig. 6). The peripheral speed affects the ventilation, and hence all surface dissipation rates are affected as well as the mean air rise through the rotor. Surface dissipation rates increase with the peripheral speed at the same rate as they increase with velocity. The ventilation loss also increases approximately as the cube of the peripheral speed, so that for large increases in peripheral speed, other factors being equal, the mean air rise would be the limiting factor with regard to increased ampere turn rating.

Thermal Resistance of Insulation (C_i, Fig. 7). The change in ampere turn rating as the insulation resistance is changed is greater with a ventilated rotor than with a nonventilated rotor. A ventilated rotor has a lower over-all thermal drop in the tooth than across the insulation compared to the nonventilated rotor. In large ventilated rotors, the probable gain in ampere turn rating which could be obtained by using aluminum oxide laminations as insulation in the space now used by the present type is about 10 per cent.

1. C_i. Over-all thermal resistivity of insulation for ventilated rotor 180 in. long
2. C_i. Same as curve 1 except rotor is not ventilated
3. C_i. Over-all thermal resistivity of insulation for nonventilated rotor 90 in. long
4. θ_0. Ambient temperature, degrees Centigrade

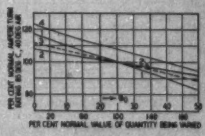


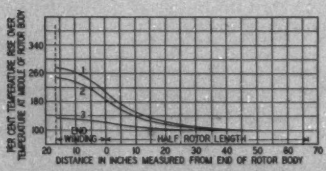
Fig. 7. Variation of ampere turn rating

Ambient Air Temperature (θ_0, Fig. 7). The curve indicates that a change from 40 deg C ambient, the 100 per cent value, to 0 deg C has the effect of increasing the ampere turn rating 23 per cent. This assumes that the rotor temperature rise plus the ambient temperature has a constant value of 125 deg C.

Effect of End Winding Ventilation (Fig. 8). The longitudinal temperature distribution for various

schemes of ventilation indicates the advantages of good end winding ventilation. A typical example is shown in Fig. 8. The rise by resistance for curve 1 is 27 per cent greater than that for curve 3. Similarly, the rise by resistance for curve 2 is 22 per cent greater than for curve 3. For the same temperature rise, the high velocity blocking between coils gives an ampere turn rating increase of 11 per cent. The length of end winding is 20 per cent of the length of the coil. In many designs, especially those for 2-pole rotors, the end winding comprises 35 to 40 per cent of the total length of coil. For these cases, the effect of end winding ventilation on ampere turn rating is even more marked, amounting in some cases to an increase of 20 per cent.

Mean Air Temperature Rise (θ_a). All temperatures given above are rises above ambient air. An appreciable portion of this rise is due to the air temperature rise in the ventilating ducts and air gap. The mean air rise of the ventilating air through the rotor body is based upon the volume of ventilating air through the body and the losses which flow to the axial and radial vent ducts. There is another mean rise in the air gap due to the rotor surface and windage losses, and some losses from the tooth tips in the stator. Without going into detail, it should be stated that the mean air rise through the body of a ventilated rotor is 50 to 60 per cent of the total air rise through the machine, and the addition of the effects in the gap raises these values to 70 and 80 per cent. A more accurate estimate of the mean air rise θ_a depends upon the ventilation system, a knowledge of the volume of air going through the body of the rotor, and total air volume through the machine, as well as distribution of rotor losses between the radial vent ducts and the air gap.



1. No ventilation through end windings
2. Holes in retaining ring, low velocity between coils
3. Special blocks between coils to give high velocity

Fig. 8. Effect of end winding ventilation on temperature distribution

Summary

The application of the equivalent thermal circuits developed by C. R. Soderberg to the calculation of temperature rises in turbine generator rotors makes available a valuable tool for steady state temperature studies. The large number of variables can be handled in a relatively simple manner, which, together with the effect of end winding temperatures and longitudinal distribution, give a reasonably complete picture which can be applied with accuracy to all sizes and types of construction of turbine generator rotors.

It is also important to note that a reasonably accurate knowledge of the physical constants which depend upon the ventilation and thermal resistance of the various parts is necessary to make the application of the method truly valuable for all sizes and types of rotors.

The method being based upon sound fundamental assumptions, is applicable with some alteration to the slot region of any type of rotating electrical machine.

Appendix I—Symbols and Solutions of Thermal Circuits of Figs. 3 and 4

Meaning of Subscripts

a = air cooled surface
c = iron in core region
cu = copper
e = end windings
i = insulation
m = mean value
r = rotor body
t = iron in tooth region

In addition, the scheme of symbols is such that b refers to breadth or width, h refers to radial length, and l refers to axial length. Wherever possible, the various lengths are designated on Fig. 2.

Symbols (Alphabetically Arranged)

Above Surface of Division, Fig. 3

$b_{ah} = \dfrac{\pi d_r - Q_r b_s}{Q_r}$	cooled width of tooth in air gap. Pole surface uniformly distributed over tooth tips
b_{al}	$^1/_3$ perimeter of radial vent duct
b_{cu}	width of copper in slot
b_s	width of slot
b_{tm}	mean width of tooth
C_{ah}	mean surface resistance at air gap (degree [Centigrade] inches² per watt)
C_{al}	mean surface resistance at radial vent duct
$C_i = \rho_i l_i + \rho_{al} g_a$	surface resistance of slot insulation
$C_{ih} = \rho_i l_{ih}$	surface resistance of insulation above top strap
g_a	air space on one side of slot
h_{cu}	radial height of single copper conductor
h_f	see Fig. 2
h_s	depth of slot above surface of division
h_w	height of wedge at top of slot
l_1	center to center axial distance between radial vents (Fig. 2)
Q_r	number of rotor slots
Q_r'	number of rotor slots if original slot spacing was extended around entire periphery of rotor
l_i	thickness of slot insulation on one side
l_{ih}	thickness of insulation under wedge
l_{is}	thickness of insulation between conductors in slot
ρ_a	thermal resistivity of cooling medium (degrees Centigrade inches per watt)
ρ_i	thermal resistivity of insulation material
$\rho_{is} = \rho_{is}\left(\dfrac{l_{is}}{h_{cu} + l_{is}}\right)$	equivalent thermal resistivity of conductors and insulation in radial direction
ρ_r	thermal resistivity of rotor tooth iron
ρ_w	thermal resistivity of rotor wedge
τ_s	center to center slot distance at air gap (slot pitch)

Below Surface of Division, Fig. 4 (Additional Symbols)

b_{ahe}	cooling perimeter of axial vent duct at the bottom of the slot
b_e	mean width between axial vents in core region
b_0	width of axial vent
C_{ahe}	mean surface resistance at axial vent duct

$C_{ts} = \rho_{ts} l_{ts}$ mean surface resistance at bottom of slot
h_d radial height of axial vent
t_{ts} thickness of insulation strip at bottom of slot

The solution outside of the surface of division combines the numbered resistances of Fig. 3 as follows:

$$\begin{aligned} C_{cul} &= h_c l_c \quad [(6) + (7)] \\ C_h &= h_c l_c \quad [(1) + (2)] \\ C_l &= h_c l_c \quad [(3) + (4)] \end{aligned} \tag{9}$$

$$C_{il} = \frac{Cl \cdot Ch}{C_l + C_h}$$

$$K = \frac{h_s}{h_t} C_{cul} + \left[\frac{h_s}{h_t} C_{cul} + C_l) + C_{il}\right]$$

A dimensionless ratio which is a measure of the division of loss between the parallel paths. Then the temperature rise constants of eq 2 are

$$C_{cu} = \frac{\tau_s}{2h_s} K \left[\frac{h_s}{h_t} C_l + C_{il}\right]$$

$$C_t = \frac{\tau_s}{2h_s} K C_B \tag{10}$$

$$C_s = \frac{\tau_s}{b_{sh}} \frac{C_{il}}{C_h} K C_{sh}$$

At the surface of division (Fig. 1), the mean temperature of the tooth above ambient is

$$\theta_m = \theta_t \left(1 + \frac{h_s{}^2 \rho_c}{3b_{tm} C_h}\right) \tag{11}$$

The distribution of copper losses in the thermal circuit of Fig. 3 is given by the values

$$m = K \left[1 - \frac{p_s}{p_{cu0}} \frac{2h_s}{b_{sh}} \frac{C_{il}}{C_{cul}} \cdot \frac{C_{sh}}{C_h}\right]$$

$$n = \frac{C_{il}}{C_h} \left[1 - \frac{p_s}{p_{cu0} \cdot m} \cdot \frac{2h_s}{b_{sh}} \cdot \frac{C_{sh}}{C_l}\right] \tag{12}$$

The quantities are dimensionless, m parts of the copper loss flow across the slot insulation to the tooth and $(1 - m)$ parts flow from the copper in a radial direction to the air gap. In the tooth, the m parts divide into n, and $(1 - n)$ parts to follow the parallel paths radially and axially, to gap and vent duct (see Fig. 3). The expressions simplify considerably when the surface losses are zero.

The solution of Fig. 4 inside of the surface of division introduces the following combination of the various numbered resistances:

$$\begin{aligned} C_{cul} &= h_c l_c \quad [(17) + (18)] \\ C_{hs} &= h_d l_t \quad [(8) + (9)] \\ C_{ls} &= h_d l_t \quad [(10) + (11)] \\ C_s &= \frac{C_{ls} C_{hs}}{C_{ls} + C_{hs}} \\ C_s{}^* &= \frac{[h_d l_t (12)] \left[\frac{h_s}{h_d} C_s\right]}{h_d l_t (12) + \frac{h_s}{h_d} C_s} \end{aligned} \tag{13}$$

The above quantities refer to the core region. For the tooth region, the following additional quantities are introduced.

$$\begin{aligned} C_l &= h_d l_t \quad [(15) + (16)] \\ C_h{}^* &= C_s{}^* + [h_d l_t (13)] \\ C_{il}{}^* &= \frac{C_l C_h{}^*}{C_l + C_h{}^*} \\ K &= \frac{h_s}{h_t} C_{cul} \div \left[\frac{h_s}{h_t} (C_{cul} + C_l) + C_{il}{}^*\right] \end{aligned} \tag{14}$$

Then the temperature rise constants are

$$C_{cu} = \frac{\tau_s}{2h_s} K \left(\frac{h_s}{h_t} C_l + C_{il}{}^*\right)$$

$$C_{cul} = \frac{\tau_s}{2h_s} K C_{il}{}^* \tag{15}$$

$$C_{cus} = \frac{\tau_s}{2h_d} K C_s{}^* \frac{C_{il}{}^*}{C_h{}^*}$$

Appendix II—Temperature Rises in Rotor End Windings

A cross section of the coil in the ventilated portion of the end windings is shown in Fig. 9. Bare copper is exposed to the cooling medium with the exception of that portion covered by the insulating

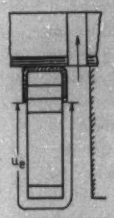


Fig. 9. Ventilated portion of end winding

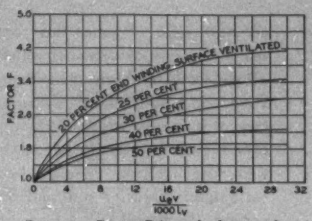


Fig. 10. Factor F for calculation of end winding temperatures

channel under the rotor retaining ring. The heat flow through the channel and retaining ring insulation is not considered because of its small magnitude. The following additional symbols are required:

u_e cooled perimeter of one coil (Fig. 9)
l_v cooled length of one coil on one side corresponding to one ventilating hole in retaining ring or one block between coils to give high velocity over coil surface
v velocity of cooling medium over cooled portion of coil
C_{ae} mean surface resistance from bare copper to cooling medium
p_{cue} copper loss in watts per square inch. This is equivalent to P_{cue} divided by $r J_t/2$, where P_{cue} is total loss generated in the coil length $l_t/2$

Defined in this manner, p_{cu} used in the calculation of body temperatures is equivalent to p_{cue}.

The temperature rise constant for the end windings is given by

$$C_{cue} = F \frac{\tau_s}{u_e} C_{ae}$$

F is taken from Fig. 10, and allows for the heat flow from the non-ventilated portions of the end winding with various percentages of the total end winding coil surface ventilated. The use of the factor F considerably shortens the work of calculating the end winding temperatures.

The mean temperature rise of the end winding, assuming no heat interchange with the rotor body, is

$$\theta_{ae} = \frac{310}{310 - p_{cue} C_{cue}} \left[\theta_{ae} + p_{cue} C_{cue} \left(\frac{235 + \theta_0}{310}\right)\right] \tag{17}$$

in which correction for changes in resistance is allowed for and the copper loss p_{cue} is evaluated at 75 deg C. θ_{ae} is the mean rise of the cooling medium through the end windings.

References

1. Steady Flow of Heat in Large Turbine Generators, C. R. Soderberg. A.I.E.E. Trans., v. 50, 1931, p. 782–98.

2. Longitudinal and Transverse Heat Flow in Slot Wound Armature Coils, Carl J. Fechheimer. A.I.E.E. Trans., v. 40, 1921, p. 589–645.

3. Reports on "Ventilation and Heat Dissipation," of Westinghouse Electric and Manufacturing Co.

4. The Cooling of Electric Machines, G. E. Luke. A.I.E.E. Trans., v. 42, 1923, p. 636–51.

A New Timer for Resistance Welding

A new type of timer and controller for use in the field of resistance welding of thin alloy sheets of brass, aluminum, stainless steel, and kindred metals where a very high current is applied for a very short interval of time is described in this paper. In this new timer, the "ignitron" type of tube is applied for obtaining precise control of the welding current. Controls for intermittent duty, high speed automatic duty, and heavy duty seam welding are described.

By
RALPH N. STODDARD
MEMBER A.I.E.E.
Westinghouse Elec. and Mfg Co., E. Pittsburgh, Pa.

SPOT or resistance welding as commonly performed employs a transformer to reduce the commercial a-c voltage to a few volts and to produce an inversely high current suitable to fuse 2 metal parts together. This low voltage is applied to electrodes which are in the form of studs or wheels, exerting pressure on each of the 2 parts to be joined. In order that a weld be satisfactory both the magnitude of the current and its duration must be controlled accurately. Where the time is short and the current correspondingly high, the weld is concentrated in a small area at the contact surface, and as a result the weld is weak under shearing stress. If the time is long and the current low the weld covers a greater area at the contact surfaces and in addition penetrates through a greater volume of metal causing burning and severe warping or deformation at the surface. Obviously a compromise between these conditions is desirable, both the time and magnitude of current varying with the physical and chemical properties of the pieces to be joined.

Electromechanical contactors have been used to establish and interrupt the current in the primary of the welding transformer at a time rate suitable to proper fusion. When spots are made in rapid succession the duty on the mechanical switch is severe. Burning of the arcing tips and mechanical wear result in high maintenance and inconsistencies between successive spots. More serious is the inaccuracy of the mechanical switch, particularly where thin stock is to be welded and this stock is an alloy carefully processed for certain physical and chemical properties. The time of welding is of the order of a few half cycles and one additional half cycle constitutes a high percentage of increased heat in the weld. Also, for consistent results, the transformer must be energized at the correct power factor angle or definite point on the voltage wave to prevent high magnetizing surges; these transients increase or decrease the heat in the weld as the time of fire is varied from that corresponding to zero current.

Full text of a paper recommended for publication by the A.I.E.E. committee on electric welding, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted May 8, 1934; released for publication July 23, 1934. *Not published in pamphlet form.*

Theory of Operation

The "ignitron" welding timer performs the function of a rapid action single-pole single-throw switch connected in series with the power source and the primary of the welding machine transformer. The function of the vital parts of the timer is illustrated in Fig. 1. Power current is carried and interrupted by 2 "ignitron[1]" tubes. These tubes are connected in parallel inverse relation, the combination serving to pass alternating current, and are placed directly in series with the power source and welding transformer primary. These tubes have been described in other papers (see "A New Method for Initiating the Cathode of an Arc" by J. Slepian and L. R. Ludwig, A.I.E.E. Trans., v. 52, 1933, p. 693–8; and "The Ignitron—A New Controlled Rectifier" by D. D. Knowles, *electronics*, v. 6, 1933, p. 164–6) so that only their important characteristics are reviewed here.

The ignitron tubes are of the mercury pool cathode type and have essentially the same characteristics as conventional pool type rectifiers; they do not have the crest current limitations of the hot cathode type. An ignition electrode or crystal dips into the mercury pool. A small ignition current fires the tube for each desired loop of welding current. Once a half-cycle of current is initiated in either ignitron tube it will continue to the end of the loop, at which time the arc is automatically extinguished. Contactors or relays are not relied upon, either to interrupt the power current or to control the duration of the weld. Timing is entirely

1. "Ignitron" is a trade name of the Westinghouse Electric and Manufacturing Company.

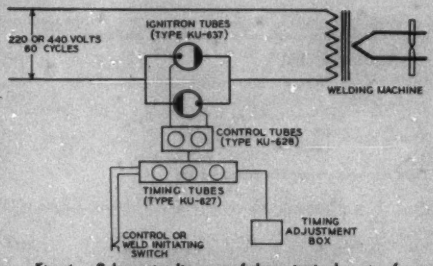


Fig. 1. Schematic diagram of the principal parts of the ignitron welding timer

electronically controlled. In operation, each closure of the weld initiating contacts will measure out a predetermined number of cycles of welding current. These contacts may be either manual or machine operated. Welding current always begins at a predetermined point on the voltage wave regardless of time of closure of the initiating switch.

A more complete schematic diagram is shown in Fig. 2. Tubes T, T_2, and T_3 are the timing tubes. T_4 and T_5 are the control tubes which control the ignition electrodes in the ignitron tubes A and B. Both the timing and control tubes are the mercury vapor arc discharge type. They are the hot cathode or filament type and are grid controlled. To block these tubes, negative potential is applied to the grid. To cause breakdown, zero or positive potential is applied. Tube T is the initiating tube and is supplied from an a-c source in synchronism with the power supply to the welder. The a-c grid cathode voltage may be varied in phase by means of capacitor C_1 and variable resistor R_4. Thus when the grid becomes positive the tube breaks down at a controllable or preset point in the positive half cycle of anode voltage. At breakdown of T a surge voltage is generated in the secondary of transformer 1. Thus tube T permits the operator to initiate welding current always at the natural zero point of current on the voltage wave, or at the correct factor power angle.

Tube T_2 may be termed the starting tube. After closure of the weld initiating switch and at the next grid voltage surge from tube T through transformer 1 tube T_2 will break down and start the flow of welding current. Up to this point T_3 has been blocked off by negative grid source S_3. After breakdown of T_2 positive or energizing grid bias is applied to the grids of T_4 and T_5 from the voltage drop across resistor R_2. Breakdown of T_4 and T_5

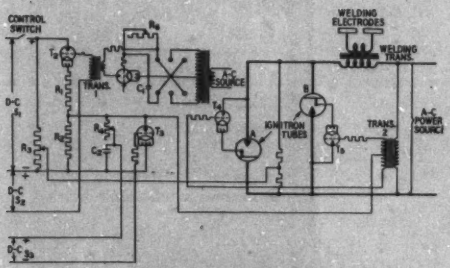


Fig. 2. A more complete schematic diagram of the ignitron welding timer

causes ignition of the ignitron power tubes and the consequent flow of welding current. It can be seen by inspection of the circuit that prior to breakdown of the start tube T_2, negative or holding potential is applied continuously to the grids of T_4 and T_5. After breakdown of T_2 this potential is shifted to positive. The function of transformer 2 and potentiometer is to nullify the a-c potential

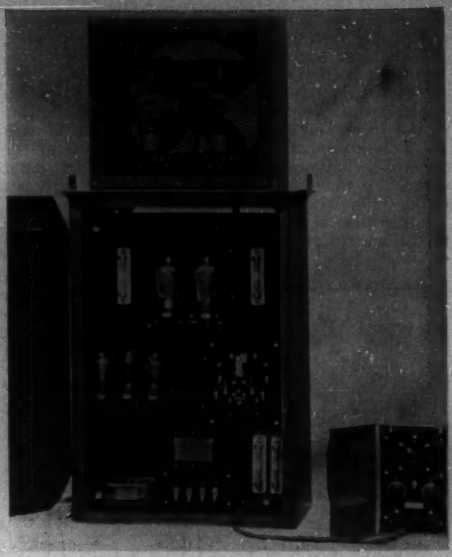


Fig. 3. Assembly of the ignitron welding timer with covers open

which would otherwise exist on the grids of T_4 and T_5 due to their circuit locations. When the current from the line through the control tube and ignition electrode has reached sufficient magnitude, the main ignition anode picks up the load and shorts out the control tube thus cutting off further flow of igniting current which is no longer necessary.

The foregoing sequence shows how welding current is initiated. Tube T_3 may be termed the "stop" tube. It normally has a negative holding source S_3 applied to its grid. After breakdown of the start tube T_2, timing capacitor C_2 is charged through a variable resistor R_4. After a definite time, controllable by C_2 and R_4, capacitor C_2 will become sufficiently charged to offset negative bias S_3 on the grid of "stop" tube T_3 and it breaks down. At breakdown of T_3 resistor R_2 is in effect shorted out and the bias voltage on the control tubes again becomes negative, thereby preventing further flow of welding current. It is only necessary that cut-off occur during the last desired half cycle of welding current, as once ignited the ignitron tube will pass current to the end of the half cycle. Between welds it is, of course, necessary to discharge capacitor C_2 and to open the control switch thereby extinguishing tubes T_2 and T_3.

Description and Rating

The ignitron welding timer consists of a panel assembly mounted in a rugged steel cabinet, and is

shown in Fig. 3. The ignitron power tubes are mounted in a metal-screened fan-ventilated housing, bolted to the top of the main control cabinet. On the upper portion of the panel and centrally located are the 2 grid glow tubes which control the ignition electrodes of the power tubes. In the mid-section of the panel and on the left-hand side are located the 3 timing tubes. On the right-hand side of the panel is an initiating relay. In the lower left-hand corner is a time delay relay to protect the cathodes of the timing and control tubes during their heating. Heating time is 45 sec. Terminal connections are at the bottom center of the panel and protective

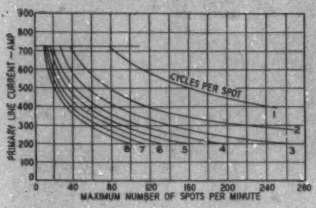


Fig. 4. Curves of current capacity of the 220–440-volt 60-cycle fan-cooled welding timer using ignitron tubes, type KU-637

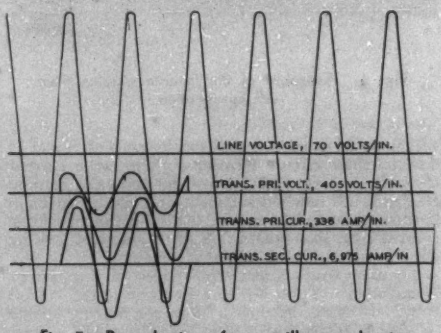


Fig. 5. Reproduction of an oscillogram showing performance of the timer when welding stainless steel

fuses for the auxilary control circuit are located in the lower right-hand corner.

In the small box shown at the right of the main control cabinet are the timing resistors and capacitors. This unit is carefully calibrated and gives accurate control of 1 to 14 cycles. Combinations of tap switch and left-hand dial give the desired number of cycles. The right-hand dial controls the point on the voltage wave where the weld is initiated. This control box is usually mounted in a convenient position near the operator. The curves in Fig. 4 illustrate the rating or power that can be handled. Primary line current in root mean square amperes during weld is plotted against maximum number of spots per minute for several values of cycles per spot. The curve shows that 710 amp at 440 volts, or 312.4 kva, may be handled at a speed of 80 spots per minute with one cycle per spot. The same kilovoltampere load with 5 cycles per spot has a maximum duty cycle of 30 spots per minute. In Fig. 5 is a reproduction of an oscillogram showing performance of the timer when welding stainless steel in 2 cycles of current. Note that the trace of transformer primary voltage indicates the weld was initiated at about 45 deg on the line voltage wave.

Heavy Duty Seam Welding

The foregoing controller is suitable for light duty intermittent spotting. For heavy-duty gas-tight seam welding another form of controller is essential. In this type of welding, spots are made in rapid succession on a roller type welder with automatic timing such that a 50 per cent overlap of adjacent spots is obtained.

The ignitron seam welding timer consists of 3 major unit assemblies: (1) A synchronously driven "photo-timer"; (2) a control tube panel assembly; and (3) an ignitron power tube assembly. These 3 unit assemblies are mounted in a suitable steel cabinet as illustrated in Fig. 6. The synchronously driven photo-timer unit is mounted on the central compartment shelf. Directly above this shelf is the control tube panel assembly. The lower section of the cabinet contains the ignitron power tube assembly. The action of this timer may be likened to the ignition system on the average automobile.

Fig. 6. The ignitron seam welding timer with covers open

The photo-timer corresponds to the distributor, the control panel to the ignition coil, and the ignitron tube assembly to the cylinders, the latter having ignition electrodes which correspond to spark plugs in the cylinders of the automobile.

Similar to the spot welder control just described this timer performs the function of a rapid action single-pole single-throw switch connected directly in series with the power source and the primary of the welding machine transformer. Power current is carried and interrupted by 2 ignitron power tubes. These tubes are connected in parallel and inversely to one another, the combination serving to pass alternating current. The ignitron tubes are controlled by control tubes located on the control panel, and these control tubes are actuated by the output of the photo-timer.

Photo-Timer

The purpose of the motor driven photo-timer is to control both the number of cycles of current per weld and the number of cycles interval between welds. This is accomplished by periodic interruption of a narrow light beam by teeth in a revolving disk. Adjustments permit variation of weld duration and weld spacing. The photo-timer therefore consists essentially of a synchronous motor driving a revolving disk, a light source, the necessary lenses, apertures, photo-electric tubes, amplifier tubes, and auxiliaries, and is shown in Fig. 7.

The timing disk of the photo-electric timer contains 120 slots around the periphery at intervals corresponding to each half cycle. The slots for which welding current is desired are left unmasked by a specially cut fish-paper disk clamped over the slotted timing disk. It will be seen that various combinations of weld duration and weld spacing may be obtained readily. An adjustment allows positioning of the light beam with respect to rotational position of the slotted disk. Since the unmasked slots correspond to welding current, it is apparent that the starting point of each current loop may be varied to any desired point on the voltage wave by the adjustment screws which shift the light beam with respect to the timing disk. In other words, current zero of the loop is removed from voltage zero by an electrical angle equal to the load power factor angle. For convenience in setting this adjustment a zero center d-c meter is connected to a shunt in the a-c load circuit. This meter indicates the presence of unequal current loops by registration of any d-c component in welding current.

Circuit Operation

A schematic wiring diagram is shown in Fig. 8. When an open slot in the revolving timing disk allows light to strike the cathode of the photo-electric tube, current flows through the tube and resistor R_1. The first stage amplifier thus receives a more positive bias and passes increased plate current through resistor R_2. Through coupling condenser C, the second stage tube has its grid forced negative, thus decreasing the plate current of the second stage tube. The output transformer primary winding is in this circuit and hence the secondary winding receives voltage corresponding in duration to the slot width in the timing disk. A weld initiating

Fig. 7. The photo-timer of the ignitron seam welding timer

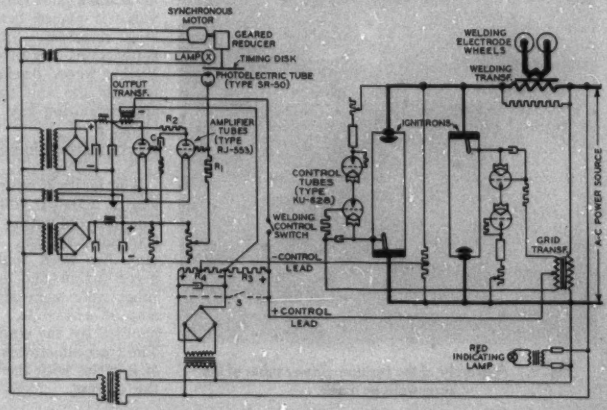


Fig. 8. Schematic wiring diagram of the seam welding timer

potential thus appears across resistor R_3 of the polarity shown.

The output of the photo-timer produces a positive potential across the control leads by overcoming the constant negative potential normally across resistor R_4. The resultant positive d-c bias is applied to the control tube grids through the grid transformer secondary. Both control tubes are now energized in so far as the grids are concerned and ignition current instantly flows through the 2 control tubes of the ignitron, which at the moment has positive anode potential. Inverse anode potential on the remaining tube prevents, as yet, its operation, which must wait upon the next succeeding current zero. Once either ignitron is fired, its low arc drop voltage prevents further ignition current to flow through the 2 series connected control tubes.

Control Tube Panel Assembly

The control tube panel assembly is shown in the upper portion of Fig. 6. Mounted at the top of the panel are 2 pairs of control tubes of the grid glow type. Their function is to control the welding current through control of the ignition or starting current of the ignitron power tubes. The grids of these control tubes are actuated by the output of the photo-timer. Each pair of tubes is connected in series and forms a circuit between the anode and ignition electrode of each ignitron power tube. In the upper center are 3 auxiliary relays used to protect against thermal overload, water failure, etc., and interlocked with the manually operated switches directly below so that complete protection and safety are provided even in the hands of an unskilled operator.

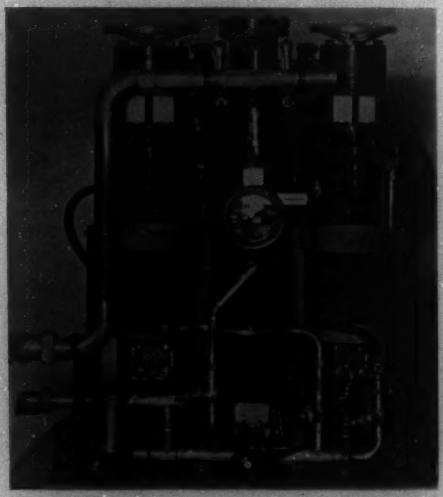


Fig. 9. Assembly of the ignitron power tubes of the seam welding timer

Ignitron Power Tube Assembly

This assembly consists essentially of 2 ignitron power tubes, a water cooling system, and a vacuum pumping system. In Fig. 9 is a detailed view of this assembly. The ignitrons are of the all-metal steel-tank type with graphite anodes. A system of water jackets on the tube and small anode cooling radiator fins at the top of the tube remove the heat generated by the arc. Their circuit relations are such that the cathodes are 440 volts apart and it is necessary to provide insulation in feeding from a common water system. Directly in front of the tubes are located insulating hose reels conveying water to the tube jackets. Near the top of the assembly are 2 hand-wheels controlling valves which close off the tubes from the pumping system when the unit is shut down for an extended period. These valves connect to a manifolding which is exhausted by a conventional jet type 3-stage mercury pump. This mercury pump discharges into an interstage reservoir whose pressure is maintained at or below 6 mm by a rotary oil pump. It is necessary that the oil pump run only occasionally as the volume of gas pumped is very small. Automatic starting and stopping of the oil pump is controlled by a glass mercury manometer switch making contact at definite pressures. To prevent air leaking back through the oil pump, an automatic valve is placed between the oil pump and interstage reservoir. Suitable bus bar and power cable connections are provided at the rear of the unit. Visible water discharge nozzles are shown at the front of the unit together with master hand valve and regulating key valves.

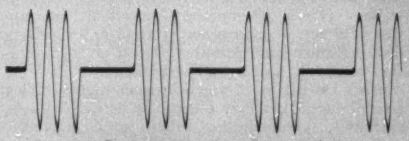


Fig. 10. Reproduction of oscillogram of current supplied by the seam welding timer

Rating and Performance

The ignitron seam welder timer is rated 350–700 kva at 220–440 volts on a 25 per cent duty cycle. The thermal rating of each ignitron power tube is 200 amp average. A peak current rating of 2,250 amp has been tentatively used pending further investigation and study. On recent tests these tubes were successful in handling a crest of 4,800 amp at 440 volts. An oscillogram of the current handled by the controller is reproduced in Fig. 10. The trace illustrates 3 cycles of current and a space of 3 cycles with the timer set at the natural zero of the current.

Wide Band Transmission Over Coaxial Lines

By
LLOYD ESPENSCHIED
FELLOW A.I.E.E.

M. E. STRIEBY
MEMBER A.I.E.E.

Both of Bell Tel. Labs., Inc., New York, N. Y.

In this paper systems are described whereby frequency band widths of the order of 1,000 kc or more may be transmitted for long distances over coaxial lines and utilized for purposes of multiplex telephony or television. A coaxial line is a metal tube surrounding a central conductor and separated from it by insulating supports.

It appears from recent development work that under some conditions it will be economically advantageous to make use of considerably wider frequency ranges for telephone and telegraph transmission than are now in use[1,2] or than are covered in the recent paper on carrier in cable.[3] Furthermore, the possibilities of television have come into active consideration and it is realized that a band of the order of 1,000 kc or more in width would be essential for television of reasonably high definition if that art were to come into practical use.[4,5]

This paper describes certain apparatus and structures which have been developed to employ such wide frequency ranges. The future commercial application of these systems will depend upon a great many factors, including the demand for additional large groups of communication facilities or of facilities for television. Their practical introduction is, therefore, not immediately contemplated and, in any event, will necessarily be a very gradual process.

Types of High Frequency Circuits

The existing types of wire circuits can be worked to frequencies of tens of thousands of cycles, as is evidenced by the widespread application of carrier systems to the open wire telephone plant and by the development of carrier systems for telephone cable circuits.[2,3] Further development may lead to the operation of still higher frequencies over the existing types of plant. However, for protection against external interference these circuits rely upon balance, and as the frequency band is widened, it becomes more and more difficult to maintain a sufficiently high degree of balance. The balance requirements may be made less severe by using an individual shield around each circuit, and with sufficient shielding balance may be entirely dispensed with.

A form of circuit which differs from existing types in that it is unbalanced (one of the conductors being grounded), is the coaxial or concentric circuit. This consists essentially of an outer conducting tube which envelops a centrally disposed conductor. The high-frequency transmission circuit is formed between the inner surface of the outer conductor and the outer surface of the inner conductor. Unduly large losses at the higher frequencies are prevented by the nature of the construction, the inner conductor being so supported within the tube that the intervening dielectric is largely gaseous, the separation between the conductors being substantial, and the outer conductor presenting a relatively large surface. By virtue of skin effect, the outer tube serves both as a conductor and a shield, the desired currents concentrating on its inner surface and the undesired interfering currents on the outer surface. Thus, the same skin effect which increases the losses within the conductors provides the shielding which protects the transmission path from outside influences, this protection being more effective the higher the frequency.

The system which this paper outlines has been based primarily upon the use of the coaxial line. The repeater and terminal apparatus described, however, are generally applicable to any type of line, either balanced or unbalanced, which is capable of transmitting the frequency range desired.

The Coaxial System

A general picture of the type of wide band transmission system which is to be discussed is briefly as follows: A coaxial line about 0.5 in. in outside diameter may be used to transmit a frequency band of about 1,000 kc, with repeaters capable of handling the entire band placed at intervals of about 10 miles. Terminal apparatus may be provided which will enable this band either to be subdivided into more than 200 telephone circuits or to be used *en bloc* for television.

Such a wide band system is illustrated in Fig. 1. It is shown to comprise several portions, namely, the line sections, the repeaters, and the terminal apparatus, the latter being indicated in this case as for multiplex telephony. Two-way operation is secured by using 2 lines, one for either direction. It would be possible, however, to divide the frequency band and use different parts for transmission in opposite directions.

A form of flexible line which has been found con-

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Aug. 21, 1934; released for publication Sept. 4, 1934. *Not published in pamphlet form.*

1. For all numbered references, see list at end of paper.

venient in the experimental work is illustrated in Fig. 2 and will be described more fully subsequently. Such a coaxial line can be constructed to have the same degree of mechanical flexibility as the familiar telephone cable. While this line has a relatively high loss at high frequencies, the transmission path is particularly well adapted to the frequent application of repeaters, since the shielding permits the transmission currents to fall to low power levels at the high frequencies.

Of no little importance also is the fact that the attenuation-frequency characteristic is smooth throughout the entire band and obeys a simple law of change with temperature. (This is due to the fact that the dielectric is largely gaseous and that insulation material of good dielectric properties is employed.) This smooth relation is extremely helpful in the provision of means in the repeaters for automatically compensating for the variations which occur in the line attenuation with changes of temperature. This type of system is featured by large transmission losses which are offset by large amplification, and it is necessary that the 2 effects match each other accurately at all times throughout the frequency range.

It will be evident that the repeater is of outstanding importance in this type of system, for it must not only transmit the wide band of frequencies with a transmission characteristic inverse to that of the line, with automatic regulation to care for temperature changes, but must also have sufficient freedom from inter-modulation effects to permit the use of large numbers of repeaters in tandem without objectionable interference. Fortunately, recent advances in repeater technique have made this result possible, as will be appreciated from the subsequent description.

An interesting characteristic of this type of system is the way in which the width of the transmitted band is controlled by the repeater spacing and line size, as follows:

1. For a given size of conductor and given length of line, the band width increases nearly as the square of the number of the repeater points. Thus, for a coaxial circuit with about 0.3-in. inner diameter of outer conductor, a 20-mile repeater spacing will enable a band up to about 250 kc to be transmitted, a 10-mile spacing will increase the band to about 1,000 kc, and a 5-mile spacing to about 4,000 kc.

2. For a given repeater spacing, the band width increases approximately as the square of the conductor diameter. Thus, whereas a tube of 0.3-in. inner diameter will transmit a band of about 1,000 kc, 0.6-in. diameter will transmit about 4,000 kc, while a diameter corresponding to a full sized telephone cable might transmit something of the order of 50,000 kc, depending upon the dielectric employed and upon the ability to provide suitable repeaters.

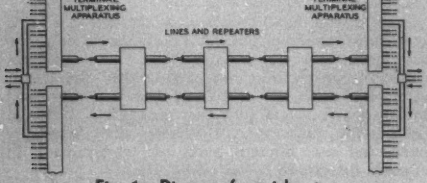


Fig. 1. Diagram of coaxial system

Earlier Work

It may be of interest to note that as a structure, the coaxial form of line is old—in fact, classical. During the latter half of the last century it was the object of theoretical study, in respect to skin effect and other problems, by some of the most prominent mathematical physicists of the time. Reference to some of this work is made in a paper by Schelkunoff, dealing with the theory of the coaxial circuit.[6]

On the practical side, it is found on looking back over the art that the coaxial form of line structure has been used in 2 rather widely different applications: First, as a long line for the transmission of low frequencies, examples of which are usage for submarine cables[7,8] and for power distribution purposes, and second as a short-distance high-frequency line serving as an antenna lead-in.[9,10]

The coaxial conductor system herein described may be regarded as an extension of these earlier applications to the long distance transmission of a very wide range of frequencies suitable for multiplex telephony or television.[11] Although dealing with radio frequencies, this system represents an extreme departure from radio systems in that a relatively broad band of waves is transmitted, this band being confined to a small physical channel which is shielded from outside disturbances. The system, in effect, comprehends a frequency spectrum of its own and

Fig. 2. Small flexible coaxial structure

shuts it off from its surroundings so that it may be used again and again in different systems without interference.

This new type of facility has not yet been commercially applied, and is, in fact, still in the development stage. Sufficient progress has already been made, however, to give reasonable assurance of a satisfactory solution of the technical problems involved. This progress is outlined below under 3 general headings: (1) the coaxial line and its transmission properties, (2) the wide band repeaters, and (3) the terminal apparatus.

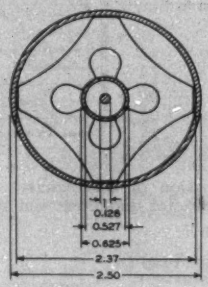
The Coaxial Line

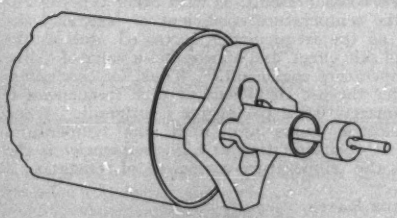
An Experimental Verification

One of the first steps taken in the present development was in the nature of an experimental check of the coaxial conductor line, designed primarily to determine whether the desirable transmission properties which had been disclosed by a theoretical study could be fully realized under practical conditions. For this purpose a length of coaxial structure capable of accurate computation was installed near Phoenix-

ville, Pa. The diagram of Fig. 3 shows a sketch of the structure used and gives its dimensions. It comprised a copper tube of 2.5-in. outside diameter, within which was mounted a smaller tube which, in turn, contained a small copper wire. Two coaxial circuits of different sizes were thus made available, one between the outer and the inner tubes, and the other between the inner tube and the central wire. The installation comprised 2 2,600-ft lengths of this structure.

The diameters of these coaxial conductors were so chosen as to obtain for each of the 2 transmission paths a diameter ratio which approximates the optimum value, as discussed later. The conductors were separated by small insulators of isolantite. The rigid construction and the substantial clearances between conductors made it possible to space the insulators at fairly wide intervals, so that the dielectric between conductors was almost entirely air.





SPACING OF INSULATORS
LARGE SIZE: 4 FT ON STRAIGHTAWAY
2 FT ON CURVES
SMALL SIZE: 1 FT ON STRAIGHTAWAY
6 IN. ON CURVES

Fig. 3. Structure used in Phoenixville installation

The outer conductor was made gastight, and the structure was dried out by circulating dry nitrogen gas through it. The 2 triple conductor lines were suspended on wooden fixtures and the ends brought into a test house, as shown in Fig. 4.

The attenuation was measured by different methods over the frequency range from about 100 kc to 10,000 kc. Investigation showed that the departures from ideal construction occasioned by the joints, the lack of perfect concentricity, etc., had remarkably little effect upon the attenuation. In order to study the effect of eccentricity upon the

Fig. 4. Phoenixville installation showing conductors entering test house

attenuation, tests were made in which this effect was much exaggerated, and the results substantiated theoretical predictions. The impedance of the circuits was measured over the same range as the attenuation. A few measurements on a short length were made at frequencies as high as 20,000 kc.

Measurements were secured of the shielding effect of the outer conductor of the coaxial circuit up to frequencies in the order of 100 to 150 kc, the results agreeing closely with the theoretical values. Above these frequencies, even with interfering sources much more powerful than would be encountered in practice, the induced currents dropped below the level of the noise due to thermal agitation of electricity in the conductors (resistance noise) and could not be measured.

The preliminary tests at Phoenixville, therefore, demonstrated that a practical coaxial circuit, with its inevitable mechanical departures from the ideal, showed transmission properties substantially in agreement with the theoretical predictions.

Small Flexible Structures

Development work on wide band amplifiers, as discussed later, indicated the practicability of employing repeaters at fairly close intervals. This pointed toward the desirability of using sizes of coaxial circuit somewhat smaller than the smaller of those used in the preliminary experiments, and having correspondingly greater attenuation. Furthermore, it was desired to secure flexible structures which could be handled on reels after the fashion of ordinary cable. Accordingly, several types of flexible construction, ranging in outer diameter from about 0.3 in. to 0.6 in., have been experimented with. Structures were desired which would be mechanically and electrically satisfactory, and which could be manufactured economically, preferably with a continuous process of fabrication.

One type of small flexible structure which has been developed is shown in Fig. 2. The outer conductor is formed of overlapping copper strips held in place with a binding of iron or brass tape. The insulation consists of a cotton string wound spirally around the inner conductor, which is a solid copper wire. This structure has been made in several sizes of the order of 0.5-in. diameter or less. When it is to be used as an individual cable, the outer conductor is surrounded by a lead sheath, as shown, to prevent the

Fig. 5. Photograph of coaxial structure with lead outer conductor and rubber disk insulators

entrance of moisture. One or more of the copper tape structures without individual lead sheath may be placed with balanced pairs inside a common cable sheath.

Another flexible structure is shown in Fig. 5. The outer conductor in this case is a lead sheath which directly surrounds the inner conductor with its insulation. Since lead is a poorer conductor than copper, it is necessary to use a somewhat larger diameter with this construction in order to obtain the same transmission efficiency. Lead is also inferior to copper in its shielding properties and to obtain the same degree of shielding the lead tube of Fig. 5 must be made correspondingly thicker than is necessary for a copper tube.

The insulation used in the structure shown in Fig. 5 consists of hard rubber disks spaced at intervals along the inner wire. Cotton string or rubber disk insulation may be used with either form of outer tube. The hard rubber gives somewhat lower attenuation, particularly at the higher frequencies.

Another simple form of structure employs commercial copper tubing into which the inner wire with its insulation is pulled. Although this form does not lend itself readily to a continuous manufacturing process, it may be advantageous in some cases.

Transmission Characteristics—Attenuation

At high frequencies the attenuation of the coaxial circuit is given closely by the well-known formula:

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}} \qquad (1)$$

where R, L, C and G are the 4 so-called "primary constants" of the line, namely, the resistance, inductance, capacitance, and conductance per unit of length. The first term of eq 1 represents the losses in the conductors, while the second term represents those in the dielectric.

When the dielectric losses are small, the attenuation of a coaxial circuit increases, due to skin effect in the conductors, about in accordance with the square root of the frequency. With a fixed diameter ratio, the attenuation varies inversely with the diameter of the circuit. By combining these relations there are obtained the laws of variation of band width in accordance with the repeater spacing and the size of circuit, as stated previously.

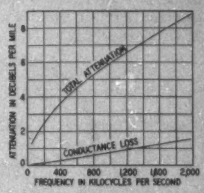
The attenuation-frequency characteristic of the flexible structure illustrated in Fig. 2, with about 0.3-in. diameter, is given in Fig. 6. The figure shows also that the conductance loss due to the insulation is a small part of the total.

It is interesting to compare the curves of the transmission characteristics of the coaxial circuit with those of other types of circuits. The diagram of Fig. 7 shows the high-frequency attenuation of 2 sizes of coaxial circuit using copper tube outer conductors, of 0.3-in. and 2.5-in. inner diameter, and that of cable and open wire pairs in the same frequency range.

Effect of Eccentricity

The small effect of lack of perfect coaxiality upon the attenuation of a coaxial circuit is illustrated by the curve of Fig. 8, which shows attenuation ratios

Fig 6. Attenuation of small flexible coaxial structure shown in Fig. 2



plotted as a function of eccentricity, assuming a fixed ratio of conductor diameters and substantially air insulation.

Temperature Coefficient

With a coaxial circuit, as with other types of circuits, the temperature coefficient of resistance decreases as the frequency is increased, due to the action of skin effect, and approaches a value of $^1/_2$ the d-c temperature coefficient.[12] Thus, for conductors of copper the a-c coefficient at high frequencies is approximately 0.002 per degree Centigrade. When the dielectric losses are small, the temperature coefficient of attenuation at high frequencies is the same as the temperature coefficient of resistance.

Diameter Ratio

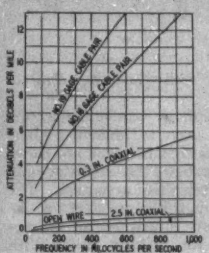
An interesting condition exists with regard to the relative sizes of the 2 conductors. For a given size of outer conductor there is a unique ratio of inner diameter of outer conductor to outer diameter of inner conductor which gives a minimum attenuation. At high frequencies, this optimum ratio of diameters (or radii) is practically independent of frequency. When the conductivity is the same for both conductors, and either the dielectric losses are small or the insulation is distributed so that the dielectric flux follows radial lines, the value of the optimum diameter ratio is approximately 3.6. When the outer and inner conductors do not have the same conductivity, the optimum diameter ratio differs from this value. For a lead outer conductor and copper inner conductor, for example, the ratio should be about 5.3.

Stranding

Inasmuch as the resistance of the inner conductor contributes a large part of the high frequency attenuation of a coaxial circuit, it is natural to consider the possibility of reducing this resistance by employing a conductor composed of insulated strands suitably twisted or interwoven.[18] Experiments along this line showed that this method is impractical at frequencies above about 500 kc, owing to the fineness of stranding required.

Characteristic Impedance

The high-frequency characteristic impedance of a coaxial circuit varies inversely with the square root of the effective dielectric constant, i. e., the ratio of the actual capacitance to the capacitance that would be obtained with air insulation. The impedance of a circuit having a given dielectric constant depends merely upon the ratio of conductor diameters and



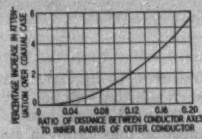


Fig. 8 (above). Increase in attenuation of coaxial circuit due to eccentricity

Fig. 7 (left). Attenuation frequency characteristics of coaxial and other circuits

not upon the absolute dimensions. For a diameter ratio of 3.6, the impedance of a coaxial circuit with gaseous dielectric is about 75 ohms.

Velocity of Propagation

For a coaxial circuit with substantially gaseous insulation, the velocity of propagation at high frequencies approaches the speed of light. Hence the circuit is capable of providing high velocity telephone channels with their well-recognized advantages. The fact that the velocity at high frequencies is substantially constant minimizes the correction required to bring the delay distortion within the limits required for a high quality television band.

Shielding and Crosstalk

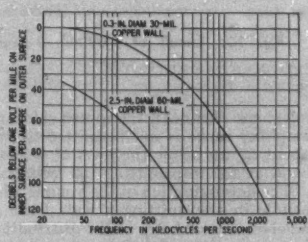
The shielding effect of the outer conductor of a coaxial circuit is illustrated in Fig. 9, where the transfer impedance between the outer and inner surfaces of the outer conductor is plotted as a function of frequency. There will be observed the sharp decrease in inductive susceptibility as the frequency rises. On this account, the crosstalk between adjacent coaxial circuits falls off very rapidly with increasing frequency. The trend is, therefore, markedly different from that for ordinary nonshielded circuits which rely upon balance to limit the inductive coupling. As a practical matter, less shielding is ordinarily required to avoid crosstalk than to avoid external interference.

With suitable design the shielding effect of the outer conductor renders the coaxial circuit substantially immune to external interference at frequencies above the lower end of the spectrum. Hence the signals transmitted over the circuit may be permitted to drop down to a level determined largely by the noise due to thermal agitation of electricity in the conductors and tube noise in the associated amplifiers. It appears uneconomical to make the outer conductor sufficiently thick to provide adequate shielding for the very low frequencies. Also it seems impractical to design the repeaters to transmit very low frequencies. Hence the best system design appears to be one in which the lowest 5 or 10 per cent of the frequency range is not used for signal transmission. The coaxial circuit is, however, well suited to the transmission of 60-cycle current for operating the repeaters, a matter which will be referred to later.

Broad-Band Amplifiers

In order to realize the full advantage of broad band transmission, the repeater for this type of system should be capable of amplifying the entire frequency band *en bloc*. Furthermore, it should be so stable and free from distortion that a large number of repeaters may be operated in tandem. Although high-gain radio frequency amplifiers are in every-day use, these are generally arranged to amplify at any one time only a relatively narrow band of frequencies, a variable tuning device being provided so that the amplification may be obtained at any point in a fairly wide frequency range. The high gain is usually obtained by presenting a high impedance to the input circuits of the various tubes through tuning

Fig. 9. Shielding in a coaxial circuit



the input and interstage coupling circuits to approximate anti-resonance.

In amplifying a broad band of frequencies, it is difficult to maintain a very high impedance facing the grid circuits. The inherent capacitances between the tube elements and in the mounting result in a rather low impedance shunt which cannot be resonated over the desired frequency band. It is, therefore, necessary to use relatively low impedance

coupling circuits and to obtain as high gain as possible from the tubes themselves. The amount of gain which can be obtained without regeneration depends, of course, upon the type of tube, the number of amplification stages, the band width, and also upon the ratio of highest to lowest frequency transmitted.

Repeater Gain

The total net gain desired in a line amplifier is such as to raise the level of an incoming signal from its minimum permissible value, which is limited by interference, up to the maximum value which the amplifier can handle.

As pointed out above, the noise in a well shielded system is that due to resistance noise in the line conductors and tube noise in the amplifiers. In some of the repeaters which have been built, the amplifier noise has been kept down to about 2 db above resistance noise, corresponding to about 7×10^{-17} watt per voice channel. In a long line with many repeaters the noise voltages add at random, or in other words, the noise powers add directly. Assuming, for example, a line with 200 repeaters, the noise power at the far end would be 200 times that for a single repeater section. In general, the line and amplifier noise will not be objectionable in a long

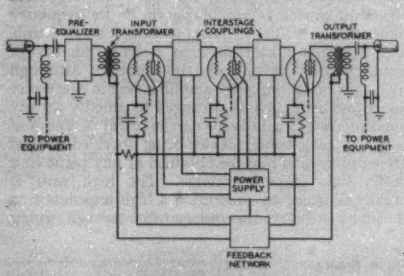


Fig. 10. Circuit of 1,000-kc 3-stage feedback repeater

telephone channel if the speech sideband level at any amplifier input is not permitted to drop more than about 55 db below the level of the voice frequency band at the transmitting toll switchboard.

The determination of the volume which a tube can handle in transmitting a wide band of frequencies involves a knowledge of the distribution in time and frequency of the signaling energy and of the requirements as to distortion of the various components of the signal. The distribution of the energy in telephone signals has been the subject of much study. This distribution is known to vary over very wide limits, depending upon the voice of the talker and many other factors. It is, therefore, obvious that the problem of summing up the energy of some hundreds of simultaneous telephone conversations is a difficult one. Enough work has been done,

Fig. 11. Gain of 1,000-kc repeater

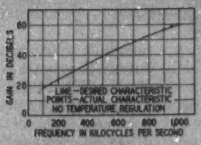


Fig. 12 (below). Photograph of 1,000-kc repeater

however, to indicate fairly well what the result of such addition will be.

As to distortion in telephone transmission, the most serious problem has been to limit the intermodulation between various signals which are transmitted simultaneously through the repeater and appear as noise in the telephone channel. The requirement for such noise is similar to that for line and tube noise, and similarly it will add up in successive repeater sections for a long line. With present types of tubes operating with a moderate plate potential, the modulation requirement can be met only at relatively low output levels. To improve this situation and also to obtain advantages in amplifier stability, the reversed feedback principle employed for cable carrier amplifiers, as described in a paper by H. S. Black,[14] has been extended to higher frequency ranges. It has been found that amplifiers of this type having 30-db feedback reduce the distortion to such an extent that each amplifier of a long system carrying several hundred telephone channels will handle satisfactorily a channel output signal level about 5 db above that at the input of the toll line.

The maximum gain which can be used in the repeater, therefore, is, in the illustrative case given above of a long system carrying several hundred telephone channels, the difference between the minimum and maximum levels of 55 db below and 5 db above the point of reference, respectively, or a total gain of 60 db. (With a 0.3-in. coaxial line of the type shown in Fig. 2, this corresponds to a repeater spacing of about 10 miles.) If a repeater is to have 60-db net gain and at the same time about 30-db feedback, it is obvious that the total forward gain through the amplifying stages must be about 90 db. The circuit of an experimental amplifier meeting the gain requirements for a frequency band from 50 to 1,000 kc is shown schematically in Fig. 10.

Gain-Frequency Characteristic

As pointed out above, the line attenuation is not uniform with frequency. For a repeater section which has a loss of, say, 60 db at 1,000 kc, the loss at 50 kc would be only about 15 db. Such a sloping characteristic can be taken care of either by designing the repeater to have an equivalent slope in its gain-

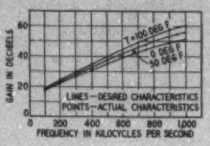


Fig. 13. Temperature regulation—line and repeater characteristics

frequency characteristic or by designing it for constant gain and supplementing it with an equalizer which gives the desired over-all characteristic. Both methods have been tried out, as well as intermediate ones. In Fig. 11 is illustrated such a sloping characteristic obtained by adjusting the coupling impedances in a 3-tube repeater, designed in this case for 60-db gain at 1,000 kc. The accompanying photograph, Fig. 12, gives an idea of the apparatus required in such a repeater, apart from the power supply equipment.

Regulation for Temperature Changes

It is necessary that the repeater provide compensation for variations in the line attenuation due to changes of temperature. In the case of aerial construction such variations might amount to as much as 8 per cent in a day or 16 per cent in a year. If the line is underground the annual variation is only about $^1/_3$ of the above value and the changes occur much more slowly. On a transcontinental line the annual variation might total about 1,500 db. Inasmuch as it is desirable to hold the transmission on a long circuit constant within about ±2 db, it is obvious that the regulation problem is an important one.

In a single repeater section of aerial line the variation might amount to ±2.5 db per day or ±5 db per year. Such variations, if allowed to accumulate over several repeater sections, will drop the signal down into the noise or raise it so as to overload the tubes. It is, therefore, advisable to provide some regulation at every repeater in an aerial line so as to maintain the transmission levels at approximately their correct position. For underground installations the regulating mechanism may be omitted on 2 out of every 3 repeaters.

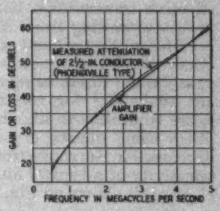
In choosing a type of regulator system the necessity for avoiding cumulative errors in the large number of repeater sections has been borne in mind. In view of the wide band available, a pilot channel regulator system was naturally suggested. Such a scheme employing 2 pilot frequencies has been used experimentally to adjust the gain characteristic in such a way as to maintain the desired levels throughout the band. The accuracy with which this has been accomplished for a single repeater section is illustrated in Fig. 13. Over the entire band of frequencies and the extreme ranges in temperature which may be encountered, the desired regulation is obtained within a few tenths of a decibel.

Repeater Operation, Power Supply, Housing, Etc.

In view of the large number of repeaters required in a broad-band transmission system it is essential that the repeater stations be simple and involve a minimum of maintenance. With the repeater design as described it is expected that most of the repeaters may be operated on an unattended basis, requiring maintenance visits at infrequent intervals.

An important factor in this connecton is the possibility of supplying current to unattended repeaters over the transmission line itself. The coaxial line is well adapted to transmit 60-cycle current to repeaters without extreme losses and without hazard. The repeaters with regulating arrangements as built experimentally for a 1,000-kc system are designed to use 60-cycle current, which in this case appears to have the usual advantages over d-c

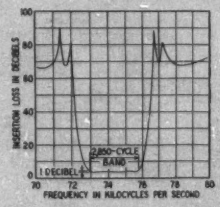
Fig. 14. Frequency characteristic of coaxial line and 5,000-kc repeater



supply. One repeater requires a supply of about 150 watts. The number of repeaters which can be supplied with current transmitted over the line from any one point depends upon the voltage limitation which may be imposed on the circuit from considerations of safety.

For a repeater of the type described with current supplied over the line, only a very modest housing

Fig. 15. Frequency characteristic of quartz crystal channel band filter



arrangement will be required. For the great majority of stations, it appears possible to accommodate the repeaters in weather-proof containers mounted on poles, in small huts, or in manholes.

Higher Frequency Repeaters

Most of what has been said above applies particularly to repeaters transmitting frequencies up to about 1,000 kc. However, study has been given also to repeaters, both of the feedback and the nonfeedback types, for transmitting higher frequencies. Experimental repeaters covering the range from 500 to 5,000 kc have been built and tested. These were capable of handling simultaneously the full complement of over 1,000 channels which such a broad band will permit. The frequency characteristic of one of these repeaters, and the measured attenuation of a section of line of the type tested at Phoenixville, are shown in Fig. 14.

Terminal Arrangements

In order to utilize a broad band effectively for telephone purposes, the speech channels must be placed as close together in frequency as practicable. The factors which limit this spacing are: (1) The width of speech band to be transmitted; and (2), the sharpness of available selecting networks.

As to the width of speech band, the present requirement for commercial telephone circuits is an effective transmission band width of at least 2,500 cycles, extending from 250 to 2,750 cycles. It has been found that a band of this width or more may be obtained with channels spaced at 4,000-cycle intervals. Band filters using ordinary electrical elements are available,[8] for selecting such channels in the range from zero to about 50 kc. Channel selecting filters using quartz crystal elements[15,16] have been developed in the range from about 30 to 500 kc. The selectivity of a typical filter employing quartz crystal elements is shown on Fig. 15.

Initial Step of Modulation

The initial modulation (from the voice range) may be carried out in an ordinary vacuum tube modulator or one of a number of other nonlinear devices. The method chosen for the present experimental work employs a single sideband with suppressed carrier, using a copper oxide modulator associated with a quartz crystal channel filter. The terminal apparatus required for 2-way transmission over a 2-path circuit is shown diagrammatically on the left-hand side of Fig. 16.

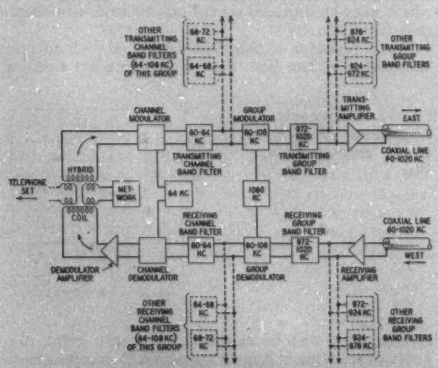


Fig. 16. Schematic diagram of 4-wire circuit employing 2 steps of modulation

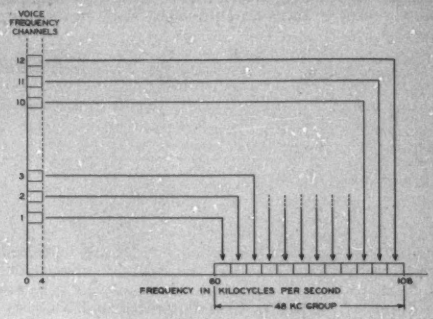


Fig. 17. Diagram illustrating frequency allocation for first step of modulation

A frequency allocation which has been used for experimental purposes employs carriers from 64 to 108 kc for the initial step of modulation. The lower sidebands are selected and placed side by side in the range from 60 to 108 kc, as illustrated in Fig. 17, forming a group of 12 channels.

Double Modulation

In order to extend the frequency range of a system to accommodate a very large number of channels, it appears to be more economical to add a second step of modulation rather than carry the individual channel modulation up to higher frequencies. Such a second step of modulation has been used experimentally to translate the initial group of 12 channels *en bloc* from the range 60 to 108 kc up to higher frequencies. It is possible to place such groups of channels one above another as illustrated in the upper part of the diagram of Fig. 18, up to about 1,000 kc, wasting no frequency space between groups and thus keeping the channels spaced at intervals of 4 kc throughout the entire range.

The apparatus required for this purpose is shown schematically in Fig. 16, which illustrates the complete terminal arrangements for a single channel employing double modulation. The figure indicates by dotted lines where the other channels and groups of channels are connected to the system.

A modulator for shifting the frequency position of a group of channels inherently yields many different modulation products as a result of the intermodulation of the signal frequencies with the carrier frequency and with one another. Out of these products

only the "group sideband" is desired. The number of the modulation products resulting merely from the lower ordered terms of the modulator response characteristic is extremely large. All such products must be considered from the standpoint of interference either with the group which is wanted in the output or with other groups to be transmitted over the system. Various expedients may be used to avoid interference as follows: (1) A proper choice of frequency allocation will place the undesired modulation products in the least objectionable location with respect to the wanted signal bands; (2) a high ratio of carrier to signal will minimize all products involving only the signal frequencies; (3) the use of a balanced modulator will materially reduce all products involving the second order of the signal; and (4) selectivity in the group filters will tend to eliminate all products removed some distance from the wanted signal group. Giving due regard to these factors, balanced vacuum tube group modulators have been developed which are satisfactory for the frequency allocations employed.

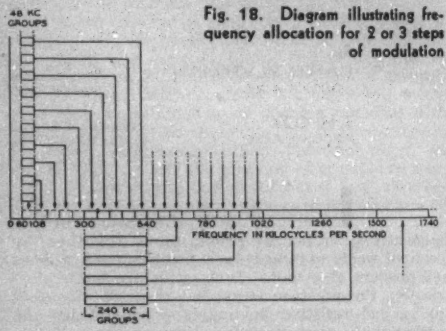


Fig. 18. Diagram illustrating frequency allocation for 2 or 3 steps of modulation

Triple Modulation

For systems involving frequencies higher than about 1,000 kc it may be desirable to introduce a third step of modulation. In some experiments along this line a "super-group" of 60 channels, or 5 12-channel groups, has been chosen. The lower part of Fig. 18 illustrates, for a triple modulation system, the shifting of super-groups of 60 channels each to the line frequency position. This method has been employed experimentally up to about 5,000 kc. It is of interest to note that even in extending these systems to such high frequencies, channels are placed side by side at intervals of 4,000 cycles to form a practically continuous useful band for transmission over the line.

Demodulation

On the receiving side the modulation process is reversed. The apparatus units are similar to those used on the transmitting side, and are similarly arranged. This is illustrated in Fig. 16 for the case of double modulation.

Carrier Frequency Supply

In systems operating at higher frequencies it is necessary that the carrier frequencies be maintained within a few cycles of their theoretical position in order to avoid beat tones or distortion of the speech band. Separate oscillators of high stability could, of course, be used for the carrier supply but it appears more economical to provide carriers by means of harmonic generation from a fundamental basic frequency. Such a base frequency may be transmitted from one end of the circuit to the other, or may be supplied separately at each end.

Television

The broad band made available by the line and repeaters may be used for the transmission of signals for high quality television. Such signals may contain frequency components extending over the entire range from zero or a very low frequency up to 1,000,000 or more cycles.[4] The amplifying and transmitting of these frequencies, particularly the lower ones, presents a serious problem. The difficulty can be overcome by translating the entire band upward in frequency to a range which can be satisfactorily transmitted. To effect such a shift, the television band may first be modulated up to a position considerably higher than its highest frequency and then with a second step of modulation be stepped down to the position desired for line transmission.

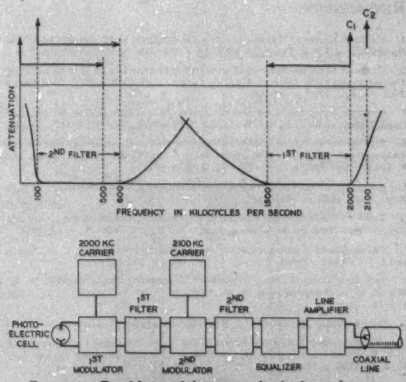


Fig. 19. Double modulation method of translating television signals for wire line transmission

This method is illustrated in Fig. 19 for a 500-kc television signal band. The original television signal is first modulated with a relatively high frequency,

2,000 kc in this case (C_1). The lower sideband, extending to 1,500 kc, is selected and is modulated again with a frequency of 2,100 kc (C_2). The lower sideband of 100 to 600 kc is selected with a special filter so designed that the low frequency end is accurately reproduced. The television signal then occupies the frequency range of 100 to 600 kc as shown on the diagram and may be transmitted over a coaxial or other high frequency line. At the receiving end a reverse process is employed. The same method using correspondingly higher frequencies may be used for wider bands of television signals.

Other Communication Facilities

The telephone channels provided by the system may be used for other types of communication services, such as multi-channel telegraph, teletype, picture transmission, etc. For the transmission of a high quality musical program, which requires a wider band than does commercial telephony, 2 or more adjacent telephone channels may be merged. The adaptability of the broad-band system to different types of transmission thus will be evident.

As already noted, the commercial application of these systems for wide-band transmission over coaxial lines must await a demand for large groups of communication facilities or for television. The results which have been outlined are based upon development work in the laboratory and the field, and it is probable that the systems when used commercially will differ considerably from the arrangements described.

References

1. Carrier Current Telephony and Telegraphy, E. H. Colpitts and O. B. Blackwell. A.I.E.E. Trans., v. 40, 1921, p. 205–300.

2. Carrier Systems on Long Distance Telephone Lines, H. A. Affel, C. S. Demarest, and C. W. Green. A.I.E.E. Trans., v. 47, 1928, 1360–7; *Bell System Tech. Jl.*, v. 7, 1928, p. 564–629.

3. Communication by Carrier in Cable, A. B. Clark and B. W. Kendall. Elec. Engg., v. 52, 1933, p. 477–81; *Bell System Tech. Jl.*, v. 12, 1933, p. 251–63.

4. Theory of Scanning and Its Relation to the Characteristics of the Transmitted Signal in Telephotography and Television, P. Mertz and F. Gray. *Bell System Tech. Jl.*, v. 13, 1934, p. 464.

5. A Study of Television Image Characteristics, E. W. Engstrom. I.R.E. *Proc.*, v. 21, 1933, p. 1631–51.

6. The Electromagnetic Theory of Cylindrical Transmission Lines and Cylindrical Shields, S. A. Schelkunoff. *Bell System Tech. Jl.*, v. 13, 1934.

7. Transmission Characteristics of the Submarine Cable, J. R. Carson and J. J. Gilbert. Frank. Inst. *Jl.*, v. 192, 1921, p. 705–35.

8. The Key West-Havana Submarine Telephone Cable System, W. H. Martin, G. A. Anderegg, and B. W. Kendall. A.I.E.E. Trans., v. 41, 1922, p. 1–19.

9. British Patent No. 284,005, C. S. Franklin, January 17, 1928.

10. Transmission Lines for Short-Wave Radio Systems, E. J. Sterba and C. B. Feldman. I.R.E. *Proc.*, v. 20, 1932, p. 1163–202; also *Bell System Tech. Jl.*, v. 11, 1932, p. 411–50.

11. U.S. Patents No. 1,835,031, L. Espenschied and H. A. Affel, Dec. 9, 1931, and No. 1,941,116, M. E. Strieby, Dec. 26, 1933.

12. Transmission Characteristics of Open-Wire Lines at Carrier Frequencies, E. I. Green. A.I.E.E. Trans., v. 49, 1930, p. 1524–35; *Bell System Tech. Jl.*, v. 9, 1930, p. 730–59.

13. H. A. Affel and E. I. Green, U.S. Patent No. 1,818,027, Aug. 11, 1931.

14. Stabilized Feed-Back Amplifiers, H. S. Black. Elec. Engg., v. 53, 1934, p. 114–20.

15. L. Espenschied, U.S. Patent No. 1,795,204, March 3, 1931.

16. Electrical Wave Filters Employing Quartz Crystals as Elements, W. P. Mason. *Bell System Tech. Jl.*, v. 13, 1934, p. 405.

A High Power Welding Rectifier

A welding rectifier embodying the "ignitron" principle, a recent development in a program of research on mercury arc rectifiers, provides predetermined welding currents for periods of time variable in steps of 1/120 sec, or less if desired. This paper describes the design and operation of the "ignitron" and illustrates its applicability to the problems involved in line welding processes.

By
DANIEL SILVERMAN*
ASSOCIATE A.I.E.E.
Arma Engg. Co.
Brooklyn, N. Y.

J. H. COX
ASSOCIATE A.I.E.E.
Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.

In sheet metal fabrication it is frequently desirable to fasten parts together by localized welds obtained by a combination of heat and pressure at a spot. Such welds are made electrically; the pressure is applied through the electrodes, and resistive heating is produced by the current at the contact surface between the 2 sheets and in the material itself. This process requires momentary currents, sometimes of very large magnitude. The short time is necessary to prevent the spread of the heat to adjacent portions of the material, particularly when working with heat treated metals. Exact control of time and current permits a weld as strong as possible without burning the material.

Contactors are used for spot welding, but their limitations as to speed of operation and the lack of accurate control of time of closure, particularly for the larger sizes, have limited their applicability to seam welding work. Consequently the most satisfactory means of controlling large welding currents utilize gaseous conduction devices.

In the field of low power apparatus there has been used effectively and variously a small grid-controlled arc-discharge device known as the "grid-glow" tube, or by any of several other names. Now, the "ignitron" in this form brings to the field of large power apparatus a similar tool—a positively

Full text of a paper recommended for publication by the A.I.E.E. committee on electric welding, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted June 15, 1934; released for publication Aug. 18, 1934. *Not published in pamphlet form.*

* Formerly of the Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.

controlled low-loss arc-discharge device capable of carrying large currents and handling extreme overloads. Just as the smaller tube has enjoyed widespread application in the recent past, so the "ignitron" may be expected to lend itself successfully to a wide variety of problems.

The "Ignitron"

The "ignitron" has been described in previous publications (Slepian and Ludwig, A.I.E.E. Trans., v. 52, 1933, p. 693; Ludwig, Maxfield, and Toepfer, Elec. Engg., v. 53, Jan. 1934, p. 75–8; Knowles and Bangratz, *Elec. Jl.*, Dec. 1933; Knowles, *electronics*, June 1933). The principle of operation might be illustrated as follows: If a material of a certain order of resistivity, such as a crystal of carborundum, is immersed in a pool of mercury in a vacuum and a voltage is applied to the crystal (positive with respect to the mercury), a cathode spot will form on the mercury and an arc will start. In Fig. 1, *A* is an evacuated glass vessel holding a pool of mercury, *C*, electrically connected to lead, *B*. Immersed in the mercury is one end of a crystal of carborundum, *D*, supported from block *E* through seal *F*. Another electrode, *G*, is brought in from the side, and maintained at a positive potential with respect to *B* by the battery, *H*. If the switch, *S*, is closed, impressing battery potential on *E*, an arc will start at *K*, the junction of crystal and mercury. Current will flow first from *E* to *C*, then between the anode, *G*, and *C*, the current being limited mainly by circuit impedance.

Developed to its present state, the ignitron combines the properties desirable in a rectifier with many features heretofore unavailable in most arc discharge devices. With the mercury pool type of cathode, unlimited peak currents are possible without destructive effects, permitting extreme momentary overloads. The igniter gives positive control of the starting of the arc; there is no holding arc; and after the zero of current the arc space quickly deionizes and remains so until time for the next cycle of current when the arc again is started. Because of this lack of ionization during the time the anode bears negative voltage, the anode need not be protected by shields and grids. With the resulting short unrestricted arc, the arc potential drop is low and the losses small. Arc-back occurs very infrequently in the ignitron because it is only during a few microseconds after current zero that an arc-back danger exists.

Novel properties of the ignitron are: (1) its positive and inherent control, (2) low loss at all loads coupled with low frequency of arc-back, and (3) its overload capability. This combination is found in no other equipment, and is sufficient to recommend the ignitron for many interesting applications, particularly those making use of its control features. It is suitable for any application demanding positive control of large currents, where intermittent operation at rather high frequency is necessary. One such application is its use as a controlling switch in spot or seam welding. Because of its high current capacity and low arc drop, the ignitron can be used directly in a low voltage circuit and so obviates the necessity of transforming apparatus to connect it into the welding circuit. The welding current passes directly through the ignitron and is maintained at zero value as long as the igniter is blocked. The use of the mercury pool cathode provides an inherent overload capacity and long life.

Ignitrons in small sizes, constructed of glass, have been used extensively for spot welding. While the peak current may be very high in such applications, the frequency of the spots (or the duty cycle) is so low that the average current is low and the physical size can be small. This paper deals only with the large-power steel-tank welding ignitron.

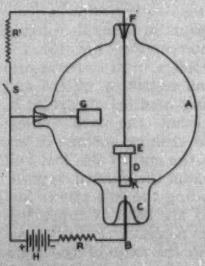


Fig. 1 (left). Diagram illustrating the "ignitron" principle

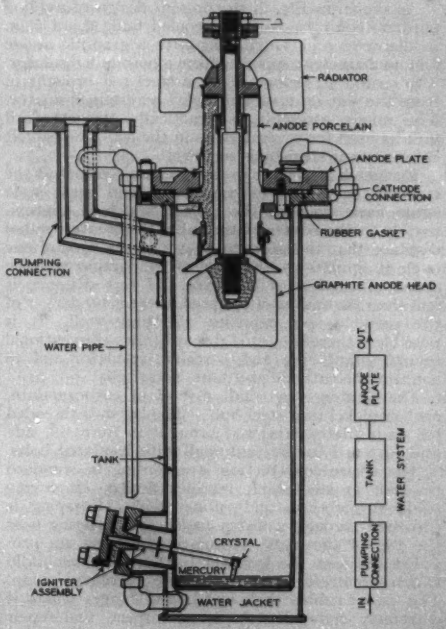


Fig. 2 (right). Cross-sectional view of the "ignitron" welding rectifier

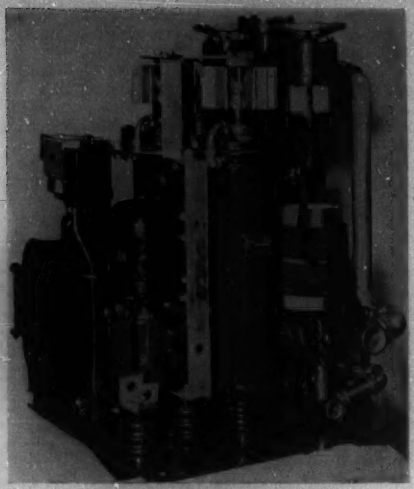


Fig. 3. Complete rectifier assembled

Construction of the Rectifier

As shown in Fig. 2, the present design of welding ignitron comprises a water cooled tank about 5 in. in diameter and 17 in. long with a graphite anode 4 in. in diameter supported from a porcelain insulator. The igniter is supported by a steel rod brought in from the side on a rubber sealed porcelain insulator. The anode assembly is practically the standard unit as used for several years in the 500-kw 600-volt conventional steel-tank rectifier.

Inasmuch as the arc in the ignitron goes out at the end of the period of conduction and must start again each cycle at the igniter, which is approximately in the center of the tube, the greatest radial distance that the spot can travel in the time of one cycle is limited by the time of conduction and the speed of motion of the spot. If this distance is less than the radius of the pool, there is no danger of the cathode spot reaching the tank wall. It is possible, therefore, to discard the conventional quartz guard ring and porcelain insulator and to connect the cathode and tank electrically.

The igniter is a small crystal of carborundum, cast in nickel in a steel hub. The latter is threaded on an insulated steel rod brought in from the side and fastened to the tank wall with insulated bolts.

The entire construction is according to standard practice in steel tank rectifier design, employing solder-to-porcelain and rubber seals. Pumping is provided through a water cooled arm entering near the top of the tank. Insulating sections are provided between the ignitrons and a small manifold which connects directly to the mercury pump. The use of rubber seals and bolted flanges makes it extremely convenient to open, inspect, and repair these rectifiers. The igniter may be removed and replaced through the side opening without disturbing the anode plate.

Figure 3 shows the complete assembly of ignitron, pumps, and cooling and protective equipment. This is a self-contained unit including all auxiliary, electrical, and water connections ready to be connected to the controller, power, and water circuits. The vacuum pumping equipment includes a mercury vapor pump and a rotary oil sealed backing pump, and is arranged for automatic intermittent operation of the rotary pump as needed to maintain a satisfactory vacuum.

A typical diagram of connections when used as a line welder is shown in Fig. 4. The 2 ignitrons are directed oppositely and in parallel; together they act as a switch in the circuit between the power transformer and the step-down transformer at the welding machine. Each igniter is connected to its own anode through a small grid-controlled rectifier, through which the starting energy passes. The control circuits end at the grids of these auxiliary rectifier tubes. The control circuit shown in Fig. 4 indicates a mechanical contactor as used in the early tests. A more flexible and positive controller, using a synchronously driven disk with a photo-electric pick up, is described in a paper, "A New Timer for Resistance Welding" by R. N. Stoddard (see p. 1366–70 of this issue). These controllers operate to impress a bias on the grid at the desired moment, the time when conduction starts depending upon when this bias becomes positive. The grids of the second set of auxiliary rectifier tubes are available for further control of the welding current within the period of conduction set by the master controller.

Operation and Limitations

The ignitron requires a certain minimum voltage on the igniter before the arc can start. If this starting voltage comes from the anode, as it usually does, (Fig. 4) rather than from a separate excitation circuit, no arc can start until the anode potential reaches this minimum value. For voltages much greater than this minimum striking voltage the starting action is exceedingly rapid, a cathode spot forming in 1 or 2 μsec. From this point of view the welding circuit, which is of rather low power factor, is advantageous in that the anode voltage rises, after current zero in the other ignitron, to almost peak line voltage and so provides a considerable overvoltage for rapid igniter action.

Low power factor conditions in general increase the difficulty of circuit interruption, because the rapid rate of rise of back voltage after current zero makes it difficult to prevent restriking of the arc. In a rectifier such a restriking is called an arc-back. However, in the welding circuit, the back voltage on one ignitron is limited to striking voltage or arc drop in the other except at the end of the last half cycle of the current group when the current is interrupted. Thus, notwithstanding the low power factor circuit, the tendency to arc back is much less than for the same ignitrons in 6-phase rectifier operation; practically, it is less in the ratio of the num-

ber of duty cycles per second to 360, which may be as small as a few per cent. Furthermore, the welding ignitrons are in operation only while work is actually between the rolls of the welder. This must be considered in interpreting the test results to follow.

Probability of arc-back seems to be highest in the short period after current zero while the anode bears negative voltage and an ionized gas exists between the 2 electrodes. The higher the vapor pressure the longer the time required for the density of ionization to be reduced to a value sufficiently low to withstand negative anode voltage safely. The lower the temperature of existing mercury surfaces the lower the vapor pressure and the lower the arc-back rate. It has been observed both in the laboratory and in service that the arc-back tendency is satisfactorily low at water temperatures as high as 45 deg C (104 deg F).

Seam welding service is not particularly exacting as regards arc-back. Service is not interrupted, and the only result is the possibility of one extra half cycle of current. The probability of arc-backs on successive half cycles is practically zero. It has been observed that many other variables are involved in the welding process, such as particles of dirt under the rolls, small roughnesses on the work, or variability in the surface oxide; these variables are much more frequent in occurrence and have a much greater effect on the character of the weld than an extra half cycle of current or an arc-back in the ignitrons.

Individual igniters may be expected to vary slightly in characteristics, one from the other, and variations in starting action from cycle to cycle for a given igniter may be as great as differences between 2 igniters. The effect of these variations tends to become smaller the higher the circuit voltage. However, the control circuit makes it possible to correct for any dissimilarity in average starter characteristics or in arc drop in the 2 ignitrons. The starting

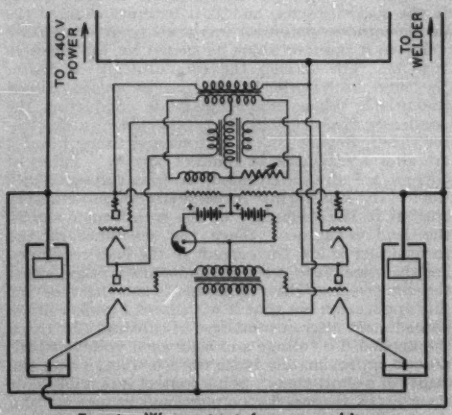
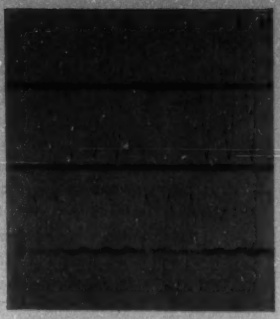


Fig. 4. Wiring circuit for seam welding

Fig. 5. Oscillogram of rectifier output while operating at full load

Top trace, line current (peak, 2,100 amp), middle trace, igniter current in one "ignitron"; lower trace, voltage between anode and cathode (peak, 575 volts)



can be controlled so that the d-c component of current in the line is a fraction of one per cent of the current through each ignitron.

Service Record

Since the first welding units were built and tested considerable operating data have been accumulated, both in the laboratory and in the field. At present, 5 units are in commercial operation: 1 welding stainless steel beer barrels, 1 aluminum beer barrels, and 3 bronze refrigerator evaporators. One of these uses a 50-per cent duty cycle with a peak current of 500 amp. Another uses a 23-per cent duty cycle with 1600 amp peak and 120 amp average per tube. All have given several months of satisfactory service. In the laboratory, extensive tests have been made under various conditions of temperature, load, and duty cycle. Even under severe conditions of all 3 variables the operation was extremely gratifying.

An oscillogram of the operation of ignitrons in welding service is shown in Fig. 5. The ignitrons were operating on a 50-per cent duty cycle (3 cycles on and 3 off) with current limited by the circuit constants. In other words, no artificial delay was introduced other than that necessary to strike the arc with the igniter. As closely as can be judged by eye, there is coincidence between the dropping to zero of current in one ignitron and the building up of current in the other. The delay introduced by the igniter is not sufficient to cause any appreciable variation from a sine wave of current through the welding transformer. This oscillogram was taken with approximately 800 amp (rms) in the line and 240 amp (avg) in each ignitron.

With loads up to 100 amp (avg) per ignitron with outlet water 60 deg C (140 deg F) no arc-backs were observed in 4 hours' running. At 160 amp with 60-deg water an arc-back rate of about 1 per hour was observed. At the same temperature and 240 amp, the rate was about 10 per hour. However, with this latter load and 40 deg C (104 deg F) water temperature the arc-back rate was less than $^1/_2$ per hour. This was for 50-per cent duty cycle and peak currents of about 2,000 amp. Peak currents as high as 2,500 amp were carried with an arc drop of about 16 volts.

The "Ignitron" Type of Inverter

The operation of inverters for obtaining alternating current from direct current is first considered in this paper, both the grid controlled rectifier and the "ignitron," a special type of mercury vapor tube, being analyzed. The duty on the inverter tube is next discussed, and special attention is then given to the "ignitron" inverter. Experimental results obtained with this latter type of inverter are given.

By
C. F. WAGNER
MEMBER A.I.E.E.

L. R. LUDWIG
ASSOCIATE A.I.E.E.

Both of Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

THE ability of the grid controlled rectifier to prevent current conduction until some predetermined point during the cycle has led to its suggestion for application to a large number of different uses among which may be mentioned voltage control of rectifiers, conversion from direct current to alternating current, commonly called inversion, and also frequency conversion. A new form of rectifier known as the "ignitron" provides another and in some respects better device for these same applications. Briefly, the ignitron consists of a mercury pool cathode and a closely spaced anode. A small current passing through a silicon carbide crystal dipping into the mercury is used to initiate the main arc between the anode and cathode. It is the province of this paper to discuss the characteristics of ignitrons in relation to the special problems arising in inverting d-c energy to a-c energy.

Operation of Inverters

Both the grid controlled rectifier and the ignitron control the instant at which conduction takes place but thereafter lose control completely. Current in individual tubes must be interrupted or commutated through the medium of the external circuit which causes the current in the tube to decrease to zero. At the instant of current zero the insulating property of the tube is reëstablished and continues so until rendered conducting again by operation of the control features.

Inverters may be grouped into 2 general classes according to the means employed to effect this current zero, namely, inverters with static loads and inverters with loads having a rotational counter electromotive force. With static loads condensers in some form must be provided so that their charge or discharge will cause the current in the anode to be commutated to zero. For the second type, the phase position of the rotational electromotive forces may be so adjusted that when 2 or more tubes are made conducting simultaneously, the current in the first one to be made so conducting will decrease to zero. Examples of the former are polyphase lighting loads and single-phase neon sign lighting in d-c districts. Of the latter, examples are provided by induction and synchronous motors. In order to illustrate the requirements of these 2 general types the operation of a single-phase inverter with resistance load and also an a-c generator connected through an inverter circuit which corresponds to a d-c commutatorless motor will be discussed.

In Fig. 1 is shown a schematic diagram for a single-phase inverter with a resistance load. The constant potential E is applied from the d-c source and tubes A and B are alternately made conducting through the functioning of their control devices, the frequency of the a-c load being determined by the frequency of the control. Assume for the moment that tube A is conducting. Condenser C assumes a potential of approximately $2E$, the right-hand side being positive. Now if tube B is rendered conducting condenser C discharges through the 2 tubes causing the current in tube A to decrease to zero. Tube A thus becomes open-circuited. The anode-cathode potential is then equal to the potential across the condenser minus the arc drop in tube B. Since the left-hand side of the condenser is negative in potential relative to the right-hand side, the anode becomes negative relative to the cathode. With the new conduction paths, the condenser tends to charge in the opposite sense and as it becomes charged the anode-cathode potential increases from a negative value to a positive value as shown by the curve in Fig. 1*b*. The smaller the commutating condenser the more rapid will be the rise in anode-cathode potential. When tube A is made conducting the condenser discharges in the reverse sense extinguishing the arc in tube B. In this manner tubes A and B are alternately made to conduct current. Pulses of current are alternately made to pass through the 2 sides of the transformer which produce an alternating current in the secondary of the transformer and in the load resistance. Since the reactance of the transformer is low the current in the load resistance has the same wave shape as that of the voltage across the condenser. The requirements for the tube for this application are that it withstand a back voltage immediately after current zero of substantially twice the applied d-c voltage and a forward voltage which rises to approximately twice the d-c voltage after the elapse of a short time. Some control is possible over the rate of rise of the voltage but, in general, the shorter the time as dictated by the characteristics of

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Sept. 10, 1934; released for publication Sept. 18, 1934. *Not published in pamphlet form.*

the tube when positive potential is permitted, the smaller the condenser.

A counter electromotive force load as exemplified in the commutatorless d-c motor is shown schematically in Fig. 2. The machine consists of a conventional synchronous a-c generator or motor with damper windings. The particular connection shown is known as a 6-phase connection with delta secondary. The problem is to produce current pulses in the 6 phases. This requires that the current be built up and reduced again to zero. The counter or generated electromotive forces of the machine are e_1, e_2, e_3, and their negatives e_4, e_5, e_6. The instantaneous values of these voltages together with the applied d-c voltage are shown in Fig. 3. It will be assumed that the ballast inductance in the d-c side is so large as to justify the assumption of constant current in the d-c side. Suppose that tube 1 is carrying current and tube 2 is ignited. In order that i_1 decrease and i_2 increase it is necessary that the instantaneous value of e_1 exceed that of e_2. Thus, the ignition point for tube 2 must lead the instant when e_1 and e_2 are equal. Furthermore, commutation must be completed before e_1 becomes less than e_2. As the ignition point is advanced the duration of the commutating period decreases but the power factor becomes worse. The ideal condition is that i_1 reach zero just before e_1 and e_2 become equal.

The commutation process in reality constitutes a short circuit between terminals 1 and 2. After commutation is complete, i_1 has reduced to zero and i_2 has increased to the value i_1 had before commutation. The current in tube 2 remains at this constant value until tube 3 is made conducting. The process thus continues.

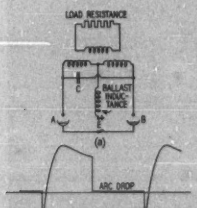


Fig. 1 (above). The static inverter, showing (a) schematic diagram, and (b) anode-cathode voltage

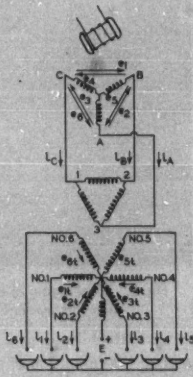
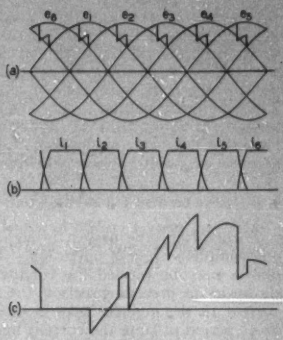


Fig. 2 (right). Schematic diagram of a commutatorless motor

During the intervals when only one tube is conducting, the voltages e_{1l}, e_{2l}, etc., in the transformers are equal to their corresponding generated electromotive forces because of the assumption of constant current in the d-c side. During the commutating periods, the transformer voltages of the 2 tubes being commutated are equal to the mean of the 2 corresponding generated voltages. The net voltage producing a back electromotive force to the applied voltage is that shown by the heavy line in Fig. 3. The average value of this line must equal the applied voltage. The instantaneous difference in voltage is absorbed by the ballast inductance.

Fig. 3. Operation of 6-phase inverter

a. Voltage between transformer neutral and cathodes of tubes
b. Anode currents
c. Anode-cathode voltage across tube 1



Immediately after the anode current in an individual tube passes to zero the anode-cathode voltage of that tube drops to a negative value. This is a necessary condition that follows from the commutation requirements. The shape of the anode-cathode voltage may be obtained from the transformer voltages e_{1l}, e_{2l}, etc. Consider that of tube 1. During its conducting period the voltage is, of course, the arc drop or if in this discussion the arc drop be neglected, it is equal to zero. To simplify the discussion still further, assume that the transformer impedances are zero. While one tube only is conducting, the anode-cathode voltage of tube 1, is equal to the transformer voltage of the tube minus e_{1l}, or, to be specific, if tube 2 is conducting, the anode-cathode voltage of tube 1 is equal to $e_{21} - e_{1l} = e_2 - e_1$. While any 2 adjacent tubes are conducting, the transformer voltages of the phases not coupled with the phases involved are zero. Thus, suppose tubes 2 and 3 are conducting, $e_{2l} = e_{3l}$, which since the transformers have zero impedance, requires that the potential of points 1 and 2 above point 3 on the delta side of transformer be equal. Points 1 and 2 are then of the same potential and $e_{1l} = 0$. The anode-cathode potential of tube 1 while tubes 2 and 3 are conducting is equal to e_{2l} which is equal to $^1/_2(e_2 + e_3)$. Similar considerations apply when tubes 5 and 6 alone are conducting, the anode-cathode voltage of tube 1 being equal to $^1/_2(e_5 + e_6)$. Because of the coupling between phases, the anode-cathode voltage of tube 1 while tubes 3 and 4 alone are conducting is equal to $2e_{3l} = e_3 + e_4$. The anode-cathode voltage based upon the above assumption is shown in Fig. 3. In general the magnitude of the negative kick and the shape of the anode-voltage curve vary with the angle of ignition, the load, reactances of the ballast, trans-

formers and machine, characteristics of the machine, and the number of phases which are simultaneously conducting. The tubes must be able to operate without back-firing under the negative voltage imposed immediately after commutation and without forward-firing when the positive potential is applied.

For the particular inverter circuits discussed, early ignition requires that inverters operate at leading power factors. In general, the shorter the interval permissible between current zero and when positive potential may be applied, the better the power factor at which the inverter will operate. These inverters cannot supply lagging reactive volt-amperes. If the a-c load on the inverter requires lagging reactive volt-amperes provision must be made to supply it by some other device.

The Duty on the Inverter Tube

An inverter tube passes through 3 phases during one complete cycle of operation. The first of these phases may be termed the conducting period. As shown in the preceding section, the wave form of the current in the inverter tube is such that in a very short period of time the current must increase from zero to its maximum value. Thus the onset of conduction must be very rapid. Furthermore, this is a matter of more importance in inverter operation than in rectifier operation because successful commutation of the inverter depends upon accurate starting at fixed time intervals as well as a low arc drop within the tube from the instant when conduction is initiated. If these 2 conditions are not fulfilled, the time required for commutation is apt to overrun the allotted period with the result that the inverter fails. In the rectifier, an occasional commutating period of extra long duration, or the delayed starting of one tube, would pass unnoticed; but in certain kinds of inverter tubes, special means to insure a rapid onset of conduction must be resorted to.

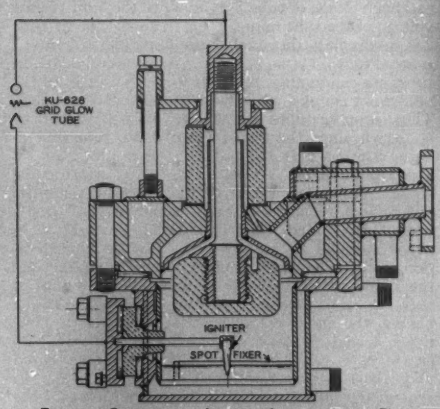


Fig. 4. Cross-sectional view of an ignitron. The over-all height of the tube shown is 10.5 in.

The second phase of inverter tube operation may be termed the rectification period. When the current in a given tube is reduced to zero by the commutating electromotive force, its rectifying property prevents the phenomenon which in rotating conversion machinery is known as over-commutation. This rectifying property is not possessed by brushes and commutators, and it is a considerable advantage of the tube type of equipment, because the commutating electromotive force in case tubes are used does not have to be made equal to a predetermined value, but it needs to be equal to or greater than this value. As in the case of the rectifier tube, the anode quickly becomes negative with respect to the cathode at the end of the conducting period. During the short interval of time throughout which the anode remains negative, there is a certain probability that the tube will back-fire. This phenomenon is of much less importance in the inverter than in the rectifier; however, a back-fire in an inverter does not short-circuit the d-c system, and in a fraction of a cycle the reverse current which flows in the event of a back-fire, will fall to zero. The back-fire is quite undesirable, however, because it may greatly increase the probability of a failure during the third phase of operation.

This third phase may be termed the positive control period. In a polyphase inverter it is the longest period of the cycle. The tube anode is positive with respect to the cathode throughout, but in spite of this the tube must be provided with means for pre-

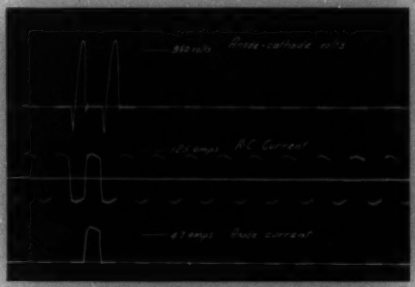


Fig. 5. Oscillogram of single-phase inverter operation with machine load. 159 cycles

venting the formation of an arc until the conduction period is reached. The accidental formation of an arc during the positive control period may be termed forward-fire. The probability of such a failure with any of the known inverter tubes depends upon the peak value of the current carried by the tube and also upon length of the rectification period, and if that period is short, also upon the manner in which positive voltage is applied to the anode. Practically, a long rectification period is not a satisfactory means for easing the duty on the inverter tube during the positive control period, because of the poor power

factor which would result. When an inverter supplies a load having a sinusoidal voltage wave form, positive voltage is applied to the inverter anode approximately sinusoidally, and this considerably simplifies the building of inversion equipment.

From this description of the duty on an inverter tube, it is evident that any of the known types of gaseous rectifiers could be used for inversion, provided they were equipped with some means for blocking conduction throughout the positive control period. The generally adopted means has been the introduction of an electrostatic control grid placed between the anode and the cathode. Such a grid has the property that if it is properly constructed and given a sufficient negative potential bias with respect to the cathode, a continuous positive ion space charge sheath will be formed around it which will prevent the formation of a current conducting arc. When conduction is desired, the grid is made positive.

Such grids have been applied to tubes of the single anode type which employ a thermionic cathode, and also to multi-anode tubes using a mercury pool cathode. The thermionic cathode inverter tube is well suited to those applications which only require small currents. In the larger sizes, the limitation of the cathode in current carrying capacity, the comparatively short life, and the limitations of the grid type of control have prevented any considerable application. The mercury pool cathode inverter has also been restricted by the limitations of the grid type of control. While it is free from the other disadvantages of the thermionic cathode type of tube, it suffers from a cumbersome and costly type of construction necessitated by the problem of restricting back-fire and forward-fire. This problem of forward-fire is a serious limitation to the satisfactory operation of inverters, and although tubes can be constructed which are sufficiently reliable, their cost and comparatively large losses have so far prevented any considerable application.

The "Ignitron" Inverter

The recent invention of a new method for initiating the cathode of an arc by Slepian and Ludwig (see "A New Method for Initiating the Cathode of an Arc," by J. Slepian and L. R. Ludwig, A.I.E.E. Trans., 1933, v. 51, p. 693–8) has led to the development of a new type of tube called the "ignitron." In Fig. 4 is shown a cross-sectional view of an ignitron, which has been tested in an inverter circuit. The tube consists of a mercury pool cathode at the bottom of a small tank of very simple design, a graphite anode insulated from the tank, and an igniter electrode which is also insulated. No insulation of the cathode from the tank is required.

The anode is spaced close to the cathode, and no grids or shields intervene between the 2. Consequently, the arc drop during the conducting period is low, and at the onset of this period, the tube quickly becomes highly conducting without requiring any special system of excitation other than the igniter electrode. This electrode is of silicon carbide. Its lower end is immersed in the mercury and the upper end is welded into the holder. When current of a few amperes is caused to flow through the rod in the direction of holder to mercury, the cathode of an arc will be started on the mercury in a few millionths of a second. The action of the igniter has been completely described in the paper mentioned in the preceding paragraph. The required accuracy of control is an important feature found in the ignitron.

Fig. 6. Oscillogram of 6-phase inverter operation on 250-volt d-c circuit with synchronous machine load. 142 cycles

During the rectification period, the ignitron is able to withstand negative voltage without failure despite the proximity of anode and cathode, because of the absence of any source of ionization during this interval. It is only necessary to keep the density of the mercury vapor sufficiently low so that the residual ions from the conducting period will vanish quickly after the current becomes zero. The special means used for fixation of the cathode spot of the arc, shown in Fig. 4, are chiefly for this purpose. A complete description of the action within the ignitron during rectification has been presented by Ludwig, Maxfield and Toepfer ("An Experimental Ignitron Rectifier," Elec. Engg., v. 53, 1934, p. 75–8). Thus, it is evident that during the rectification period, the small size and high efficiency realized in the ignitron rectifier, are also present in the inverter.

During the positive control period, the ignitron functions in an essentially different way than the grid controlled tube. With grid control, the cathode is always in a live state of emission, and the grid has a preventive duty to perform. That is it must resist the formation of the plasma of an arc. In the ignitron, the cathode is normally in a nonemitting state, and the igniter has the duty of initiating conduction within the cathode region.

The first advantage of this type of control is the complete absence of the grid from the conducting path within the tube. The igniter electrode in no way hinders the conduction of the arc after it has formed, whereas the grid does do so, and adds about 2 volts to the arc drop. In addition, the control grid is often a source of trouble within the tube since conditions are difficult to avoid under which it will be burned by the arc.

The starting current is easily supplied to the igniter electrode at the proper time by the circuit shown in Fig. 4. A small thermionic cathode tube is connected between the anode of the ignitron and its starting electrode, and this tube may be grid controlled. It is quite small in size, because the average current of the igniter is only a fraction of an ampere. With this circuit, the effect has been to remove the grid from the main tube, and place it in an auxiliary tube where it in no way interferes with the conduction of the inverter current. The arrangement for operating the igniter is quite flexible, of course, and many other circuits are useful for special applications.

The second advantage of the igniter type of control is associated with the forward-firing probability. In the grid-controlled tube, the grid can only prevent conduction after a positive ion space charge sheath has formed about it. The thickness of this sheath depends upon the density of ionization. Since it is impractical because of too high an arc drop to use a grid with highly constricted passages, the density of ionization must be only a few per cent of that during the conducting period if the space charge sheath is to be sufficiently thick to make the grid effective. Thus, it is generally necessary to allow for a "deionization" time of a few hundred microseconds after current zero before considerable positive voltage is applied to the anode. Even after the grid has blocked the tube, there is no assurance that the accidental formation of a cathode spot upon the grid itself will not destroy the blocking action. Thus, either a failure of the grid to block initially, or a "back-fire" to the grid, will cause a forward-fire within the inverter tube.

In the ignitron, no space charge sheath needs to be formed about a grid, but at the cathode region itself. This sheath is of very small dimensions, however, and it can be shown that its formation, or "loss of a cathode spot" as the phenomenon has been termed, requires only a few microseconds instead of a few hundred. Afterward, there is, of course, no assurance that the accidental formation of a cathode spot on the cathode will not permit a forward-fire, and in this sense the ignitron will also have a "deionization" time. This deionization time is of a statistical nature, however, because of the random nature of the "back-fire" phenomenon (see "Backfires in Mercury Arc Rectifiers," by J. Slepian and L. R. Ludwig, A.I.E.E. Trans., v. 51, 1932, p. 92–104). That the ignitron inverter can be made to run reliably, and still retain its inherent advantages of small size and low loss, will be shown by the experiments which will be described.

Experimental Results

In order to test their performance, 2 ignitrons were set up for a single-phase operation. The load consisted of a 100-kva 3-phase 180-cycle synchronous generator equipped with damper windings. Two terminals were connected to the 302-volt windings of 2 50 kva transformers, the 440–880-volt windings being connected through the ignitrons and ballast inductance to the 250-volt shop d-c circuit. A resistance of 0.25 ohm was also placed in series in the d-c supply to limit short-circuit currents. Control of the ignitrons was provided through the medium of a phase shifter connected to the 3 machine terminals, the secondary of the phase shifter supplying by means of a peaking transformer, voltage impulses to the grid glow tubes in the starter circuits. The oscillogram reproduced in Fig. 5 is a typical record of the results obtained. The anode-cathode voltage shows the negative kick as the current goes to zero and also the subsequent rise to a positive value. At 250 volts direct current, 140 amps, or 35 kw, were inverted by 2 tubes of the kind shown in Fig. 4 from direct current to 180 cycles alternating current, and during a 100 hr test there were no failures. The temperature of the cooling water in the tubes was from 35 deg C to 40 deg C throughout the test. The arc drop in the tubes was very substantially less than that of the conventional rectifier. At 500 volts direct current, 100 amps or 50 kw were inverted by 2 tubes to 180 cycles alternating current without failure during a test which lasted for 50 hr. The water temperatures remained the same as in the last test.

Six similar tubes were also connected for 6-phase operation. The control for this test was likewise by means of a phase shifter, peaking transformers, and grid glow tubes. As yet no long time tests have been completed, but satisfactory operation of the circuit has been established, and the action of the polyphase inverter is shown by oscillograms reproduced in Figs. 6 and 7. In Fig. 6 the phenomenon is somewhat more complicated than the simple description given previously due to simultaneous conduction of current in more than 2 tubes. In general, however, the same negative kick occurs in the anode-cathode voltage.

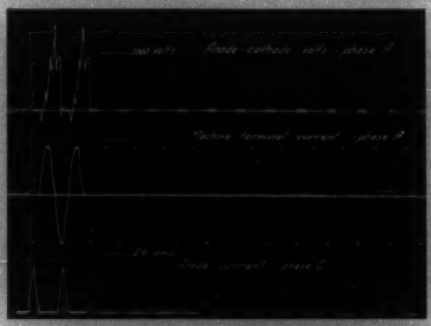


Fig. 7. Oscillogram of 6-phase inverter operation on a 500-volt d-c circuit with synchronous machine load. 178 cycles

In view of the small physical size of the ignitron and its low arc drop, the provisional rating as indicated by the tests seems to be sufficient to demonstrate the practical advantages of this type of tube.

Dielectric Properties of Cellulose Paper—I

Studies of the dielectric properties of pure cellulose paper as used for high voltage insulation are reported in this paper. The studies reported in Part I, presented herewith, include investigation of the dielectric loss, phase difference, and capacitance of paper insulated specimens as related to the moisture content of the paper. In Part II, which is scheduled for publication in a subsequent issue, these studies are extended to the variations in dielectric properties as related to temperature when the paper is extremely dry.

By
J. B. WHITEHEAD
FELLOW A.I.E.E.

E. W. GREENFIELD
ASSOCIATE A.I.E.E.

The Johns Hopkins University, Baltimore, Md.

ACCURATE engineering design of insulation for high voltage alternating current service is as yet not possible. The electrical characteristics of complex insulation can be predicted only approximately, from earlier measurements on the several constituents. This is particularly true of impregnated paper insulation such as used in high voltage cables. Aside from the uncertainty attaching to the changes in cable insulation in service and to the life of the insulation, almost equal uncertainty pertains to the final values in the assembled product of dielectric loss, power factor, and capacitance. As a simple example, it may be mentioned that the volumetric ratio of paper to oil in a cable, and measurements in advance of the separate properties of each, are not sufficient for the predetermination of either phase difference or capacitance in the assembled product.

In an earlier paper,[1] extensive studies of the relations between the basic physical and electrical properties of a number of oils and the subsequent properties of a single grade of paper as impregnated with the oils have been described. Various definite relationships were found. Among other things, it was shown that in the best grades of impregnated insulation, the properties of the paper before impregnation play a dominating part in fixing the properties of the assembled insulation. The paper, however, is far more complex and anomalous in its behavior than is a good oil. It therefore becomes of great interest to examine the properties of the paper itself and to determine if possible their bearing on the finished product. Several studies in this direction already have been reported.[2,3] In this paper is described a series of studies of loss, phase difference, and capacitance in a typical wood pulp paper, as related particularly to the moisture content and to temperature variation. From the results, the following conclusions have been reached:

1. Drying at a constant temperature 100 deg C produces stable conditions of moisture content and electrical properties. The values so found have been studied as related to evacuation pressures between 765 mm and 0.25 mm of mercury.

2. The studies permit quantitative determination of the amount of moisture present under different conditions and show that at 100 deg C, under final steady conditions, the moisture content at a pressure of 765 mm of mercury is 0.26 per cent, and at 0.25 mm is 0.05 per cent of the total volume of the sample. The moisture content at constant temperature varies closely as the $^1/_4$th power of the vacuum pressure.

3. Short-time d-c charge and discharge current curves, and a-c loss measurements have been used to determine the part played by moisture in affecting the values of the various electrical properties. Several interesting relationships have been found as follows:

(*a*) The total capacitance varies approximately as an exponential function of the moisture content.

(*b*) The component of total geometric capacitance attributable to occluded water varies directly with the moisture content.

(*c*) The component of capacitance due to dielectric absorption, the total power factor, and the absorption component of power factor all vary as exponential functions of the moisture content.

(*d*) The conduction component of power factor varies as exponential function of the moisture content only in the lower ranges, increasing thereafter more rapidly and no longer in simple relation.

4. At 100 deg C and 1 mm (of mercury) vacuum, high grade cable paper contained 0.07 per cent by volume of water. This water contributes substantially to the dielectric loss, the power factor, and the capacitance of the paper as measured before impregnation.

General Properties of Paper for Insulation

Although every effort is made to reduce the chemical and physical properties of the paper to those pertaining only to the cellulose of wood pulp fiber, nevertheless the electrical properties of the purest paper are not those commonly expected in a simple substance and the behavior of the best and purest paper is highly complex. The explanation is to be found in the fibrous structure of the paper which results first in a mesh-like combination of air and fiber, and second in a microscopic structure possessing the finest filaments and channels with consequent pronounced capillary properties. Such a structure is avidly absorbent of both gas and thin liquids such as water, and it is practically impossible to extract completely the air and moisture from the paper before impregnation. The anomalous properties of paper are to be ascribed principally to its moisture content. Under the best commercial methods, the electrical conductivity of dry paper is extremely small and difficult to measure. Nevertheless, under alternating stress it shows a definite dielectric loss and phase difference. These are due to the presence of dielectric absorption, in some way due to residual moisture. A similar influence is found on the ca-

Part I of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–26, 1935. Manuscript submitted July 12, 1934; released for publication Aug. 24, 1934. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

pacitance which, when measured at 60 cycles, is noticeably greater than the geometric value.

The explanation of the dielectric absorption and loss in cable paper is not clear. Several explanations have been offered, as for example the layer theory of Maxwell, the capillary films of Evershed, the elongated filament of Dubois, the 3-layer dielectrics of Setoh and Toriama and of U. Meyer, and various pictures of the behavior of water ions adsorbed by the cellulose fiber, as for example, those of P. Böning and Murphy and Lowry. The Debye theory of polar molecules also has been invoked. None of these suggestions is as yet susceptible of experimental test because of inability to control and measure the submicroscopic processes involved. The case would be almost hopeless if reliance had to be placed on direct observation and measurement of moisture content and its distribution.

Fortunately, however, powerful indirect methods are now available. The short-time charge and discharge curves under continuous potential as observed in the amplifier oscillograph, by methods described in earlier papers, from the electrical engineering laboratory of The Johns Hopkins University, permit, through the von Schweidler method of analysis, the complete separation of the various constituents of all the electrical properties of a sample, and thereby through variation of experimental conditions to reach definite conclusions as to their origin. Now, the basic dielectric constant of cellulose fiber, the amounts of moisture present at various stages of dryness, and the contributions of such moisture to conductivity, absorption, dielectric constant, and loss are determined to close approximations.

Test Samples and Measurements

The test samples were made up in the form of cylindrical capacitors in which the high voltage electrode was a brass cylinder 61 cm long, 0.026 cm thick, and with outside diameter 6.35 cm. On this cylinder an uncalendered chemical wood pulp "kraft" paper 2.54 cm wide, and approximately 0.01 cm thick was spiralled cable fashion to a depth of 15 layers, each spiral making a butt joint and each layer having a registration of 0.63 cm. The outer electrode was of 0.04 cm sheet lead molded closely to the paper and bound down with a single layer of linen thread. The outer electrode was in 3 parts, one in the center being the measuring electrode, and a shorter one separated from the one in the center by a 0.02-cm gap, these 2 being used as guards. The lead electrodes were perforated with small holes at a spacing of 2.54 cm to aid in the drying process. For drying and temperature control, the sample was mounted within a tank having vacuum and electrical heating connections. A complete description of the tanks, method of heat control, various measuring and auxiliary connections have been given in an earlier paper.[8]

At atmospheric pressure cable paper absorbs large amounts of water, say from 5 to 10 per cent by volume. In this condition it shows high electric conduction and has no special interest as an insulator. A large proportion of this absorbed moisture may be driven off by raising the temperature to 80 deg C, but vacuum drying and higher temperatures are necessary in order to obtain the full insulating value. In the final condition the volume of water present is very small, but apparently it is distributed in adsorbed layers and capillary channels in such form as to render the paper highly anomalous in its electrical characteristics. Under continuous potential, polarization with a definite time element results in a behavior commonly described as dielectric absorption. Under alternating potential there are dielectric loss and increased capacitance due to dielectric absorption.

Direct measurement of the moisture content in the advanced stages of dryness is difficult. However, as will be shown, it is possible to compute the moisture content from electrical measurements taken on the paper when in stable condition at various evacuation pressures. In earlier work, it has been shown that at constant temperature and constant evacuation pressure, a stable condition as to conductivity and dielectric absorption is always reached. This indicates a condition of equilibrium as regards moisture content. Consequently, a standard drying temperature of 100 deg C has been adopted for all specimens and all measurements, with pressure as the only variable; the range of pressure studied was from 765 to 0.25 mm of mercury. The method also eliminates the important question of change of capacitance with temperature, of which a separate study has been made. Throughout the period at each pressure, electrical measurements were taken, tracing the effect of the progressive elimination of moisture and the arrival at the stationary condition pertaining to each pressure. For the taking of these measurements, the pressure was raised tempo-

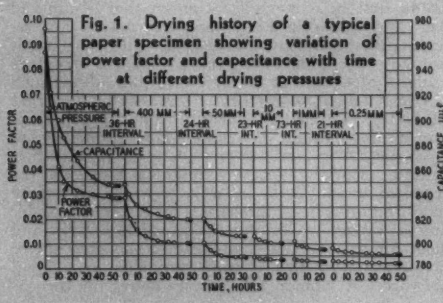


Fig. 1. Drying history of a typical paper specimen showing variation of power factor and capacitance with time at different drying pressures

(Left) All pressures expressed in millimeters of mercury. Temperature maintained constant at 100 deg C; frequency, 60 cycles

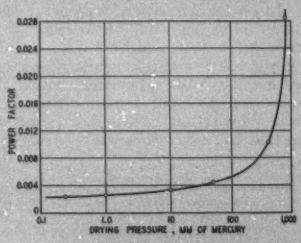


Fig. 2. (right). Variation of apparent power factor with drying pressure; 1,500 volts, 60 cycles

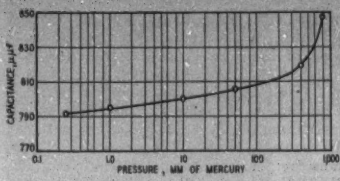
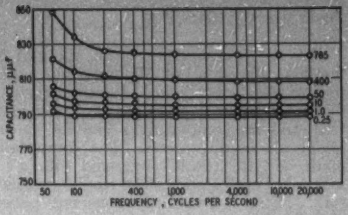


Fig. 4 (right). Variation of capacitance with frequency for different drying pressures

Numerical designations on curves indicate pressures in millimeters of mercury



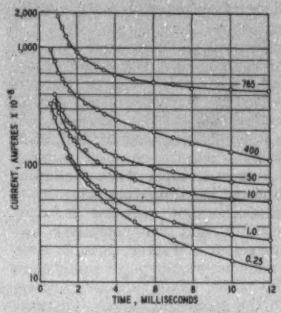


Fig. 3 (above). Variation of apparent capacitance with drying pressure, 1,500 volts, 60 cycles

Fig. 5. Discharge curves (d-c) for various drying pressures

Numerical designations on curves indicate pressures in millimeters of mercury

rarily to that of the atmosphere by the admission of dry air. In this program 6 stages of dryness were investigated, the last one corresponding to an evacuation pressure of 0.25 mm. As may be seen, there appeared to be no reason why the evacuation should be carried to lower pressures.

The electrical measurements at each evacuation pressure were as follows:

1. *Frequency-Capacitance.* These measurements were made with a Hartley circuit oscillator of low harmonic content as source, and a shielded resistance capacitance Wien bridge, with 3-stage amplifier and d-c galvanometer as detector. The frequency range was from 60 to 40,000 cycles. The sensitivity was such that at 1,000 cycles and 70 volts bridge input, a difference of capacitance of 0.1 μμf in 800 μμf could be detected.

2. *Phase Difference and Capacitance at 60 Cycles.* These were made with a high sensitivity Schering bridge with a-c galvanometer detector. The construction of the bridge, its operating characteristics and its sensitivity have been described in an earlier paper.[4] It has a capacitance sensitivity almost as great as that of the Wien bridge and a sensitivity for phase difference that is amply high (0.000005 power factor). As source, a 5-kva sine-wave generator was used.

3. *Dielectric Absorption.* A combination of amplifier and electromagnetic oscillograph with auxiliary rapid tripping circuit was used for the measurement of short time continuous current charge and discharge current curves.[6,8] The maximum sensitivity of this instrument is about 1.7×10^{-8} amp per millimeter deflection. It records a charge or discharge curve beginning 1 millisecond after the application of voltage or short circuit. As shown by Whitehead and Banos,[7] these curves may be used by the method of von Schweidler for the accurate computation of a-c loss and phase difference and the component of capacitance due to dielectric absorption.

4. *Long-Time Conductivity.* For charge and discharge current under continuous potential beyond 15 sec, a high sensitivity (3×10^{-13} amp per millimeter deflection) d'Arsonval galvanometer was used. Readings of final steady state current usually were taken after from 40 min to 1 hr.

The following properties of the dielectric sample are obtained from the foregoing measurements: (*a*) capacitance, dielectric constant, and phase difference at 60 cycles; (*b*) the geometric capacitance and the geometric dielectric constant; (*c*) the component of phase difference due to absorption; (*d*) the component of phase difference due to conduction; (*e*) the component of capacitance due to absorption; (*f*) the relaxation time of the dielectric; and (*g*) the steady state conductivity.

A general view of the results of progressive drying is shown in Fig. 1. Two series of curves are shown, one giving the variation of capacitance, the other that of phase difference at 60 cycles. As may be seen, these quantities change rapidly in the first stage (100 deg C at atmospheric pressure) because of the evaporation of moisture under temperature elevation only.[8] At the end of about 50 hr, the curves flatten out and reach approximately constant values. The succeeding steps of diminishing pressure all show initial decreases in both quantities, always leveling off into equilibrium. The final state of dryness studied was at a pressure of 0.25 mm of mercury; it may be seen that the phase difference and capacitance show no variation after 40 hr. The value of phase difference reached is extremely small. In this final condition some moisture is still present in the form of thin films or adsorbed layers, as is evidenced by the presence of dielectric absorption and loss. Further reduction of evacuation pressure undoubtedly would result in further reductions in phase difference and capacitance. However, it may be seen that the final values at each pressure are approaching approximately constant values. These final values, as shown later in the paper, may be deduced readily from the forms of the curves, and they permit the computation of the actual amount of water present at each state of dryness. The experimental points indicated by solid circles have been taken as representing the steady state as to moisture content, and the corresponding values have been used in the computations.

In Fig. 2 is shown the phase difference and in Fig. 3 the apparent capacitance at 60 cycles, each as function of the evacuation pressure. The capacitance frequency relation at various evacuation pressures is shown in Fig. 4. It should be noticed that the range up to 40,000 cycles is amply sufficient to determine the geometric capacitance at each pressure. In Fig. 5 is given the d-c discharge current in the interval 1 millisecond to 12 milliseconds for each evacuation pressure. These curves have been replotted from the corresponding oscillograms of which Fig. 6 shows a typical example. Even at the lowest pressure dielectric absorption is still present.

Discussion of Results

D-C A-C Correlation. Using the von Schweidler method, the curves of Fig. 5 may be used for computing the dielectric loss, the components of phase difference and of capacitance due to dielectric absorption, and the component of loss due to conduction, under alternating stress. The computations were made and the results compared with a-c measurements. Table I shows the results of this comparison. There is excellent agreement between computed and measured a-c values. Column 2 shows the phase difference as measured at 60 cycles, columns 3 and 4 the computed values due to absorption and conduction, respectively, and column 5 their sum. The agreement between columns 5 and 2 is well within the experimental error. Column 6 gives the capacitance at 60 cycles and column 7, the geometric capacitance determined by extrapolation to infinite frequency of the values given in Fig. 4. The differences between these 2 columns is given in column 8, which thus represents the component of capacitance arising in dielectric absorption. Column 9 gives the component of capacitance due to absorption as computed from the d-c discharge curve. Excellent agreement is seen also between columns 8 and 9.

Analysis of Phase Difference. The progressive variation of the separate components of the over-all phase difference at each pressure is shown in Fig. 7. The height of each block is the measured power factor at 60 cycles and its several components as measured and as computed are given on the same scale. At the left the phase difference in the driest condition is shown; it is very small and is accounted for entirely by dielectric absorption. No measurable short time conduction exists, and the long time conductivity is extremely small (2.0×10^{-17} mho per cm^3). The next block to the right represents a condition of slightly increased residual moisture. The original absorption has been increased by a small amount and a new component due to measurable conductivity has appeared. With further increase of moisture both absorption and conduction components increase, the rate of increase of the conduction being very rapid in the regions of higher residual moisture.

Analysis of Capacitance. The 60-cycle and geometric capacitances, each as function of the drying pressure, are shown in Fig. 8. Each decreases rapidly with pressure in the upper range, but below 10 mm, a linear relation to the logarithm of the pressure is indicated. The insert shows the lower pressure range with both coördinates linear and with extrapolated extensions (see later paragraphs.)

The excess of the 60-cycle capacitance over the geometric capacitance is attributed to dielectric absorption. (See Table I for agreement between computed and measured values.) The decrease in both geometric and 60-cycle capacitances with decreasing drying pressure results from the decrease in residual moisture. It has long been known that the further elimination of moisture reduces both conductivity and dielectric absorption in insulating materials. Figure 7 shows that at a pressure of 1.0 mm of mercury conduction practically has disappeared and the absorption component is very small. Conduction is not measurable at a pressure of 0.25 mm although absorption is still present. Figure 8 shows a corresponding decrease in the geometric capacitance which is simply because more and more moisture, with its high dielectric constant, is being withdrawn. The geometric capacitance containing no absorption component is a composite value due to a mixture of 3 substances, fiber, air, and moisture, their dielectric constants, and their volumetric proportions and arrangement. Were it possible completely to remove all moisture, the paper would show no absorption, zero power factor, and 60-cycle capacitance equal to the geometric value. The pure cellulose air structure would show no anomalies, but only the property of dielectric constant. Up to this time, however, it has not been found possible to remove *all* the moisture and so reach this ideal condition.

Computation of Moisture Content. The nature of the mechanism by which moisture causes dielectric absorption is not known. Conducting filaments or layers would suggest the mixture theory of Maxwell. Murphy and Lowry and P. Böning have presented pictures of the adsorption of layers of moisture on the capillary walls of the cellulose tissue; this picture makes a stronger appeal in the advanced stages of dryness of the present studies. Obviously, with more moisture present and with possible traces of impurities, it is possible to picture limited conducting paths increasing both conduction and absorption components more in accordance with the Maxwell picture. In the present studies, the treatment at a pressure of 0.25 mm of mercury represents the best condition of dryness obtained. It is evident that some absorption is still present with components of power factor and of capacitance due to absorption, these components being a function of the amount of moisture present.

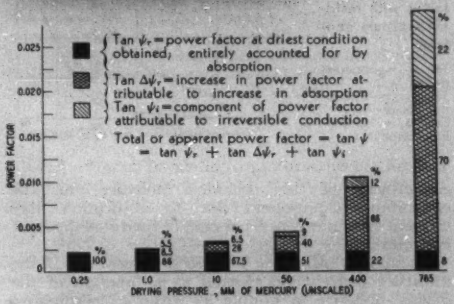
Table I—Analysis of Power Factor and Capacitance of Paper Samples Versus Drying Pressure

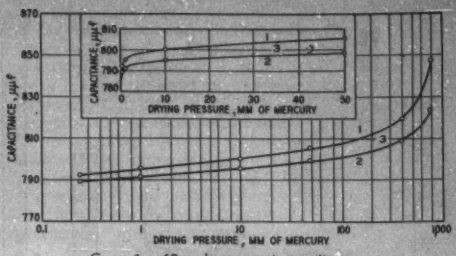
1	2	3	4	5	6	7	8	9
	Power Factor				Capacitance, $\mu\mu f$			
	60-Cycle	D-C Short-Time Analysis						
Pressure, In. of Mercury	Bridge Measurement	Absorption	Conduction	Abs. + Cond.	60-Cycle Bridge Measurements C	Geometric Capacitance (∞ frequency) C∞	Absorption Capacitance C − C∞ or ΔCr	D-C Analysis Absorption Capacitance ΔCr
0.25	0.002255	0.00221		0.00221	791.5	788.5	3.0	2.9
1.0	0.002599	0.00245	0.000233	0.002685	795.3	791.7	3.6	3.43
10.0	0.003314	0.003114	0.000254	0.003370	800.0	795.1	4.9	4.3
50.0	0.004394	0.0040	0.000483	0.004495	805.5	799.6	5.9	5.01
400.0	0.01021	0.00938	0.000906	0.010296	819.0	808.5	10.5	10.6
765.0	0.02865	0.02045	0.00930	0.02995	847.0	823.1	23.9	23.1

Fig. 6. Typical d-c charge and discharge current oscillograms of a well dried paper specimen

Fig. 8 (right). Variation of components of capacitance with drying pressure

Fig. 7 (below). Analysis of power factor at various stages of dryness





Curve 1. 60-cycle apparent capacitance
Curve 2. 40,000-cycle capacitance (equivalent to geometric capacitance)
3. Component of capacitance attributable to absorption

From Fig. 8 it may be seen that both apparent (i. e., measured) and geometric capacitance decrease continually with decreasing pressure. The former decreases more rapidly. The point of intersection of the 2 curves if obtainable would mark the condition of zero absorption component of capacitance, and presumably of zero moisture content; conductivity has disappeared at much higher pressures, and at this point absorption also disappears. The apparent and geometric capacitances have the same value, which is that of the perfectly dry paper fiber plus air. If this value is known, the moisture content at various pressures can be computed and other interesting deductions may be made, all as based upon the electrical measurements.

The semilogarithmic curves of Fig. 8 invite extrapolation for the determination of their point of intersection. They have approximately zero curvature below 10-mm pressure, thus permitting a high degree of accuracy in graphical extrapolation. The 2 curves so extended must intersect in the neighborhood of 10^{-4} mm pressure and 780 μμf capacitance. The point of intersection also was determined by well-known methods of analytical geometry using the slopes of the curves at 1-mm and 0.25-mm pressures. This computation gave a value of 780.6 μμf for the capacitance at the point of intersection. As a further check, the values of ΔC, (the component of capacitance due to absorption, i. e., the difference between the ordinates of the 2 curves of Fig. 8) were plotted against the pressure and the curve extrapolated to zero capacitance. The curve is accurately exponential below 60-mm pressure and indicates zero value for ΔC, at a pressure of 9.5×10^{-5} mm of mercury, corresponding closely with that determined by the first method.

The insert in Fig. 8 shows the capacitance-pressure relations in the lower range as plotted in linear coordinates. The experimental points at 0.25-mm and 1.0-mm pressures are shown, those at higher pressures not appearing. It may be seen that below 1.0 mm the curve begins a definite change of curvature downward. The fact that this change takes place in accordance with the uniform decrease of curvature of the semilogarithmic curve, is strong indication that the law of the change continues to lower pressures and that the values obtained from the extrapolation are closely accurate. In the insert the experimental curves have been continued below 0.25-mm pressure to intersections at 780 μμf and in the neighborhood of zero pressure. The mean of the 2 extrapolated values of the capacitance of the moisture-free paper is 780.3 μμf, and this is the value used in computing the moisture content of the paper at various pressures.

Knowing the value of the capacitance of dry fiber plus air, it is possible to compute also the probable minimum moisture content of the specimen in per cent of the total volume for each drying pressure under equilibrium conditions. This value is given by

$$M = 100 \frac{C_m - C_g}{K_w - 1} \cdot \frac{K_m}{C_m}$$

where

M = minimum moisture content in per cent of total volume
C_m = geometric capacitance of paper sample as measured
K_m = geometric dielectric constant of paper sample corresponding to C_m
C_g = geometric capacitance of dry fiber and air (taken as 780.3 μμf)
K_w = geometrical dielectric constant of water

The question of the dielectric constant of water, K_w, arises. A review of the literature[9,10,11] as related to temperature and the thin layer state, has led to the selection of a value of 48 as most probable for the conditions of this study. In this manner, the moisture content in per cent of total volume of the specimen as between electrodes was computed

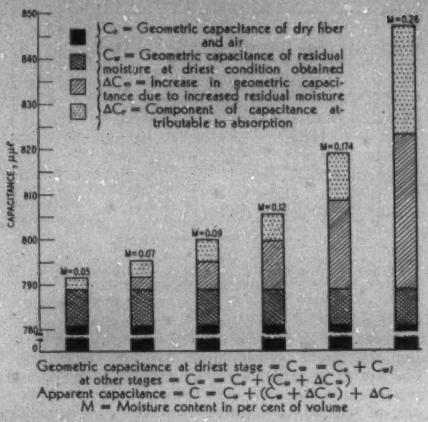


Fig. 10. Residual moisture content as a function of drying pressure

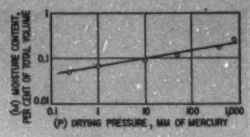


Fig. 9 (left). Analysis of capacitance at various stages of dryness

Fig. 11. Variation of components of power factor with residual moisture content

Tan ψ = apparent power factor
Tan ψ_r = absorption component
Tan ψ_c = conduction component

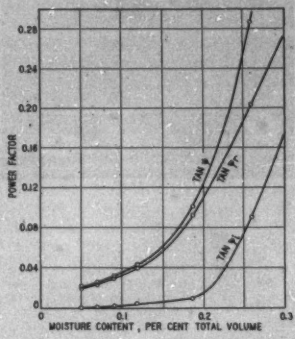


Table II—Data on Computation of Minimum Moisture Content

P Mm Hg	C_m μμf	K_m	K_w	C_o μμf	M Per Cent
0.25	788.6	2.375	48	780.3	0.05
1.0	791.7	2.382	48	780.3	0.07
10.0	795.1	2.395	48	780.3	0.09
50.0	799.6	2.406	48	780.3	0.12
400.0	808.5	2.435	48	780.3	0.175
765.0	823.1	2.478	48	780.3	0.26

P = drying pressure in millimeters of mercury
C_m = total geometric capacitance of composite paper
K_m = geometric dielectric constant of composite paper (corresponding to C_m)
K_w = dielectric constant of adsorbed water
C_o = geometric capacitance of dry fiber-air structure
M = minimum moisture content in per cent of total volume

for each state of drying pressure. Table II shows the values of the various components of the apparent capacitance and the resulting computed residual moisture in per cent of specimen volume. It may be seen that the range of moisture content was very narrow; the ratio between atmospheric pressure and 0.25 mm of mercury, both at 100 deg C, is about 5 to 1. (Also see Fig. 10.)

Influence of Residual Moisture on Capacitance. Analysis of the apparent capacitance of the paper at 60 cycles for different conditions of dryness is shown in Fig. 9. Starting with the driest condition the apparent capacitance is made up of 3 components. The solid portion is the geometric capacitance of the fiber and air alone computed from the results of Fig. 8 as already described. The cross-hatched portion is the geometric capacitance of the residual moisture in the driest condition studied. The hatched portion is the addition to the geometric capacitance brought about by increased residual moisture. The dotted portion is the component of the capacitance arising in dielectric absorption, that is, due to the polarizing properties of the adsorbed layers of residual moisture. In all cases the total capacitance of the paper is made up almost entirely of the composite fiber and air. However, it may be seen that for 0.26-per cent moisture content, the geometric capacitance of this occluded moisture plus the capacitance component due to absorption may amount to as much as 8 per cent of the total apparent capacitance.

Relation of Moisture Content to Pressure. If the moisture content be plotted as a function of the drying pressure in double logarithmic coördinates, the result is a straight line, as shown in Fig. 10. Accordingly, the moisture content, as function of the drying pressure, may be expressed as $M = KP^n$, where M is the moisture content, P the drying pressure, and K and n constants. If M be expressed in per cent of total volume and P in mm of mercury, $M = 0.068P^{1/6}$; it should be remembered that this relation holds only for the constant drying temperature of 100 deg C and with final steady conditions under the various values of pressure. No obvious reason has suggested itself for the apparently simple relation here found.

Power Factor Moisture Relation. Variation of the power factor with moisture content is shown in Fig. 11. The absorption component increases rapidly, and so also does the conduction component beyond 0.18-per cent moisture content. The apparent power factor is thus very sensitive to slight residual moisture changes, and particularly so at the higher values. Taking into account the whole range studied, there is an increase of 15 times in power factor as against a corresponding increase of 5 times in residual moisture content. Absorption contributes the greater proportion of this increase.

In Figs. 12 and 13, the power factor and its components are plotted as functions of the residual moisture in semilogarithmic coördinates. It is interesting to note that both the total power factor and the absorption component of the power factor vary in exponential relation to the moisture con-

tent, and so the variation for each may be expressed by the equation $\tan \psi = Ke^{\alpha M}$ where $\tan \psi$ is the power factor, M the per cent of moisture content, and K and α constants. The component of power factor due to conduction appears to follow a similar relation for small values of moisture, but departs therefrom above 0.2-per cent moisture content.

Capacitance-Moisture Relation. In Fig. 14 the apparent capacitance with its several components are plotted against moisture content in semilogarithmic coördinates. Curve C gives the total capacitance as measured at 60 cycles. Curve C_o gives the geometric capacitance of the composite pure fiber plus air, which obviously does not vary with moisture content. The geometric capacitance of the occluded moisture is shown in curve C_w, and the component of capacitance due to dielectric absorption in curve ΔC_r. The geometric capacitance of the residual moisture is obviously a simple linear function of the moisture content. However, it may be seen that the component due to absorption, like that of the corresponding component of power factor, follows an exponential relation to the moisture content as shown by $\Delta C_r = Ce^{bM}$.

Theoretical Discussion

If an attempt be made to picture the mechanism by which the absorption of moisture affects the phenomena of absorption and conduction, the procedure might be somewhat as follows: When entirely free of moisture and soluble impurities, the paper consists of a structure of pure cellulose with interspersed air spaces, this structure being free under electric stress from both conduction and energy loss. Electrically, the paper then shows only the property of dielectric constant, which should vary only in the classical Clausius-Mosotti manner. The addition of water naturally introduces ionic conduction. For relatively small moisture content the moisture probably exists in the form of adsorbed layers over the fiber structure and possibly in capillary channels. Few if any continuous ionic paths exist that are continuous through the insulation wall, and conduction, if present at all, must be very small. However, in accordance with the mechanism of an adsorbed ionic system, as set forth by Polyani, Gouy, and Eucken and extended to the dielectric case by Murphy and Lowry, the dielectric now shows the phenomenon of dielectric absorption with consequent absorption of energy under alternating stress. The picture here is that the adsorbed ions either move in limited paths or undergo elastic displacement under the action of the field. Obviously, the phenomena might be explained equally well in accordance with the Maxwell picture of a dielectric, made up of components having different values of conductivity and dielectric constant. In either event an equivalent resistance-capacitance picture, as proposed by Murphy and Lowry,[12] may be set up, representing the over-all behavior of the dielectric. For small values of moisture, conduction is absent or negligible, and dielectric loss is entirely due to reversible dielectric absorption. Increased residual moisture increases the geometric capacitance and also changes the form of the relaxation function characteristic of reversible absorption. The nature of this change is the addition of a slow decaying element of reversible absorption, due to increased thickness of adsorbed water films. Furthermore, increased residual moisture soon increases the number of through ionic paths from electrode to electrode, and so causes a measurable value of irreversible conduction current under continuous potential. This component of the current increases very rapidly with further addition of moisture, and for moisture contents of more than 0.5 to 1 per cent it may predominate over the other elements of the observed loss.

It is surprising to find the simple relationships between moisture content and electrical properties indicated in this study. While as yet no obvious

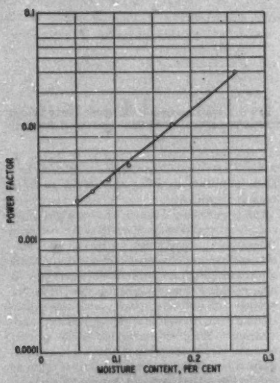


Fig. 12. Apparent power factor versus moisture content

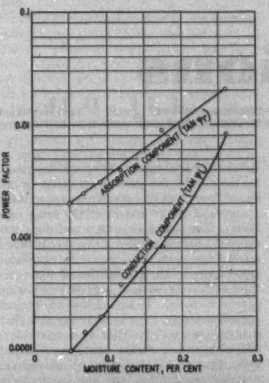


Fig. 13. Components of power factor versus moisture content

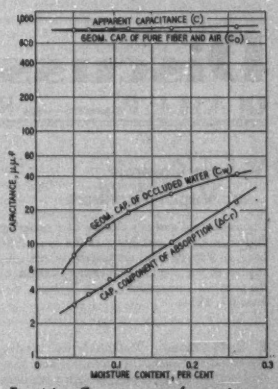


Fig. 14. Components of capacitance versus moisture content

explanations have suggested themselves, these simple relationships seem to indicate clearly that the phenomenon of adsorption of moisture by the fibrous materials commonly used in insulation is much more regular than heretofore supposed.

In these studies and in others conducted in the electrical engineering laboratory at The Johns Hopkins University in this field, the aim has been to determine the ultimate basic electrical properties of impregnated paper insulation without special reference to the question of whether full utilization can be made of these properties under various limitations imposed by the methods of manufacture for the cable trade. Obviously, it is important to know these ultimate properties if the value attaching to possible alterations or improvements in the methods of manufacture are to be ascertained. The results of the studies reported in this paper seem to bear more directly than usual upon methods of manufacture, since they give information as to the amount of moisture contained in a standard grade of wood pulp paper. It is found, for example, that at 100 deg C and 10-mm, 1-mm, and 0.25-mm (of mercury) pressures, the moisture contents of the paper are 0.09, 0.07, 0.05 per cent by volume, respectively. The reduction of moisture by decreasing the pressure is very much less rapid in the lower than in the upper ranges. Obviously, still further reduction of moisture may be accomplished by elevation to higher temperatures. It commonly is understood, however, that at any temperature the paper itself will stand without destruction, it still will retain a certain proportion of moisture.

In an earlier paper the influence of the original conducting properties of various impregnating oils on the electrical properties of the impregnated product have been traced. It was shown that by far the larger component of the dielectric losses is due to the paper. A reduction of these losses therefore would be reflected as a reduction in the total losses for any type of impregnating oil. Furthermore, an intimate relationship has been shown to exist between the properties of the oil and the dielectric strength and probable life of the impregnated insulation.[12] It appears very probable that these relationships must be dependent on the amount of moisture originally in the paper. It may be well to repeat that all statements as to electrical properties, dielectric strength, and life of insulation, as made in these papers, refer to the inherent properties of impregnated paper and assume complete impregnation and the absence of gas voids such as commonly cause a rise in the power factor-voltage curve.

References

1. The Dielectric Losses in Impregnated Paper, J. B. Whitehead. A.I.E.E. Trans., v. 52, 1933, p. 657–81.

2. Fundamental Properties of Impregnated Paper, J. B. Whitehead and W. B. Kouwenhoven. A.I.E.E. Trans., v. 50, 1931, p. 690–704.

3. Half Degree Temperature Control, W. B. Kouwenhoven and S. K. Waldorf. *Elec. World*, v. 95, 1930, p. 1214–17.

4. A High Sensitivity Power Factor Bridge, W. B. Kouwenhoven and A. Banos, Jr. A.I.E.E. Trans., v. 52, 1932, p. 202–10.

5. An Amplifier to Adapt the Oscillograph to Low Current Investigations, S. K. Waldorf. A.I.E.E. Trans., v. 47, 1928, p. 1418–24.

6. Oscillographic Measurements, S. K. Waldorf. *Jl.* Franklin Inst., v. 213, 1932, p. 605–22.

7. Predetermination of the A-C Characteristics of Dielectrics, J. B. Whitehead and A. Banos, Jr. A.I.E.E. Trans., v. 51, 1932, p. 392–403.

8. Influence of Residual Air and Moisture in Impregnated Paper Insulation, J. B. Whitehead and F. Hamburger, Jr. A.I.E.E. Trans., v. 47, 1928, p. 314–33; p. 826–36.

9. Physical Phenomena at Interfaces With Special Reference to Molecular Orientation. *Trans.*, Faraday Soc., v. 22, 1926, p. 434–71.

10. International Critical Tables, v. 5.

11. Dielektrizitatskonstanten Guter Leiter, Reinhold Furth. *Physik. Zeit.*, v. 25, 1924, p. 676–9.

12. The Complex Nature of Dielectric Absorption and Dielectric Loss, E. J. Murphy and H. H. Lowry. *Jl. Phys. Chem.*, v. 34, 1930, p. 598–630.

13. The Life of Impregnated Paper, J. B. Whitehead. Elec. Engg., v. 53, 1934, p. 244–51.

Discussions

Of A.I.E.E. Papers—as Recommended for Publication by Technical Committees

Voltage Control of Vapor Rectifiers

Discussion and author's closure of a paper by Didier Journeaux published in the June 1934 issue, p. 976–88, and presented for oral discussion at the electrical machinery session of the summer convention, Hot Springs, Va., June 27, 1934.

R. E. Hellmund: The analytical studies presented by Messrs. Journeaux and Herskind in their papers on controlled rectifiers appear to be quite timely. In a discussion presented at the last summer convention, I pointed out that of the various electronic devices the pool-type rectifier and its modifications hold the greatest promise in all future applications involving appreciable amounts of power and especially large currents. The papers presented and the great amount of work evidenced by the material given seem to indicate increasing appreciation of the future possibilities of the pool-type device for various purposes requiring control features. In saying that the papers are quite timely, I do so with the idea that it is the engineer's function to concern himself with and to vision future possibilities even though the chances of immediate practical application are not particularly good. However, since it is also the engineer's function to study the economic aspects as applying to the immediate future, a brief review of the various devices and their applications from this point of view may be justified.

As is generally known, the straight mercury-pool rectifier is already with us as a thoroughly practicable, reliable, and economically competitive device for converting alternating current into direct current. It has occupied this position for some time for voltages of 600 and above, and more particularly in its application to railway substations. With the progress made during recent years in lowering the losses in the rectifier through refinements in design, such as the sectionalized construction and the use of the igniter principle, the way has been paved for extending the economical application of rectifiers to lower voltages such as

encountered in electrochemical work and possibly lower voltage d-c systems.

As pointed out in the 2 papers, the addition of the grid control or similar arrangements for the purpose of voltage control brings with it problems relating to power factor and interference, and the greater the range of voltage regulation the more troublesome these problems become. Various technical means are known or can be devised for taking care of these problems. One of the papers suggests a combined transformer tap and grid control to improve the power factor when large voltage variations are required. In a patent issued January 15, 1924 (No. 1,480,722), I suggested the use of a synchronous machine floating across the a-c terminals for the combined purpose of power-factor correction and interference elimination. Static condensers and stationary filtering equipment also can be used for these purposes. Another possibility has been brought out in Mr. Ludwig's discussion. All of this, however, means extra expense and complications, and in a great many cases where wider ranges of voltage regulation are required it results in conditions making the application of the rectifier uneconomical and noncompetitive with other means accomplishing similar results. On the other hand, the controlled rectifier may find fairly extensive application in some special fields where there are no competitive devices accomplishing the same results; the most outstanding example of this is the use of the ignitron in connection with spot and seam welding in cases where the mechanical control of the welder does not work out satisfactorily.

The prospects of extensive early application of the mercury-pool device as inverter or frequency changer, or of combinations of these devices and rectifiers seem to be even less promising. While the papers make little mention of experimental work along these latter lines, such work is being carried on in various places, and, as a matter of fact, inverters of the ignitron type have been very successfully operated over extended periods in connection with adjustable-speed motors at the Westinghouse laboratories in East Pittsburgh. However, this fact in itself, while demonstrating the workability of such schemes, does not prove that they are justified economically under present conditions. This question can be answered only by a study of the various possibilities of their application in comparison with other means for accomplishing the same results.

A good deal of attention has, for instance, been given at various times to the use of rectifiers and inverters for d-c power transmission. However, very careful and extensive studies of the economics of transmission indicate that d-c transmission of the type mentioned shows economic possibilities only in special cases where considerable amounts of power have to be transmitted over very long distances, or perhaps in a few cases where extensive use of cables has to be made in power transmission. Applications of the latter kind are exceedingly rare and limited to a few metropolitan districts. In water power projects involving large amounts of power and long distance transmission, it is very common that the sources of the water power are distributed over different localities, and in addition there are usually many points of power utilization. In these projects the number of rectifier and inverter stations and their incident cost is so great that the use of direct current cannot compete with the ordinary a-c systems at the present stage of the art.

Another application of rectifiers or inverters, or both, which has received considerable attention over an extended period of time is that of speed control of motors, outstanding among these being the application to railway work. Ever since the first experimental operation of rectifiers on a motor car of the New York, New Haven, and Hartford Railroad over 20 years ago, numerous rectifier and inverter schemes have been discussed in technical literature and considerable progress in the improvement of these schemes has been made. However, during the same period other types of apparatus for railway work, as, for instance, the single-phase commutator motor, also have been continuously and appreciably improved. As a consequence, arrangements with electronic devices have not during this entire period reached the point where they could compete with other possibilities for operating cars or locomotives.

The same might be said of motor applications in industry. While the problem of devising adjustable-speed motors has been before electrical engineers ever since the more general use of alternating current, and though the use of electronic devices for this purpose has been given repeated consideration and study, they are still not quite competitive with other solutions of the problem. Furthermore, the total number of adjustable-speed motor applications in industry for which the mercury-pool rectifier could be considered is after all not very great, and because of this rather small total demand and the various competitive schemes able to fill a large part of such demand, the use of the mercury-pool device for motor control in industry undoubtedly will be limited to a few very special cases for a long time to come.

Electronic devices have also been considered in connection with ship propulsion, and here again it would seem that their use can hardly be justified economically except perhaps in very special cases.

One of the papers makes mention of a need for inverter operation of substations for d-c railways, and of course a similar condition may be met in large d-c operated buildings where there may be occasional inverse power from the operation of elevators. It is quite evident that the regenerative arrangements discussed in Mr. Herskind's paper entail appreciable complication and expense. Since the amount of regenerated power in both of the applications mentioned is usually of small magnitude and occurring only for short periods, it probably can be taken care of to best advantage by dissipating the power in a resistance or by the use of batteries in the case of a building. With railways operating induction machines on locomotives, it is common practice to use resistances for dissipating regenerative energy. For this reason I do not believe that early use will be made of inverter operation either in railway substations or in large buildings.

From the previous discussion of the specific application possibilities, it seems quite evident that for some years to come there will be very little practical application of the mercury-pool device for anything except rectification. This, however, should not be surprising, because it is quite common that considerable time elapses between the conception of certain ideas and their practical and economical application. An illustration of this is the mercury-arc rectifier itself, the more general application of which has been very slow in materializing; it is only now, more than 20 years after the first field trials of rectifiers, that its application to lower voltages is becoming economical for larger amounts of energy.

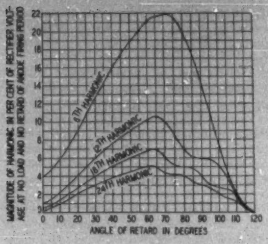
Nevertheless, the practical and operating engineer undoubtedly wishes to keep informed on developments such as described in the papers because some of them may become of practical importance in the future. The immediate interest of the operating engineer should, however, be directed toward expanding the applications of the rectifier which are now becoming economical, such as low-voltage applications and some special applications to welding and similar processes. This will greatly assist further progress because it will lead toward reduced costs and further perfection in performance of the mercury-pool device and its various auxiliaries. These factors in turn are the principal prerequisites for extending the economically justified applications of the devices and therefore should command the principal attention of both the operators and the manufacturers.

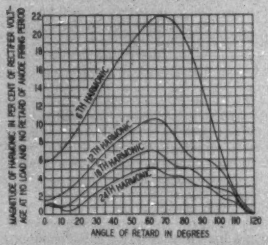
It should be appreciated in this connection that it is difficult for new devices, even though they possess inherent merits, to compete with older devices which have had the benefit of many years of development and continuous improvement. The rectifier art is still new and we are still far from the fundamental limits of size, cost, and efficiency—all factors of determining importance in economic considerations. Therefore, if more extensive use of rectifiers where they are now competitive paves the way for improvements of these various factors, some projects which are now uneconomical will become justified in the future.

F. O. Stebbins: In Figs. 10, 11, and 12 of this paper the author presents some excellent curves showing the relations between the 3 lower orders of harmonics present in the output voltage of grid controlled recti-

Discussions in This Issue

On these and the following 25 pages appear discussions of technical papers presented during the sessions on electrical machinery and education of the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. All discussions received in complete and acceptable form at Institute headquarters within 2 weeks after the convention, and subsequently reviewed by the technical committees and recommended for publication, are included. Authors' closures, where they have been submitted, will be found at the ends of the discussions on their respective papers.





Figs. 1 (top) and 2 (bottom). Curves showing the 4 lower orders of harmonics for a 6-phase controlled rectifier: (1) at light load supplying a noninductive d-c load; (2) at approximately full load supplying a noninductive d-c load

fiers and the d-c load as represented by the factor KX_w when the d-c load is highly inductive and the angle of retard is small. He does not attempt to discuss these same harmonics when the d-c load is noninductive, and the following discussion of output voltage wave shape will be confined to this type of load.

The continuous voltage wave shape depends upon the angle of retard and the angle of overlap. In a given rectifier developing a constant value of continuous voltage the angles of retard and overlap will be different when the d-c load is highly inductive than when the d-c load is noninductive. The output voltage wave shape and magnitudes of harmonics will therefore be different for these 2 cases.

If P' represents the total number of transformer secondary phases, it can be shown that for noninductive d-c loads when the angle of retard is greater than $\frac{\pi}{2} - \frac{\pi}{P'}$, there is no overlapping and the angle of overlap is zero. For 6 phase and 12 phase rectifiers the values of $\frac{\pi}{2} - \frac{\pi}{P'}$, are 60 and 75 deg, respectively.

If it is assumed that during commutation the load current is flat, but that at all other times it is proportional to the continuous voltage, formulas for the angles of retard and of overlap can be developed in terms of the continuous load current which are approximately correct. By substituting these values of retard and overlap in formulas 26 and 27 of the paper, the magnitudes of the harmonics in the continuous voltage can be calculated for rectifiers with and without interphase transformers when the angle of retard is less than $\frac{\pi}{2} - \frac{\pi}{P'}$.

For rectifiers without interphase transformers and angles of retard greater than $\frac{\pi}{2} - \frac{\pi}{P'}$, a new analysis of the output voltage must be made in order to calculate the wave shape. For rectifiers with interphase transformers there is considerable difference of opinion as to just what takes place when the angle of retard is greater than $\frac{\pi}{2} - \frac{\pi}{P'}$. The author presents a clear and concise description of this phenomenon in a 6-phase rectifier with interphase transformer when certain conditions are assumed. It is my belief, however, that the author's assumptions regarding the behavior of the interphase transformer do not hold true in al' cases. Does the author have experimental evidence which justifies his assumptions? For rectifiers having interphase transformers my discussion is confined to the output voltage wave shape obtained with angles of retard less than $\frac{\pi}{2} - \frac{\pi}{P'}$.

Figures 1 and 2 of this discussion show the 4 lower orders of harmonics present in the output voltage at light load and approximate full load for a particular 6-phase rectifier without interphase transformer. These 2 figures also apply to a particular 6-phase rectifier with interphase transformer for angles of retard of less than $\frac{\pi}{2} - \frac{\pi}{P'}$, or 60 deg.

C. W. Frick: One of the features of the controlled-voltage rectifier which is of interest is the wave shape of the output voltage. Figures 10, 11, and 12 of the paper give the percentage values of the 6th, 12th, and 18th harmonics when the angle of delay X_0 and the factor KX_W are known. Equations 15 and 17 show that the factor KX_W is equal to $\frac{IX}{E\sqrt{2}\sin\frac{\pi}{p}}$ which in many cases may be easier to evaluate than X_W. It also shows that the abscissas of the curves are proportional to the load in any given set-up. It may be of interest to show how to evaluate the expression $\frac{IX}{E\sqrt{2}\sin\frac{\pi}{p}}$ when there are interphase transformers. Since commutation then takes place between anodes in the same group, I must be taken as the load direct current in each group and p the number of phases in the group. The proper value of commutating reactance for the connection considered must be used. For the benefit of those who wish to evaluate X_W from the circuit constants, it is suggested that the author give definitions of I_p, E_p and X_p. These definitions are needed to determine the factor K for any particular connection. The paper gives a value of K for "the 12-phase interphase transformer connection." Twelve-phase operation can be obtained with several arrangements of interphase transformers, for instance 4 groups of 3 phases or 2 groups of 6 phases. The connection or connections to which the given value of K applies should be stated.

The curves show values of the harmonics plotted against the factor KX_W for various values of the angle of delay, also called the angle of retard. Generally it is the output voltage obtained by grid control rather than the angle of delay which is of interest. In order to use the curves when the output voltage is given it is necessary to refer to equations in the paper to obtain the angle of delay. By making use of the relation between the output voltage, angle of delay, and the factor $\frac{IX}{E\sqrt{2}\sin\frac{\pi}{p}}$ the values of the harmonics can be plotted against the last factor for various values of output voltage as a percentage of the output voltage without grid control. These curves make it unnecessary to calculate either the angle of delay or the angle of overlap. A set of curves for the 6th, 12th, 18th, and 24th harmonics has been incorporated in a paper by F. O. Stebbins and myself, which has been accepted by the A.I.E.E. for publication. (September 1934 issue, p. 1259–65.)

The author suggests that the 6th and 18th harmonics which are theoretically zero in the 12-phase rectifier but are actually present in small amounts may vary in accordance with the curves on Figs. 10 and 12, read with larger scales of ordinates. This assumption does not seem justifiable in all cases. There are several causes besides unequal division of load between 2 sets of 6 phases which may cause these harmonics to appear in the 12-phase rectifier. In some cases the cause may be the presence of corresponding odd harmonics in the voltage on the a-c side and the 6th or 18th harmonic on the d-c side should be practically constant provided the a-c voltage wave shape remains the same.

The example chosen to illustrate the TIF (telephone interference factor) shows principally the effect of grid control at light load. It does not show the effect of adjusting the voltage at normal load by grid control. It would be of interest if the author also would show in the same example the TIF obtained when the voltage at normal load is adjusted 5 per cent with grid control. The formula (eq 35) for the TIF when the voltage is not regulated does not include the effects on the output voltage of arc drop and losses in the rectifier transformer, although these effects were allowed for in calculating the TIF with regulated voltage. This has only a small effect on the TIF values in the example considered. It appears that X_W is expressed decimally when used in eq 35 although eq 16 gives it as a percentage.

C. C. Herskind: Mr. Journeaux's paper presents a very thorough analysis of the characteristics of the mercury arc rectifier when operating with grid control. It covers the operation of the rectifier with inductive, resistive, and counter emf loads. The curves of Fig. 5 showing the output voltage wave shapes as the voltage is reduced by retarding the grids should be particularly noted, as they give an excellent physical conception of the effect of grid control upon the rectifier characteristics. The only thing Mr. Journeaux appears to have omitted is the difficult subject of harmonics on the a-c side of the rectifier.

In connection with the voltage regulation

characteristics shown in Fig. 9 of the paper, I wish to point out that these curves, as well as similar curves in the writer's own paper, apply only as long as the commutation period is so short that one commutation is completed before the next one is begun. For example, if the commutation period in a 6-phase diametrical circuit is so long that 2 anodes fire all the time, then the output voltage will be less than that shown by the regulation curves. This condition arises only at the higher overloads in the usual rectifier.

I wish to call attention to the load scale used in plotting the regulation curves and harmonic components of the output voltage. This load factor is denoted by the symbol KX_W where K is a coefficient whose value depends upon the type of circuit and X_W is the working reactance. The value of this factor is the same as that of the load factor IX used in the writer's own paper if the latter factor E_0 is multiplied by $\frac{1}{\sin\frac{\pi}{p}}$.

The use of these load factors facilitates comparison of the different circuits. Of these 2 factors, the form $\frac{IX}{E_0}$ seems to be more desirable as it is more generally applicable, does not involve the calculation of the factor K, and gives a better physical conception of the relations involved.

The factor K cannot be calculated directly for all connections by substitution in the formula given in the paper (eq 18). Also, it does not indicate the relative effect of primary line reactance and commutating reactance. The effect of primary reactance depends upon the type of connection, for example, in the 6-phase diametric connection the commutating reactance is equal to the phase reactance, in the 6-phase forked connection the commutating reactance is $^1/_3$ of the phase reactance, and in other circuits different ratios are obtained.

When the load factor KX_W is used, the variation in load current is represented as a variation in working reactance. In an actual circuit the reactance remains constant while the current varies. This is represented physically if the load factor $\frac{IX}{E_0}$ is used. In some cases involving the solution of circuits containing capacitance as well as inductance the factor $\frac{IX}{E_0}$ has been further extended to the form $\frac{I\sqrt{\frac{L}{C}}}{E_0}$ where $\sqrt{\frac{L}{C}}$ is the impedance of the commutating circuit.

L. R. Ludwig: The last section of this paper raises several questions whose answers do not seem to be entirely clear. If the text has been correctly understood, the proposal is made to reduce the output voltage of a rectifier by both starting and stopping each anode at instants earlier in time than the normal transition points in the case of the uncontrolled rectifier. If this is done, the fundamental of the current wave in each phase would lead the voltage of that phase, and at first sight a considerable improvement would result. In other words, leading reactive power is to be drawn from the line by virtue of repeated switching operations.

The rectifier and transformer are analogous to a commutator machine, in which the alternating currents generated in or supplied to the armature are rectified by the commutator. In a simple machine of this type the brushes are shifted in one direction from the neutral if commutation is to be effected. This shifting of the brushes also supplies the wattless power needed in the armature. Now Mr. Journeaux proposes to shift the brushes (advance the axis of commutation) but to shift them in the wrong direction for commutation to take place normally. Then in order to effect the commutation, a portion of the brush circuit (that tube which has been carrying current) is to be forcibly opened. The commutating emf, therefore, must originate in the tube or brush itself. The commutating time will have a finite length depending on the magnitude of this tube voltage, and the inductance of the phase, as well as the angle at which commutation is caused to begin. During this time, must not the stored magnetic energy of the phase be dissipated in the tube? And will not the transformer associated with such a rectifier be larger than if this means of voltage control were not used? Furthermore, can the phase angle of the fundamental of the current wave be advanced by any desired amount? If the improved power factor is being obtained at the expense of additional loss and size of apparatus, the advantage of the proposed means might be questioned. I would like to ask if any actual test results are available on this scheme?

Didier Journeaux: In his discussion of the present paper, P. W. Blye considers the rectifier from the standpoint of inductive coordination with telephone circuits affected by the rectifier voltage or current. The formulas given in the paper, however, all relate to the continuous voltage of the rectifier, and none to the direct current. Although grid control causes the harmonic a-c components of the continuous voltage to increase appreciably, this action does not generally result in an increase of corresponding magnitude in the harmonic a-c components of the direct current, because, in general, d-c circuits apt to cause telephone interference, such as traction circuits, are highly inductive and the harmonic current components are choked to an extent proportional to their frequency. In general, telephone interference caused by rectifiers result from inductive coupling between the communication line and the power line. The extent of the disturbance is then proportional not to the voltage TIF of the rectifier, but to the current TIF, which may be computed similarly to the voltage TIF by the following formula:

$$TIF = \frac{\sqrt{\sum \frac{1}{Z_n^2}\left(\frac{H_n}{E_{do}}\right)^2 W_n^2}}{I_d}$$

in which Z_n is the impedance of the rectifier load circuit for the harmonic of order n, or its reactance if the circuit resistance is negligible compared to it, and I_d is the rms load direct current.

Curves a and b, Fig. 3 of this discussion, give the current TIF to be expected from a 600-volt 3,600-kw rectifier, feeding a d-c circuit having an inductance of 1 mh, the rectifier being uncontrolled or controlled, as in the example chosen in the paper, p. 987. The current TIF is thus obtained under the conditions causing the voltage TIF to follow the curves illustrated in Fig. 16 of the paper, and it will be noted that the current TIF, and therefore also the interference in telephone lines, are increased by grid control to a much smaller extent than the voltage TIF. The curves of current TIF may also represent the TIF for other values of the d-c line reactance by changing the scale of ordinates.

Grid control does not introduce any harmonics not present in unregulated rectifiers, for the reason that in either case the successive firing of the anodes causes the appearance of p identical ripples in the output voltage and current during each cycle, so that the frequencies of all harmonics must be the frequency, pf, of the ripple and its multiples in either case.

With regard to Mr. Herskind's discussion, the choice of the particular load factor in computations is largely a matter of convenience. For instance, in computations relating to 6-phase rectifiers with interphase transformers, coefficient K is equal to 0.01, and the working reactance is equal to the phase reactance multiplied by the ratio of the load value considered to full load, and may even be computed mentally, without reference to the actual values of the voltage and current.

In answer to the query of Mr. Stebbins I would state that the curves relating to interphase transformer operation, illustrated in Fig. 5, are based to some extent on oscillographic records of tests in which, of course, the assumptions of the paper could only be approximated.

Referring to C. W. Frick's discussion, the 12-phase connection referred to in the paper is the familiar connection considered on p. 152 of "Mercury Arc Power Rectifiers" by Marti and Winograd. The quantities I_p, E_p, and X_p intervening in the computation of X_m are the values of current, voltage, and reactance of the transformer, referred to the primary side.

The appearance of the 6th and 18th harmonics in the output of 12-phase rectifiers as a result of unequal division of load does not preclude the appearance of these and of other harmonics as a result of the presence of odd harmonics in the primary voltage. The effect of these primary harmonics, mentioned on p. 984, is general for all types of rectifiers.

The TIF curve illustrated in Fig. 16 was selected as being representative of the effects of flat regulation, and it was not desired to burden the figure with additional curves for arbitrary amounts of regulation at full

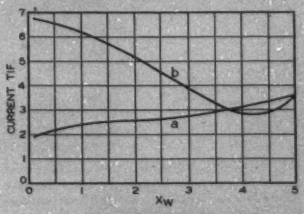


Fig. 3. Current TIF curves for a 600-volt, 3,600-kw rectifier

load, which would be without particular significance.

It is believed that the answers to the questions proposed by Mr. Ludwig will be found in reference 16 of the paper.

Although Mr. Hellmund's discussion does not directly relate to the subject of the present paper, it should be stated that the present paper was written much more as a synthesis of past performance than as a prophecy of what Mr. Hellmund calls "future possibilities of the pool-type rectifier." Out of more than 2,000 rectifiers of the general type illustrated in Fig. 2 of the paper, now in operation or under construction, and rated at a total of 1,700,000 kw, already more than 150 rectifiers, having a total output of more than 300,000 kw, are provided with grid control for voltage regulation or for current interruption. Of the above mentioned rectifiers 63 units, having a total output of 155,000 kw, are used for supplying d-c to electrolytic cells, showing that the application of rectifiers to electrochemical work is already an accomplished fact. The prospects of early application of the rectifier as a frequency changer certainly cannot be called unpromising, as 2 trial installations of frequency changers for supplying a-c railway lines are already being built or are in use in Europe (see *Elektrische Bahnen*, March 1932, p. 66, and *Elektrotechnische Zeitschrift*, Jan. 18, 1934, p. 65).

P. W. Blye: See discussion below.

Grid Controlled Rectifiers and Inverters

Discussion and author's closure of a paper by C. C. Herskind published in the June 1934 issue, p. 926–35, and presented for oral discussion at the electrical machinery session of the summer convention, Hot Springs, Va., June 27, 1934.

R. E. Hellmund: See p. 1396.

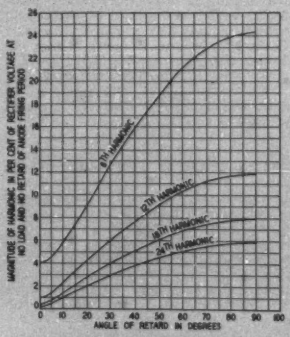
P. W. Blye: The papers by Messrs. Herskind and Journeaux are interesting from the standpoint of inductive coördination with telephone circuits because of the attention given to the effects of the grid controlled rectifiers on the wave-shape voltage and current of the associated a-c or d-c circuits. The effects on wave shape and the corresponding difficulties from noise interference on exposed telephone lines encountered with the usual type of rectifier is, I believe, well known. Information presented in these 2 papers indicates that the complexity of the problem may be increased by the addition of control grids.

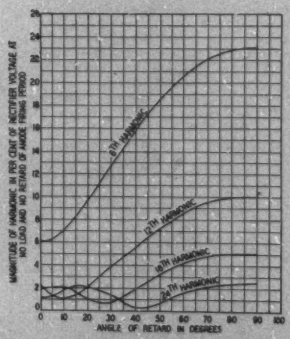
It is interesting to note that the addition of the control grids to rectifiers does not add any new harmonics to the system which would not be present without the grids. However, from the data given in the papers it seems evident that the magnitudes of the harmonics in both the a-c and d-c circuits may, under many conditions, be considerably increased. In order to reduce the wave-shape distortion to the same degree as without the control grids, more effective measures such as resonant shunts of lower effective resistance may need to be employed.

It is gratifying that recognition is being given to these wave-shape problems in the early stages of the development of these devices, so that orderly development of suitable measures for coördinating the power and telephone plants affected can proceed at the same time.

F. O. Stebbins: The author of this paper has presented a concise analysis of grid controlled rectifiers when the instantaneous d-c load current is constant. Since he does not give detailed information on the wave shape of the output voltage, a few outstanding points will be presented herewith.

Calculations and measurements on rectifiers without grid control which are now in service in the field indicate an angle of overlap of approximately 25 deg at full load upon the rectifier, though values over a range of from 12 to 30 deg were obtained. The use of grid control removes some of the limiting factors in rectifier design which influence the angle of overlap, but it will be assumed in order to simplify this discussion that these factors are still present.





Figs. 1 (top) and 2 (bottom). Curves showing the 4 lower orders of harmonics for a 6-phase controlled rectifier: (1) at light load supplying a highly inductive d-c load; (2) at approximately full load supplying a highly inductive d-c load

Substituting zero angle of overlap in formulas 16 and 17 gives the magnitudes of the harmonics in the output voltage of a grid controlled rectifier at no load. The 4 lower orders of these harmonics as they appear in the output voltage of a 6-phase rectifier are shown in Fig. 1 of this discussion. Substituting 25 deg angle of overlap in formulas 16 and 17 gives the magnitudes of the harmonics in the output voltage of a grid controlled rectifier at approximately full load. The 4 lower orders of these harmonics as they appear in the output voltage of a 6-phase rectifier are shown in Fig. 2 of this discussion.

It will be noted from Figs. 1 and 2 that where a large angle of retard to give a wide range of voltage control is desired, the magnitudes of the harmonics in the output voltage becomes appreciable.

The output voltage wave shape of controlled voltage rectifiers has been analyzed for different conditions of loading in a paper by C. W. Frick and myself, which has been accepted by publication by the A.I.E.E. (Sept. 1934 issue, p. 1259–65.)

L. R. Ludwig: In discussing the duty on a grid-controlled rectifier, Mr. Herskind points out that in 2 ways this duty is more severe than in the case of the uncontrolled rectifier. First, the grid must block the anode when it is positive with respect to the cathode, and second, the anode must withstand a greater rate of rise of negative voltage at the end of its conducting period. It is interesting to note that in a controlled rectifier of the ignition type in which no grid is used the first of these added duties is practically nonexistent due to a complete absence of any arc or ionization in the vessel during the interval when the anode is positive.

In the portion of the paper dealing with the inverter the author has made reference to the "deionization time" (Fig. 11) which follows the conducting period. It would be very interesting to know the lower limits to the magnitude of this deionization time found during the tests with the experimental inverter.

It would be interesting to know also if the problem of pick up of the arc in the inverter has required modification of the excitation system from that used in the rectifier.

So far as the duty on the tubes is concerned, the inverter requirement has one advantage over the rectifier requirement when a counter emf load is being supplied. As shown by Mr. Herskind's Fig. 11, positive voltage is applied to the anode approximately as a sine wave of voltage with time, whereas in the rectifier circuit a considerable negative voltage is usually quite suddenly applied. A small negative voltage is also suddenly applied in the case of the inverter, but the magnitude of this voltage may be limited. During tests with an experimental ignitron inverter, for example, it has been found that the magnitude of this negative voltage needs to be only a fraction of that applied in the case of the rectifier.

Mr. Herskind has pointed out that rectifier-inverter equipment does not function in the same way as a motor generator set in

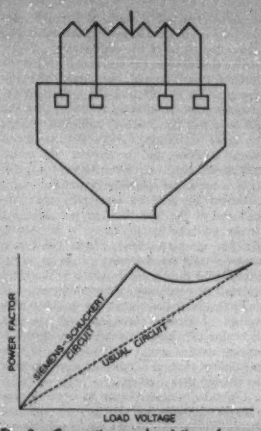


Fig. 3. Connections and variation of power factor with voltage of the Siemens-Schuckert type of voltage control

railway substations during periods of regeneration. That is, inversion does not begin automatically, and a pilot machine or other means are required for control. This proposed solution appears to be quite operative, and it forms the subject of U.S. patent 193,798 issued in Jan. 1933 to R. E. Hellmund and L. R. Ludwig.

The type of voltage control developed by Siemens-Schuckert has the advantage over the simple means of grid control which are shown of permitting good power factor over a wide voltage range. Extra anodes are required. The method has been described in *Siemens Zeitschrift*, Band 13, Sonderheft, p. 291, Oct. 1933. Figure 3 is reproduced here to show the connection used and the power factor variation with voltage.

As the rectifiers are improved and costs reduced, this method will show increased advantage over comparable schemes, such as transformer tap changing.

C. C. Herskind: In his discussion of this paper Mr. Ludwig has called attention to the fact that there are 2 types of controlled rectifiers: namely, the grid type and the ignition type. It is interesting to note that the same characteristics may be obtained from both, either rectifying or inverting, although the duty on the 2 is different, as Mr. Ludwig points out.

The deionization time required by the experimental inverter mentioned in the paper has a value estimated as less than 250 microseconds. In this connection it should be noted that when the inverter is operating near its commutation limit a large increase in the time available for deionization may be obtained by advancing the grid excitation only a small amount. This may be seen by reference to the curves on Fig. 9.

In order to assure pick up of the arc when operating as an inverter, it has been found necessary to provide the rectifier tank with more excitation anodes than is usual for rectifier operation. The experimental inverter was fitted with half as many excitation anodes as there were main anodes. One excitation anode was located between each pair of main anodes. All of the various schemes which have been devised for improving the power factor of controlled rectifiers operating over a wide voltage range involve costly complications. However, as the development of rectifiers is continued, these difficulties will undoubtedly be overcome.

Mr. Hellmund has reviewed some of the economic considerations involved in the various applications which have been proposed for controlled rectifiers. He has indicated the large number of possible applications. While the use of the rectifier is not now economically justified in many of these cases, we are confident that it will continue to develop rapidly as the technical problems are solved.

Factors Influencing the

Insulation Coördination of Transformers—II

Discussion and authors' closure of a paper by P. L. Bellaschi and F. J. Vogel published in the June 1934 issue, p. 870–6, and presented for oral discussion at the electrical machinery session of the summer convention, Hot Springs, Va., June 27, 1934.

L. V. Bewley: The scheme shown in Fig. 7 of the paper has been proposed during the last few years for the direct stroke protection of stations on both low and high voltage circuits. Various estimates and recommendations have been given for the length of the ground wire. In this discussion I wish to show how this length may be rationally determined; and in particular to point out that the length of the ground wire may have to be as much as several miles if the station capacitance is small.

Assume that the wave chopped by the line gap flashover is triangular in shape, rising to E kv in T μsec. As this wave travels along the line it suffers attentuation and distortion, but the total charge carried by it remains substantially constant. Examination of the oscillograms of chopped waves taken at different distances from their origin discloses that for the first mile or 2 the time to crest remains nearly constant, but the crest is rounded off and a tail develops, so that the wave acquires the typical shape of an impulse. However, when an attempt is made to represent this wave in the usual way as the difference of 2 exponentials, subject to the conditions that its average value shall be equal to the average value of the original triangular wave (that is, having equal charges) and that fronts shall be of the same length, it is found that the assumed wave shape is incompatible with the imposed conditions. Another possibility is to assume the wave shape of the form

$$e = AT\epsilon^{-at}$$

but in this case there are not enough parameters to meet the 3 conditions of amplitude, average value, and time to crest. A loop of a damped sinusoid also proves incompatible. About the only thing left which will permit analytic solution is to consider the arriving wave as still triangular in shape, rising to a voltage e_1 in time T, then falling to zero by time T', and with average value

$$\frac{1}{2}(e_1T') = \frac{1}{2}(ET) \text{ or } T' = \frac{E}{e_1}T \qquad (1)$$

The amplitude e_1 can be estimated by means of the Foust and Menger empirical attenuation formula,

$$e_1 = \frac{E}{1 + KEx} \qquad (2)$$

where

E = crest of original triangular wave
e_1 = crest of arriving wave
x = miles of travel = length of ground wire
K = empirical constant
$\cong 0.0006$ for short chopped wave

The arriving wave is therefore

$$e = \begin{cases} \dfrac{e_1}{T}t & \text{for } 0 \leq t \leq T \\ \dfrac{e_1}{(T - T')}(t - T') & \text{for } T \leq t \leq T' \end{cases} \qquad (3)$$

When this wave strikes the station capacitance it produces a voltage at the station of

$$e_0 = \frac{2e_1}{\alpha T}[\alpha t + \epsilon^{-\alpha t} - 1] \text{ for } 0 \leq t \leq T$$

$$e_0 = \frac{2e_1}{\alpha T}[\alpha T + \epsilon^{-\alpha t} - \epsilon^{-\alpha(t-T)}] - \frac{2e_1}{\alpha(T' - T)}[\alpha(t - T) + \epsilon^{-\alpha t} - \epsilon^{-\alpha(t-T)} - 1] \qquad (4)$$

where $\alpha = 1/ZC$, Z = line surge impedance, for $T \leq t \leq T'$ and C = station capacitance. Thus the station voltage can be computed directly in terms of the original wave and the length of the ground wire. As an example take

E = 1,600 kv K = 0.000625
C = 0.001 μf T = 0.4 μsec
x = 1 mile Z = 500 ohms

Then by eq 2

$$e_1 = \frac{1,600}{1 + 0.000625 \times 1,600 \times 1} = 800 \text{ kv}$$

and by eq 1

$$T' = \frac{1,600}{800}(0.4) = 0.8 \ \mu\text{sec}$$

and by eq 4

$$e_0 = 2,000\,[2t + \epsilon^{-2t} - 1] \text{ for } 0 \leq t \leq 0.4$$
$$e_0 = 2,000[2.6 - 2t - 3.45\,\epsilon^{-2t}] \text{ for } 0.4 \leq t \leq 0.8$$

The results are shown in Fig. 1 of this discussion. The station voltage reaches a maximum of 720 kv. If the permissible voltage at the station is 530 kv, then by trial the appropriate length of ground wire is found to be 2 miles.

If the station capacitance is negligible, then the arriving wave doubles by reflection and

$$e_0 = 2e_1 = \frac{2E}{1 + KEx}$$

from which there is

$$x = \frac{2E/e_0 - 1}{KE} \qquad (5)$$

Thus if E = 1,600 and e_0 = 530, then

$$x = \frac{2 \times 1,600 \times 530 - 1}{0.000625 \times 1,600} = 5 \text{ miles}$$

It is therefore seen that a very moderate

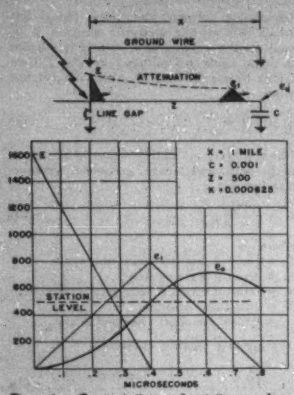


Fig. 1. Computation of station voltage

amount of station capacitance is quite effective in reducing the necessary length of ground wire.

The above argument applies specifically to circuits not equipped with reliable lightning arresters. For circuits so equipped the length of ground wire (on a most conservative basis) need not be longer than half of the length of the chopped wave. This means that in practice there is no real need for extending the ground wire for more than a normal span away from the station, if lightning arresters are provided.

J. E. Clem: The paper by Messrs. Vogel and Bellaschi touches briefly upon the problem of the protection of transformers. It seems reasonable that good operating engineering necessitates protective measures to keep service stresses at a reasonable margin below the strength of the transformer as demonstrated by the factory impulse test. This discussion will be supplementary rather than critical and will review briefly the problem of protection and the factors that should be considered in deciding how much protection should be provided.

In order to protect transformers it is necessary to know 3 things: the strength of the transformer, the probable overvoltages, and the performance of protective devices.

The A.I.E.E. proposed impulse test code applying to power transformers having voltage ratings of 15 kv or higher, which has been in use for more than a year, enables operating companies to purchase power transformers having an impulse strength subject to demonstration by test. At present the impulse test code requires that the transformer be tested in parallel with a plain rod gap, called the test gap, and the test demonstrates that the strength of the transformer is greater than that of the gap used. The strength of the transformer is determined on the basis of a positive 1.5×40-μsec wave and affords the operating engineers a definite basis on which to consider the need and value of protective measures.

Switching surges may range in magnitude up to $5^1/_2$ times normal voltage. These switching surges are usually of relatively long duration so that 60-cycle flashover characteristics of insulation usually must be considered in dealing with them. During the lightning investigations of recent years some evidence was obtained which indicates that switching surges in excess of about 4 times normal may have an appreciable impulse ratio.

Modern systems with directly grounded neutral are not affected by arcing ground troubles. Arcing ground overvoltages on ungrounded systems are of such duration that the 60-cycle flashover characteristics of insulation must be considered in dealing with them.

The problem of transformer protection can be simplified by considering the lightning overvoltages as divided into 3 general classes: direct strokes at the station; closely adjacent to the station; and more remote from the station, including induced strokes with the latter.

Direct strokes on the station structure will impose a very rapidly rising voltage, the magnitude of which will be limited only by the flashover of some piece of station equipment. As a rule the flashover voltage will be extremely high under these conditions so that extremely high overvoltages of relatively short duration will be imposed on station equipment.

Direct strokes on the circuits nearby will impose on the station insulation a very rapidly rising voltage of a magnitude dependent upon the flashover of the line insulation at the point where the stroke occurred. If the grounding resistance at the point in the line where the flashover occurs is high, a voltage dependent upon the current in the stroke will be built up and passed into the station. As a rule the rate of voltage rise at the station for these strokes is less than that for direct strokes at the station but the duration of appreciable overvoltages (caused by high grounding resistance) will be longer.

Direct strokes to the line at more remote points cause overvoltages at the station with a more sloping front and a lower magnitude than either of the 2 preceding. Induced strokes may impose on the station overvoltages of relatively slow front and of a magnitude limited in some cases by the flashover on the line insulation.

Since the overvoltages from switching and arcing grounds are usually considered on the basis of 60 cycles, it seems desirable to bring out the fact that the present accepted insulation levels are such that the problem of coördination as regards 60-cycle flashover characteristics is relatively unimportant. This is so because the 60-cycle strengths of the various component parts of the system are invariably above the overvoltages caused by switching and arcing grounds, so that there is usually no need to attempt to bring the 60-cycle strength of any part up to that of any other part.

Based upon the lightning overvoltages which might be expected, it is clear that it is necessary to protect transformers from both direct strokes and travelling waves. There are 3 types of protective equipment which may be used for this purpose: direct stroke shielding, lightning arresters, and plain air gaps.

Direct stroke shielding may take the form of ground wires over the station, of the steel structure extending above the circuit conductors, or of vertical projections extending above the plane of the conductors. Direct stroke shielding on the line usually takes the form of 1 or 2 ground wires above the conductor. To be effective the grounding resistance must be sufficiently low so that the *IR* drop will not build up sufficient voltage to cause a flashover between the direct stroke shielding and the circuit. An essential part of direct stroke shielding for a station is adequate shielding of the line out a sufficient distance to interpose surge impedance of the line between the lightning stroke and the apparatus to be protected. Briefly, adequate direct stroke protection requires that the lightning stroke be intercepted and discharged to earth without involving the equipment being protected.

In a case of direct stroke, extremely high values of current are involved so that lightning arresters cannot be considered as direct stroke protection because of the possibility that the lightning current may be beyond their capacity.

Lightning arresters may be used to provide protection from strokes on the line beyond the area of direct stroke protection. Modern arresters are available to meet certain specified volt-ampere characteristics which may be demonstrated by commercial impulse tests. The performance of these arresters is predictable, and this gives the operating engineers a definite basis for estimating the service stresses to which the transformers may be subjected when protected by them.

During the past few years in the study of coördination the plain air gap was given a status as a protective device which it did not merit. Plain air gaps will limit, by a flashover, the magnitude of the voltage applied to station apparatus and may be considered as giving a minimum amount of protection. The plain gap alone cannot be considered as a practical protective device for 3 reasons:

1. The volt-time characteristic of the gap is such that a higher and higher voltage is required to cause flashover as the time to flashover becomes shorter and shorter. Consequently, extremely steep wave fronts result in extremely high overvoltages before the gap flashes over. This imposes excessive overvoltages on the insulation being protected. In order to keep the stresses below the strength of the transformer, as demonstrated by the impulse test, it is necessary to keep the setting of the gap extremely low when the time to flashover becomes less than 2 or 3 μsec.

2. Flashover of the gap will usually cause a system outage.

3. If the setting of the gap is low enough to give a reasonable factor of safety below the demonstrated strength of the transformer, the gap may flashover on switching surges.

It is obvious that all stations do not merit the same treatment, and, consequently, there will be 2 varieties of protective set-ups. Large and important stations will be given complete protection, while the smaller ones may or may not be given partial protection.

Complete protection consists in adequate direct stroke shielding combined with the use of an arrester. With this arrangement the use of the plain air gap is not necessary for protection, and whether or not one is installed will depend upon the value given to the possible benefits resulting from it. The gap might be considered as a reserve in the contingency of the other protective equipment becoming inoperative, and also it might be considered as giving a check upon

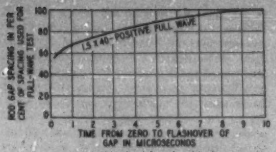


Fig. 2. Curve for estimating rod gap setting as percentage of test gap

the arrester operation. If the gap is installed it should have a setting not in excess of 90 per cent of that of the test gap used in the impulse test of the transformer at the factory. Briefly, complete protection consists in adequate direct stroke shielding and the use of a standard lightning arrester whose performance may be predicted.

Partial protection is provided by the use of arresters alone. For many years it has been common practice to use lightning arresters without direct stroke protection on 15-, 22-, 33-, and 44-kv systems. Modern arresters afford protection for such a station for strokes terminating on the line a moderate distance away so that the surge impedance of the line becomes effective in limiting the amount of current to be discharged by the arrester. All lightning strokes are not of the same magnitude, so that the arrester will discharge some of the milder direct strokes terminating very close or even at the station. For these stations the plain air gap can be used to limit the magnitude of the voltage for those cases where the lightning current is excessive.

If it is desired that the stresses in the transformer be kept below its strength as demonstrated by the factory impulse test, it will be necessary to reduce the setting of the plain air gap below the setting of the test gap. The amount of reduction will depend upon the assumed time to flashover. Figure 2 of this discussion may be used to estimate the setting. For instance, if it is desired to keep the same margin of safety for all flashovers occurring not sooner than 2 μsec to flashover, the setting of the plain air gap would be 75 per cent of that of the test gap. It should be recognized, however, that the lightning arrester may not be able to prevent the gap with a reduced setting from flashing over on long surges and, consequently, the setting of the gap must be a compromise between the protection desired and the possibility of an outage.

Where direct stroke protection is installed but the lightning arresters omitted, the station equipment may be stressed up to the flashover of the station insulation by lightning strokes terminating beyond the direct stroke protection, providing some means are not taken to limit the voltage. In such cases, the plain rod gap with reduced setting might be considered as an economic means of obtaining a minimum amount of protection. As before, the use of the plain air gap will necessitate a compromise between the amount of protection desired and the possibility of system outages.

When both the arresters and direct stroke protection are omitted some protection may be obtained at a minimum of cost by the use of a plain rod gap. As before, the setting of the plain air gap will be a compromise between the degree of protection desired and the possibility of outage.

There arise occasions when it is desired to consider the protection of transformers already installed. In such cases the procedure is to estimate the strength of the transformers in terms of the impulse test which could have been given when the transformers were built, and the procedure then is the same as outlined. It should be recognized, however, that the operation of the transformer without protection may have caused the insulation of the transformer to be damaged so that its present strength may be appreciably reduced, thus rendering the problem of protection more difficult or even impossible.

C. L. Fortescue: In this paper the principle of coördination has at last been presented in proper perspective. Following the intensive field investigation of lightning, there has been great activity in the various engineering laboratories in determining the impulse characteristics of various types of insulation structures. The determination of these characteristics for line insulation structures had progressed rapidly, outdistancing knowledge of impulse characteristics of insulation structures associated with apparatus such as transformers. Until this knowledge was available coördination was purely a matter of speculation, and as a result of this a stage of loose thinking has been experienced similar to that in transmission line insulation preceding the lightning field investigations.

As the authors show, 100 per cent coördination in the apparatus itself does not at the present time appear to be economically feasible, at least not with the use of edge gaps, because their impulse time lag characteristics do not correspond point to point with the true dielectric strength characteristic of insulating barriers. The sphere gap in this respect is the most satisfactory type of coördinating gap and it appears to be possible with a properly designed gap of this type to obtain 100 per cent coördination, but as the authors point out, it also has serious limitations. Prior to the field investigations, the theory of lightning arrester protection was on a rather unsubstantial basis, but this increased knowledge has brought about a better understanding of the requirements of arresters in the way of discharge capabilities. The further knowledge of the short time dielectric strength of insulating barriers brought about by this paper will, I believe, place the theory of lightning protection of apparatus on a secure basis.

What does the word coördination mean when applied to electrical apparatus? Does it not mean that the parts of the apparatus which are essential to its normal operation have a higher level of impulse strength so that if failure does take place it will be in some unessential part? The coordinating edge gap has been elected to be this unessential part, but as we see it has inherent defects for this purpose. First, its failure results in an interruption of service. Second, its impulse strength at time lags below 2 μsec is greater than that of the insulation with which it is associated. It is true that more insulation strength could be used with a given gap or for a given insulation strength a shorter gap could be specified, but this does not seem to be a satisfactory expedient. Unfortunately, the word coördination has been used by many during the past few years, as if in itself it had some mystic power, and in some quarters has been looked upon as a measure which would do away with the necessity of lightning arresters. But what is a lightning arrester but a coördinating gap with flat characteristics and having the additional ability of arresting the flow of power current after breakdown has taken place. Looked upon as a coördinative measure, the modern lightning arrester with its high discharge capacity appears to be closer to the ideal coördinating gap than anything that has yet been proposed, and as the result of the increased knowledge of lightning a continual improvement in their characteristics may be expected in the future.

In a paper by R. N. Conwell and the writer entitled "Lightning Discharges and Line Protective Measures," ELECTRICAL ENGINEERING, July 1931, p. 478, the protective value of overhead ground wire for substations was pointed out. Prior to that date the Plymouth Meeting substation of the Philadelphia Electric Company and the Roseland substation of the Public Service Electric and Gas Corp. of New Jersey were protected with overhead ground wires, and subsequent to it, this type of protection has been installed over stations in practically every new high voltage development. It was pointed out in the paper that as long as the insulators supporting the conductors did not flash over when the ground wire was struck, the transformers in the substation connected to the line would be subjected to only a small potential as the result of a direct stroke to one of the structures. If corona on the overhead ground wires is ignored the actual potential impressed on the transformers would amount to the potential of the top of the structure receiving the stroke multiplied by the coupling factor between ground wires and conductors. Since this potential is not accompanied by any surge current there will be no building up of this potential at the terminals of the transformer; on the contrary the capacity of the transformer will pull down the potential. The energy of the resulting surge in the transformer winding will be derived from the ground wires through their mutual surge impedances with the conductors.

To form some idea of the magnitudes that might be expected, consider a 220-kv line entering a substation through a 1,000 ft span with ground wires 100 ft above ground level, and let us suppose the resistance of the structure footing to be 5 ohms at the station. The tower top potential per 1,000 kv of stroke potential will be about 137 kv. For a 20,000-kv stroke the tower top potential would be 2,740 kv reached in 1 μsec. If the coupling factor is 35 per cent the potential applied between the transformer terminals and ground will be 960 kv. If the tower footing resistance is so low that it may be considered zero the tower top potential will be 2,000 kv and the potential applied between transformer terminals and ground will be 700 kv. If flashover of the line insulators took place the line conductor would be raised to approximately the same potential as the ground wire after flashover had taken place, and this potential would be impressed on the transformer with all the energy in the tower top and ground wires

behind it. This potential is not the full potential of the tower top but what remains after flashover is completed and the conductor is charged; thus, for example, if flashover takes place after 2 μsec, what remains of the tower top potential would be less than 1,000 kv in the first case and a very small value in the second case. In the meantime, the potential of the point to which the transformer is grounded has also been raised to practically a like amount so that the net value of the surge entering the transformer terminal will be very small. If the line insulation were such that flashover took place on the front of the wave, say in $^3/_4$ μsec, then the line wire would take approximately the same potential as the ground wires had at that instant and thereafter.

The above discussion indicates why overhead ground wires for substation protection are not as effective for the lower voltages as for the higher voltages. The lower voltage substations and lines cannot justify the amount of insulation required to make them completely proof against lightning outages. There are, however, mitigating circumstances which make the protection level of the substation higher than that of the line. First, the height of the structures can be made considerably less than that of the towers, thereby reducing the tower top potential. Second, the distances between structures can be reduced so that the length of the tail of the tower top potential is reduced and if the span length is below 400 ft a substantial reduction of the tower top potential is also effected. The time permitted in a discussion of this kind does not allow me to go into detailed computations of these potentials for different heights of structures and spacings but they can be computed by the method of reflections, examples of which are given in my Paris paper, "Lightning and Its Effects on Transmission Lines," and the series of articles by Torok and Ellis, Monteith, and Beck which appeared in the latter part of 1933 and the early part of 1934 in the *Electric Journal*, reprints of which are available. It suffices to say that the effectiveness of ground wire protection against direct strokes depends upon the same factors as that of the transmission line itself and may be summed up as follows:

1. 100% shielding.
2. Low structures.
3. Short spans.
4. Low structure footing resistances.

If a transmission line emanating from a generating station is designed for an outage factor n per 100 miles per year and the generating station and substation has the same protection level, the probability of a lightning stroke producing a dangerous potential at the terminals of the transformers will be less than $2\,n/100$ per year. This is based on the assumptions that the exposure of a substation is equivalent to 1 mile of line and that there are 2 lightning flashovers for every outage. Illustrating this by a numerical example, the 132-kv lines protected by 2 overhead ground wires in the Great Lakes district show an outage factor of 1.7 per 100 miles per year. The probability of an outage due to lightning at a substation having the same level of protection as the lines is less than 3.4 per 100 years or 0.034 per year. This, of course, is a mass figure; it would be of little consolation to the utility engineer whose substation should be the one that is hit. From this it will be seen that for a line which is practically lightning proof the probability of an outage at a particular substation is very small.

In the case of an unprotected substation, the transformer is subjected to the full steepness of the lightning surge after it hits the line and until flashover takes place, then the potential is determined by the surge impedance of the tower and its footing resistance. With wood pole lines the potential to which the line may rise before breakdown is completed may be as high as 10,000 kv if the combined resistance of the pole butts to ground is of the order of 100 ohms. The danger to apparatus is higher the higher the insulation and with wood pole construction where there are no guyed poles in the vicinity it reaches its maximum. The probability of a dangerous potential from a stroke at a substation with wood pole construction is also high. If we assume that all strokes above 4,000 kv are dangerous the probability of strokes of this magnitude or larger causing dangerous potentials is for an isoceraunic (lines of equal thunderstorm occurrence) level of 30 approximately 0.24 per year, and for an isoceraunic level of 60 it will be double this or 0.48 per year.

G. D. Floyd: The authors state in the second paragraph of their paper that time lag curves still indicate that coördination is obtained even for surges of very short duration. As this point has been a subject of some controversy, I believe they might well have submitted the data on which their conclusion was based.

Previous papers on this and related subjects have been chiefly concerned with the strength of insulation and gaps against impulse voltages, and have given very little information as to how such data could be applied in practice. The authors of this paper have attempted to outline how such a problem should be attacked. It is to be hoped that as a result of the information now made available on the insulation strength of apparatus against surge voltages, the application of these data in station design will receive some attention, which should provide material for a very valuable paper.

I believe the question of service outages due to flashover of the coördinating gap has been stressed more than its importance warrants. If the station is a large one with several banks of transformers, each bank with its coördinating gap, the gap flashover will usually cause an interruption to service only if all gaps in the station operate. This is hardly likely to occur unless the surge is a very severe one indeed, in which case, if the gaps have adequately protected the transformers by having relatively low setting, the momentary interruption is nothing compared to the difficulty arising from loss of one or more transformers. If only one gap operates, the transformer bank and bus section associated with it will relay out, but the remaining transformer banks can usually carry whatever overload there may be until the transformer bank affected is picked up again.

If the station is small with a single circuit and transformer bank, it usually is of very little consequence if it be momentarily out of service. It is infinitely more desirable that such a momentary outage occur, if as a consequence the transformers are not damaged permanently. I believe that better all around results would be obtained if the coördinating gaps were set, say, 10 per cent lower than the equivalent gap corresponding to the voltage class of the transformer protected by the gap. This would provide an additional factor of safety, and would help to take care of possible deterioration in the transformer insulation due to the effect of repeated surges or to other causes.

K. B. McEachron: It is well recognized today that transformers should not be subjected to direct strokes, and that lightning arresters cannot be expected to perform all of their intended functions if the current associated with direct strokes is allowed to pass through the arrester. Therefore, for some time past, shielding of the station or substation, and adjacent lines and conductors, has been regarded as proper where economics allow the use of such protective means. To make such shielding effective, proper precautions with regard to ground resistance of tower footings and location of ground wires must be taken. The shielding need not extend more than $^1/_3$ mile from the station for this purpose.

The modern lightning arrester has characteristics which may be demonstrated by laboratory test; likewise the strength of the transformer can be demonstrated with reference to the assigned test gap. Thus it becomes possible to determine the margin between the arrester protection level and the transformer test gap with a reasonable degree of accuracy.

Frequently it is not economic to provide line shielding from direct strokes, and this is particularly true of the low voltage circuits where wood pole lines are used and no definite limitation of an incoming traveling wave provided, as would be the case with lines on steel towers. For such lines, expulsion protective gaps may be used on several poles adjacent to the station, thus limiting the traveling wave potential to values of the order of from 6 to 8 times normal line to ground crest potential. Of course, good grounds must be provided for the expulsion gaps, and as an added precaution the last gap or 2 could be tied in with the station ground using a buried conductor. Of course the expulsion gap on the line does not protect the transformer in the station, but could reasonably be expected to prevent direct stroke currents from reaching the arrester in the station unless the direct stroke occurred in the span adjacent to the station. Even in this event the gap would be helpful, as it would limit the length of tail of the impulse reaching the arrester.

Such use of the expulsion protective gap will have an additional advantage when used with arresters in the station, since limiting the potential of the incoming traveling wave will lower the protection level of the arrester and thus increase the margin of protection. If a reasonably definite level of line insulation through the use of the expulsion protective gap or other means is established, a greater dependence can be placed upon the arrester's performance than is now the case when there is no limit placed on line insulation except the wood pole itself.

Worth while reductions in arrester protection levels may be obtained at stations whose lines enter on steel towers if the insulation level is of the order of 10 times normal or more. In such a case, expulsion gaps located on the last few towers would bring the level of the incoming impulse down to the order of 6 to 8 times normal.

In those cases where ground wires do not perfectly shield the line from direct strokes, expulsion gaps would perform the same function as with the wood pole line.

It has been suggested that the lightning arrester be made the basis of coördination. This requires an arrester whose potential could be depended upon to maintain a certain margin below the transformer test gap for all kinds of lightning conditions in service. To do this requires some control over the impulses which reach the arrester, which means some limitation of the incoming traveling wave.

If the station and associated overhead lines are protected from direct strokes and a modern arrester installed in the station, there seems to be no good reason for installing gaps in the station, unless it be for the purpose of supplying a degree of protection in the event that the arrester is out of service.

If arresters are not used, the station gap to be effective for direct stroke conditions requires either an extremely low setting or else shielding of the line over a considerable distance, as indicated in Mr. Bewley's discussion.

H. V. Putman: When the transformer subcommittee undertook the formulation of recommendations for impulse testing 2 years ago, one of the principal points of discussion centered around the possibility of damage to the insulation during test. The subcommittee recognized this problem but considered that it was reasonably safe to proceed with impulse testing because it did not appear that the problem of insulation damage in connection with impulse tests was much different than the problem of insulation damage in connection with the regular low frequency dielectric tests.

In my talks with utility engineers I have occasionally run across an engineer who was unalterably opposed to impulse testing because of the possibility of damage to the insulation. The data presented in this paper I think will do much to settle this question and will allay the fears of those who have felt that impulse testing was dangerous. I believe it will therefore help to establish impulse testing on a firmer foundation.

The subcommittee now has before it certain proposals for simplifying impulse testing procedure and making it more effective. At the same time the manufacturers have occasionally received requests for very much more complicated and expensive impulse testing procedure consisting of a large number of tests at very steep wave fronts with the test gap flashing over on the rising front of the wave. These requests have come from engineers who have not been fully satisfied with the test procedure recommended by the subcommittee, and who have felt that these recommended tests were not an adequate demonstration of protection against very short waves.

It is obvious that the work of the committee is not successful unless its recommendations can be accepted by the industry, and the subcommittee is anxious to have its recommendations reflect the needs and desires of the industry. The test procedure recommended by the subcommittee has only one purpose and that is to demonstrate a given level of insulation in the transformer. It is not their purpose to demonstrate the effectiveness of any scheme of protection. The data presented in this paper enable one to determine what the performance of a transformer will be under a large number of repeated surges at very short time lags if one knows the insulation level which is demonstrated by the regular tests. Therefore, I hope this paper may help to avoid any need for a test procedure involving large numbers of impulses at very short time lags—tests which are often difficult and sometimes impractical to make, particularly on large transformers.

V. M. Montsinger: I believe that everyone will agree that this paper is a valuable contribution to the subject of coördination of transformers and also to the material given in the symposium of papers presented on the same subject at the winter convention in January 1933.

This paper is of particular interest to me because it presents the results of an investigation quite similar to one which I have been following; namely, to determine (1) the effect that various shapes of impulse waves have on the breakdown of transformer insulations, (2) the effect that repeated applications have on the breakdown of transformer insulations, and (3) a study of the best means of providing protection in the field against steep waves associated with direct strokes on or near the terminals of transformers.

I have noted with interest that the authors obtained practically the same average "impulse ratio" that was given in the paper "Coördination of Insulation" (V. M. Montsinger, W. L. Lloyd, Jr., and J. E. Clem) presented at the 1933 winter convention. As a matter of fact, it is a little higher for barrier *B*, being 800 kv for the single impulse failure divided by the 60-cycle 1-minute failure of 316 kv crest, or 2.53. Our data indicated a ratio of 2.35. At that time Mr. Vogel's data indicated a ratio of 2.2. The average of 2.2 given for barrier *A* and 2.53 for barrier *B* is 2.37; consequently, we now agree quite closely on the average impulse ratio of the major insulation of transformers.

The statement that the insulation and point gap characteristic curves are closest at 2 μsec is too important to pass over without comment. I take this statement to mean that the margin between the insulation and a rod gap, if tested in parallel, is a minimum at 2 μsec as indicated by the volt-time curves covering the entire range of waves, including the steepest fronts. In other words, if a gap just protects a transformer at 2 μsec time, there is no danger of it not protecting it at any other time of flashover either shorter or longer than 2 μsec. If my interpretation of their statement is correct (and I don't see how it can mean anything else), this statement is not consistent with the data given later in the paper where it is shown (1) that the full 1.5 × 40-μsec wave single-shot equivalent gap breakdown of barrier *B* is approximately 50 in. (800 kv), (2) that the 2.5 to 4 μsec repeated-shot equivalent gap breakdown is around 30 to 35 in. (610 kv), and (3) that the repeated short chopped wave equivalent gap is 14 in. (600 kv).

The data in Table III of the paper on "Coördination of Insulation" referred to above (later tests also bear this out) show that the equivalent rod gap spacing (to protect insulation) must be continually decreased as the waves become shorter and steeper. This is also shown in the volt-time curves, Fig. 2 of the same paper.

This data together with that cited for barrier *B* seems to prove beyond any reasonable doubt that the volt-time curves will cross if the insulation strength is above, but not too far above, the gap strength for long waves.

I would like to ask how many shots the dotted line in Fig. 1 entitled "several shots" represents? The word "several" is too indefinite to mean very much.

In reference to the data on barrier *A* which shows that the voltage values are approximately the same for full 1.5 × 40-μsec waves and waves chopped in 2.5 to 4 μsec, I would like to ask at what point on the waves failure took place in the insulation. In our work we find that puncture of solid insulation (or solid and oil in series) almost invariably takes place quite near the crest of the wave. It seems to be almost impossible to get it to break well down on the tail of the wave. This probably accounts for the authors obtaining approximately the same values on barrier *A* for both full waves and waves chopped beyond the crest by a rod gap within 2.5 to 4 μsec. We have found that the flashover of a full wave causing failure by creepage usually takes place well beyond the crest, the same as it does for the sparkover of an air gap.

I think the authors have handled the definition of short waves rather loosely. They call any wave that flashes over between 2.5 and 4 μsec a "very short wave." To me a "very short wave" means one that flashes over around 1 to 2 μsec. I should define them as either "moderately short waves" or "short waves." I agree with their definition of "extremely short waves" as waves which flash over in approximately $^1/_3$ μsec.

With reference to the effect of repeated shots on the breakdown of insulation, I would like to suggest that the "interval between shots" be given. This may be an important factor when making life tests.

Our tests in which failure is either by creepage or puncture show that to prevent markings and failure after a large number of shots the equivalent gap must be set at not over approximately 70 per cent of the single shot breakdown value.

As shown previously in Table III of our paper on "Coördination of Insulation," the equivalent gap spacing for extremely short waves may be as low as from 35 to 40 per cent of the full wave equivalent gap.

The data in the paper does not reveal what the equivalent gap for the life tests on barrier *B* with full waves was, but when applying the same percentages as cited above, we agree quite closely on the equivalent gaps for a single shot failure and failure for a large number of steep waves. For example, 70 per cent of the single shot equiva-

lent gap of 50 in. (800 kv, Fig. 1) gives a 35 in. equivalent gap for the life test strength as obtained with full waves. Now 40 per cent of the 35 in. gap gives a 14 in. gap for the equivalent gap for the life tests made with extremely short waves. Their values in Table III are 14, 14, 14, 14, 16, and 17 in.

I believe that there is one conclusion that is irrefutable; namely, that it is not possible from an economic standpoint to protect transformers from severe direct strokes of lightning simply by either increasing the insulation or by reducing the line insulation at or near the station. Something more must be done to keep the direct strokes off the nearby lines. Overhead ground wires and modern arresters supplemented by a rod gap whose spacing is as low as the arrester can protect, or not too low to give undue outages from switching surges, seem to be the answer in the present state of the art.

With reference to the present method of impulse testing of transformers, I believe that we have now progressed far enough to consider modifying the tests to fit in more nearly with the latest methods available for protecting transformers in service. I refer particularly to modern lightning arresters which have practically flat volt-time characteristics, quite similar to the volt-time curve of a sphere gap.

In view of the fact that we now have available protective equipment—the arrester—which holds the crest of the impulse voltage to practically a constant value, I propose that the Institute consider modifying the present method of impulse testing of commercial transformers.

In a general way the present method of testing would be supplemented by chopping off the 100 per cent impulse test gap wave on the crest by a sphere gap and then applying a sufficient overvoltage across the same sphere gap setting to cause flashover on the front of the wave.

In this manner the transformer would be tested with the entire range of impulse waves to which it can be subjected in service provided, of course, it is properly protected.

If it is decided that it is advisable to modify the method of impulse testing, the details should be worked out by the proper technical committee, either the transformer subcommittee of the electrical machinery committee or the A.S.A. sectional committee on transformers.

P. L. Bellaschi and F. J. Vogel: All the discussions are in general accord that the problems of coördination and their solution, proposed in our paper, are fundamentally sound. Specific questions have, however, been raised and certain viewpoints expressed which warrant reply.

There has been some misunderstanding of the data presented in Fig. 1 of the paper, so it may be well to explain in greater detail than stated in the paper the various curves given in the figure. The full line under "barrier" represents failure for single surges of the duration indicated. This barrier was similar to barrier *B* described in the paper. We note a rapid increase in strength with decrease in the length of the surge below 2 μsec. These data confirm the conclusion No. 1 reached in the paper that "Transformer insulation of conventional types is probably coördinated with the proposed standard coördinating gaps, except that, in the case of very high short surges, marked deterioration results." The dotted curve shows the results obtained in the previous paper. In this case the applied voltage is gradually increased from approximately 10 per cent below breakdown up to failure. Successive surges of increasing magnitude were therefore applied in the procedure of these tests. Several surges, as described in the paper, should therefore be construed to mean these surges taken in increasing intervals, which were in the order of 6 to 10 in number.

Obviously, from the impulse voltage value of the dotted line, 730 kv, and the 1 minute hold 60-cycle crest for this barrier of 316 kv, the impulse ratio is close to 2.2. This ratio was fully established in the preceding paper.

It is therefore seen that the data are actually furnished in the paper upon which the statement is based that time lag curves still indicate that coördination is obtained even for surges of very short duration. This question was raised by G. D. Floyd. Coördination here is, however, interpreted to mean that the impulse strength of the transformer under single surges should be stronger than the impulse strength of the gap even for surges of very short duration. Figure 1 in the paper actually shows these relations between a coördinating gap and the major insulation in a transformer, and is generally representative.

Mr. Montsinger has commented upon the statement that the insulation and point gap characteristic curves are closest at 2 μsec. A further detailed discussion of what is meant by this statement therefore appears in order. What was meant was that the insulation and point gap characteristic curves were closest at approximately 2 μsec if single surges only were to be applied, which is obvious from Fig. 1. However, nothing is said as to the effect of deterioration or what would have happened to this barrier if repeated surges of the same magnitude had been applied. If repeated surges are applied, it is readily seen from the dotted curve and the gap curve that the 2 curves intersect at some definite short time lag depending upon the insulation and gap levels.

As Mr. Montsinger has found out, we also have found that puncture of solid insulation almost invariably takes place near the crest of the wave, whereas for creepage around barriers failures are characterized by distinct time lag curves much the same as for rod gaps. With respect to the time interval between shots for the tests with repeated impulses, the interval was varied over a wide practical range in our tests with apparently no effect whatever upon the results. We believe that this is reasonable when we consider that deterioration occurs at some definite voltage gradient. Being of a disruptive nature rather than due to the effects of heat, it should be independent of the time interval between voltage applications.

We agree with Mr. Montsinger's value of 70 per cent as the ratio between the equivalent gaps for a large number of shots in contrast to the single shot breakdown value in the case of puncture. This is not necessarily the case for creepage breakdowns.

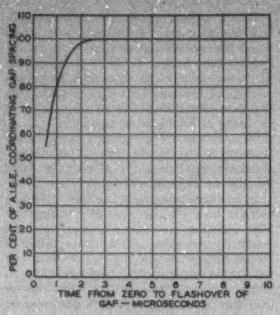


Fig. 3. Gap coördination for negative surges

Gap spacing expressed in per cent of standard A.I.E.E. edge gaps for constant factor of safety in power transformer insulation

We are interested in Mr. Clem's statements as to the impulse strength of transformers. He states in his discussion under the subtitle of "Strength of Transformers" that the strength of the transformer is demonstrated to be greater than that of the gap used. This statement appears to us to be inaccurate when thoroughly analyzed. In the beginning (A.I.E.E. Trans., v. 51, 1932, p. 923) the edge gap was advocated as a means of coördination. In the previous paper (A.I.E.E. Trans., v. 52, 1933, p. 411) on the same subject it was indicated that coördination of major insulation or of a surge proof transformer was generally obtained down to 2 μsec. Furthermore, in this paper it has been shown that major insulation or a surge proof transformer should stand surge voltages of a magnitude represented by the flashover of a coördinating gap near 2 μsec. This paper also gives complete data for edge gaps for time lags below 2 μsec and for very high rate of rise of voltages. In addition we must take into consideration the polarity of the surge. It has now been well established that the higher voltage surges in service are negative in polarity. Full waves with negative polarity may be a considerable percentage higher than positive waves and even at 2 μsec the flashover of edge gaps for negative waves is still somewhat higher than for positive. Therefore it seems time to take account of all of these facts and consider the subject of coördination with gaps upon a more logical basis. It seems then reasonable to base coördination upon negative surges as limited by the standard coördinating gap. As the 2-μsec value of the gap approaches the insulation level and therefore, as stated completely in the beginning of this discussion, this is the critical point for both 2 μsec and longer waves, it seems logical that the gap setting be based corresponding to this point, thus covering automatically and completely waves of greater duration. However, for shorter waves of durations as indicated in Fig. 5 of the paper, if deterioration is to be avoided a derating of the gap is essential. Taking into account all these facts, Fig. 3 in this discussion gives our recommended equivalent coördinating gap levels for wave duration from a

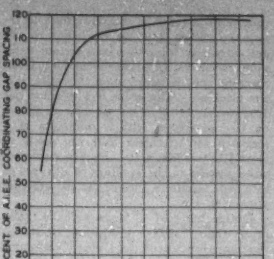


Fig. 4. Gap coördination for positive surges

Gap spacing expressed in per cent of standard A.I.E.E. edge gaps for constant factor of safety in power transformer insulation. This curve is based on the requirements for negative surge coördination

fraction of a microsecond through the critical 2 μsec and greater.

It will be noted from Fig. 1 that surge proof transformers are just as strong as the coördinating gap for negative surges. Also an inspection of the time lag curves for positive and negative waves will show that the present A.I.E.E. tests do not demonstrate this. For example, the test on a 230-kv transformer, according to the present test code, need be only 1,240 kv, whereas a surge of negative polarity chopped at 2 μsec with a 64 in. gap would impose 1,430 kv. It is for this reason that the authors have advocated a change in the test code to provide a test of at least 2.9 times the 60-cycle test voltage. An example of a test of this kind was reported in the paper for a 230-kv surge proof transformer. Mr. Clem has stated, as indicated by his Fig. 2, the policy of his associates in giving out the strength of transformers in terms of the impulse tests which could be applied. We prefer to give out the values which could be appli d at 2 μsec, indicated in our Fig. 3. If this figure is translated in turn to correspond to gap lengths for positive surges, we obtain Fig. 4 which is merely of academic interest; however, it may be useful for comparing with other data.

Modifications to the present transformer test code have been proposed but we see no reason for making any change in the test code other than to increase and conform its severity in line with service requirements, as indicated by the coördination problem, and to provide a further simplification in the test code.

A considerable part of the discussions by Mr. Bewley, Mr. Clem, Mr. McEachron, and Dr. Fortescue pertain largely to the problem of protection against direct strokes. In substance, these discussions are well covered in our paper under "The Coördination Problems: Direct Strokes and Short Waves," and in fact we see nothing really new except possibly a detailed extension of the basic principles we have developed. The general use of the ground wire over stations is now well known and it has been used for a number of years, as outlined in Dr. Fortescue's discussion. However, we believe that the use of 2 gaps or protective devices, as indicated in Figs. 7 and 9 of the paper, were first proposed by the authors, as described in the A.I.E.E. Trans., June 1933, p. 445. Furthermore, the present paper covers the effect of repeated surges on insulation and its deterioration. All these important additional facts underlying the protection problem against strokes, and their proper coördination, are developed in the paper into the methods of protection indicated in Figs. 7 and 9 of the paper. These methods of protection in the final form indicated are, we believe, original contributions of this paper.

We are in accord with the analysis of Mr. Bewley on the shielding and protection of substations against direct strokes. In considering chopped waves traveling over a considerable distance, such as 1 mile as is considered by Mr. Bewley, the authors have clearly stated that account must be taken of attenuation. The analysis Mr. Bewley presents is a specific application of the fundamental principles developed in the paper; in fact the eqs 4 which he gives may readily be arrived at from the application of eq 1 in the paper. However, even in the case he considers, multiple coördinating gaps will serve a useful purpose.

Both Mr. Clem and Mr. McEachron have given a very complete and detailed discussion of protection against surges and direct strokes. The general facts, stated in their discussions, are well recognized and accepted.

In the paper an important statement was made that the question of transformer protection against direct strokes was one of economics in that it might be decided to run the risk of failure due to direct strokes, or to so coördinate the transformer insulation that it would withstand direct strokes, or to avoid any possibility of direct strokes at the apparatus. Of these 3 propositions it appears that the second proposition is not feasible. This appears to be generally agreed to. The third proposition is the most expensive since it involves shielding by means of ground wires, gaps, lightning arresters, and ground networks, but such applications may be fully warranted in large and important stations. In such stations not only freedom from outage but no possibility of deterioration of the apparatus within the station can be permitted. From the requirements of such a station to those of smaller and generally less important stations the degree of risk which may be run may extend over a considerable range. Consequently, with smaller and less important stations various protection schemes are possible, each adapted to the economics and the risks of the particular station in question. The greatest amount of risk may obviously be run in small stations where an occasional outage or some deterioration or transformer failure may be well compensated in reduced cost of substation expense.

It might be of interest here to furnish an idea of the degree of risk which might be encountered in a station using the least amount of protective equipment, such as the coördinating gap alone. In conjunction with the smaller and less important stations, which are no doubt numerous, an idea of the amount of risk incurred is illustrated in the very interesting discussion given by Dr. Fortescue. Referring to his example on 132 kv lines having ground wire protection, the probability of an outage due to lightning near and at the substation is once in 30 years. In such a case it seems reasonable to expect good performance from a plain rod gap coördination. However, where lightning is more severe and in general for constructions involving wood pole lines, as indicated by both Dr. Fortescue and Mr. McEachron, additional protection in the way of a lightning arrester seems desirable. In actual practice this is particularly the case for low voltage lines ranging from 15 kv to 44 kv. These observations are to some extent justified by the fact that transformers in the past, which were obviously very poorly protected, still have had a remarkably low mortality. On the other hand, exceptions have been brought to light where transformers in certain localities have had repeated failures. These conflicting data show the probability of obtaining fairly good protection for transformers in stations of small and no importance and equally well the desirability of providing all the protection for stations that are large or of great importance. To this general statement we may add that occasionally in small stations, where lightning severity is unusually high, either for geographical or topographical reasons, better protection than is normally used for such a station is justified.

Insulation Resistance of Armature Windings

Discussion of a paper by R. W. Wieseman published in the June 1934 issue, p. 1010–21, and presented for oral discussion at the electrical machinery session of the summer convention, Hot Springs, Va., June 27, 1934.

P. L. Alger: I should like to emphasize the fact that Mr. Wieseman's paper is not intended to set any definite standard or allowable limit of insulation resistance for any purpose. The paper is chiefly intended to explain the known types of variation which occur in insulation resistance, particularly the effects of dimensions and other design characteristics.

By suggesting a definite test procedure, pointing out the importance of moisture and temperature effects, and giving the definite effects of design changes, it is intended to bring out in clear relief the remaining factors of variation. Study of these remaining factors should enable much valuable information on insulation condition and life expectancy to be obtained.

I am convinced that, despite the tremendous and seemingly erratic variations in insulation resistance which are known to occur, patient analysis will finally disclose the reasons for, and thence the meanings of, all these variations. Hence, I believe that we shall in time be able to tell a great deal about the fundamental quality, the present condition, and the likelihood of failure of insulation of machines under operating conditions, if we pursue the study which Mr. Wieseman has thus well begun.

I should like to appeal particularly to the

operating engineers to obtain data by the methods Mr. Wieseman suggests, or other methods which may be found expedient, and to publish their data so that a rational technique can be developed for judging machine insulation in the manner already laid down in the testing of cable and bushing insulation.

The present situation in regard to insulation appears to me much the same as that of core loss 30 years ago. It was then repeatedly said that core loss could not be predicted and was too erratic to make it worth while to attempt its calculation. Nevertheless we can now predict the core losses of most machines to within a very few per cent, and the studies that led to this result also led to very important improvements in design. Similarly, by studying insulation resistance we should find not only better means for judging insulation but also means for improving it.

K. A. Reed: I regret that the discussion of this paper was closed before all discussers had an opportunity to present their views inasmuch as oral discussion at the time of the presentation of a paper is much more effective than written discussion that is published at a later date.

The author is to be commended for his contribution to a subject to which we have devoted much study over a long period of years, but one to which some of our electrical manufacturers have given scant consideration until within the past few years. We hope that the subject will continue to receive due attention; at least until such time as better and more definite means are devised for obtaining information concerning the condition of the insulation of electrical apparatus.

We agree with Mr. Wieseman that the minimum insulation resistance formula embodied in the A.I.E.E. Standards for many years is of no real value, since the results obtained from this formula are, by far, too low for the safe operation of electrical apparatus. We have endeavored for a long time to bring about a proper change in the formula, and the subject was discussed with the National Electrical Manufacturers' Association early in 1927 in an effort to obtain some action from that source. A revision of this formula has been under consideration by the electrical machinery committee of the A.I.E.E. for the past 2 or 3 years, and the formula it has recommended for adoption is inadequate.

A number of points brought out in Mr. Wieseman's paper will be discussed in the order in which they appear. With respect to item No. 1 at the beginning of the paper, many cases arise where a single insulation resistance reading taken under the conditions mentioned does have a great deal of significance. For example, a machine may be removed from service and a reading taken while the machine is hot shows the insulation resistance to be low, despite the fact that the machine appears to be clean and there has been no opportunity for the winding to absorb moisture. There may be a coil loose in its slot and the chafing has worn the insulation to a dangerous point, or the low reading may be due to numerous causes. The discovery of such a condition by taking a random reading may avoid the breakdown of a winding.

With reference to the latter part of item 3, it is practically impossible to determine in the field, without cutting into the insulation, whether class *A* or class *B* insulation has been used, and formulas that take such items into account are impracticable for field use.

We disagree with the first part of item 11 which states that a low insulation resistance is the result of several months of moisture accumulation because the winding requires considerable time to absorb moisture. There are many things other than moisture that cause low insulation resistance and many cases come to our attention where, under certain "operating and local conditions," low insulation resistance may develop within a few days with respect to a winding that remains dry when the machine is in normal operation.

The items that are taken into account by the author in devising his formulas for armature winding insulation resistance, as shown on p. 1011, may be all right for exact values that are desirable in a laboratory, where storage batteries and other unusual test apparatus are available, but we do not believe that for ordinary practicable purposes so many variables are either necessary or desirable. It is, of course, true that the large, slow speed machine has a much greater area of insulation exposed to iron than a small machine or a high speed machine and, in general, one might expect to find the insulation resistance of the former machine lower than that of either of the 2 latter machines when all are subjected to the same operating conditions. However, from actual experience, we have found that such is not the case, as will be outlined later in this discussion.

Among the disadvantages that are involved in the author's scheme are:

1. Armatures only are covered.
2. Numerous formulas are required, one each for machines of several types and capacities.
3. Many variables are involved, such as the class of insulation on the winding, the relative humidity, whether or not the machine is clean and dry, built in the summer or the winter, etc.
4. A great many constants are involved and it appears that they are of a more or less arbitrary nature.
5. "Reasonable assumptions" are made and "average values" are used for certain factors that vary somewhat from one machine to another.
6. Special consideration has to be given a single-phase machine if it is equipped with a 3-phase, wye connected winding.

The author has very ingeniously devised a scheme whereby the numerical solving of more or less complicated equations is avoided, and this scheme would, doubtless, be of tremendous value to many maintenance men. However, a material amount of graphical computation is still necessary and it would be impracticable for a person to carry around with him a number of sheets applying to different types of machines from which he could determine the insulation resistance of various sizes and kinds of armatures, only to find it necessary to obtain the insulation resistance of the other parts of the machines in some other manner.

From our point of view, there is only one purpose for which insulation resistance is determined, namely, to obtain a "more or less" definite indication as to whether or not the condition of the insulation of a given machine is such that it is safe to place the machine in service. We are not at all interested in exact or specific insulation resistance values, but, on the contrary, we are extremely interested in a certain minimum insulation resistance value for a given machine that is based upon the voltage of the machine. This value is 1 megohm per 1,000 volts rating of the machine as shown on its nameplate, with a minimum of 1 megohm for machines that are rated at from 100 to 1,000 volts. Such a minimum value applies to the windings of all types of rotating machines, transformers, starting apparatus, etc.

During the past 12 years we have taken more than 750,000 insulation resistance readings throughout the United States and Canada. These readings have applied to all types and capacities of electrical apparatus, and they were taken with care by experienced engineers under all weather and load conditions that arise. Throughout this entire experience we have invariably found that when the windings of a piece of electrical apparatus are in proper operating condition, a minimum insulation resistance reading of at least 1 megohm per 1,000 volts rating of the object can always be obtained.

In view of the fact that minimum insulation resistance values such as those just described have been found by a very broad experience over a long period of years to indicate that windings with such insulation resistances are safe to operate, it appears to us to be unnecessary to spend considerable time in an effort to develop exact values that will, in a very large percentage of cases, be higher than the minimum necessary for safe operation. The method of procedure that we are following gives instant results and it is definitely known without any computation whether or not the object requires attention. It is, of course, essential to properly analyze insulation resistance readings with respect to weather conditions, whether the machine was hot or cold, etc., inasmuch as these factors may influence the value of the information that the readings are intended to develop.

We are in disagreement with that part of Mr. Wieseman's discussion of his paper at the time of presentation wherein he expressed the view that practically all insulation resistance readings are improperly taken. Our method of procedure is uniformly followed by all field engineers and the results obtained make it clear to us that we are "getting somewhere" along this line. I might further add that our experience has shown that the minimum values we have set up may always be obtained regardless of the capacity, type, or speed of the machine, and our readings are taken with conventional types of ohmmeters and meggers.

In the examples shown by the author in Figs. 9, 10, 11, 12, and 13, minimum insulation resistance values of 0.65 megohms, 2 megohms, 0.9 megohms, 0.6 megohms, and 0.6 megohms, respectively, are given for armatures only. We would expect to obtain on all windings and other insulated parts of these objects minimum insulation resistance values of 4 megohms, 2.5 megohms, 1 megohm, 1 megohm, and 1 megohm, respectively, and if such values were not obtained, insurance would be withheld until the causes of the low readings were located and removed and the insulation resistance values brought up to the minima prescribed.

S. L. Henderson and J. F. Calvert: This paper is of value for the many important points concerning the resistance of armature insulation which are carefully summarized at the first of this paper. Most of the facts emphasized here are well known, but when assembled in this concise form they should furnish a more solid foundation for the future discussion of insulation resistances.

A further contribution is the discussion of the relations between armature resistance and time. This indication of the condition of armature resistance may prove quite useful, particularly to operating engineers.

The fact that the formulas are complicated by fractional exponents has been very neatly overcome by the introduction of graphical methods of calculation which are very easy to use.

A comparison is given between the proposed American Standards Association method of calculating insulation resistance and the methods proposed in this paper. We believe that a comparison with actual test data is the important thing here and that it is very unfortunate that this comparison is not made. Test data is the only thing which can be used as the basis for judging the real merits of these formulas. We believe that if such data were taken on "run of mine" cases such variations would be found in the test data that the differences obtained by the different formulas would seem much less important. The fact that tremendous differences in test data may be expected is shown by the very large allowable variations in the equation constants given in Table I of Mr. Wieseman's paper. In one case a 12 to 1 range is allowed for good insulation, all at the same temperature. Of course, a very large variation is to be expected with temperature, for in many of the bonding materials used in built up mica insulation the resistance decreases many times as the bonds reach temperatures where they become fairly plastic.

In the past few years, considerable data have been collected on insulation resistances by another of the large manufacturing companies. The following is summarized from tests on over 300 machines:

I. Tests on Induction Motors at the Factory:
Number of machines tested—43
Insulation—class *A*
Temperature—"cold" or about 21 deg C
(All but 4 measured armature insulations were 100 megohms or above. These 4 were 14, 30, 30, and 50 megohms.)
Percentage of the machines failing to test up to the calculation values:
By Wieseman's formula using K_t = 0.015, the value given for good operation at 21 deg C..... 25.6 per cent
By the proposed A.S.A. formula $\dfrac{E}{\dfrac{\text{Rated kva}}{100} + 1{,}000}$ ..... None
By the proposed A.S.A. formula times 40..... 9.3 per cent*

II. Tests on Induction Motors at the Factory:
Number of machines tested—17
Insulation—class *A*
Temperature—"hot," or about 75 deg C
(The range of measured insulation resistances was from 4 to 100 megohms with approximately half of the machines having resistances of 45 to 100 megohms.)
Percentage of the machines failing to test up to the calculation values:
By Wieseman's formula using K_t = 0.0002, the minimum value given for 75 deg C..... None
By the proposed A.S.A. formula $\dfrac{E}{\dfrac{\text{Rated kva}}{100} + 1{,}000}$ ..... 5.9 per cent
By the proposed A.S.A. formula times 4..... 5.9 per cent

III. Tests on Turbine Generators at the Factory:
Number of machines tested—40
Insulation—class *B*
Temperature—"cold," or about 21 deg C
(With the exception of 3 values, all insulation resistances were 100 megohms or above. These 3 were 25, 38, and 50 megohms.)
Percentage of the machines failing to test up to the calculated values:
By Wieseman's formula using K_t = 1.0, the value given for good operation at 21 deg C..... 57.5 per cent
By the proposed A.S.A. formula $\dfrac{E}{\dfrac{\text{Rated kva}}{100} + 1{,}000}$ ..... None
By the proposed A.S.A. formula times 40..... 22.5 per cent*

IV. Tests on Turbine Generators at the Factory:
Number of machines tested—13
Insulation—class *B*
Temperature—"hot," or about 75 deg C
(The lowest resistance was 15 megohms and all but one were below 100 megohms.)
Percentage of the machines failing to test up to the calculated values:
By Wieseman's formula using K_t = 0.1, the minimum value given for 75 deg C..... 15.4 per cent
By the proposed A.S.A. formula $\dfrac{E}{\dfrac{\text{Rated kva}}{100} + 1{,}000}$ ..... None
By the proposed A.S.A. formula times 4..... 7.7 per cent*

* These values are all for higher voltage machines. This shows that the higher voltage machines have less margin under the proposed A.S.A. standard than do the lower voltage machines.

From the summaries of the megohm resistances given for each of the above group of tests, it is seen that all are sufficiently high to be quite safe. Practical operating experience bears this out. An extremely high insulation resistance may mean the insulation is very dry. It may still have voids, be brittle, or both, and therefore not be in good condition.

As indicated above, great variations in test values are found. These variations cannot be accounted for satisfactorily on the basis of insulation thickness and the area in contact with ground as is undertaken in this paper. A possible explanation of this is that unless the coils all have a good grounding material on their surface, the path for the resistance currents to ground may be very uncertain. The essential thing is that the insulation resistance be high enough to indicate a sufficiently dry insulation. We believe that the proposed A.S.A. formula meets these requirements when modified for a-c machines to state that the minimum value allowed will be one megohm. A simplification of the proposed A.S.A. formula for the insulation resistance of a-c armatures, which is more convenient and gives practically the same value, is:

$$\text{Megohms} = \frac{\text{Voltage}}{1{,}000}, \text{ with a minimum value of one megohm.}$$

It is unfortunate that Mr. Wieseman has not included field insulation resistance in his paper. We believe that on large a-c machines this is of practically equal importance. We have collected data on a large number of machines and are convinced that this subject is well worth studying.

It will be noted that all our data is based on tests at the factory. Operating engineers are in the best position to discuss what are safe and usual values and it is hoped that helpful data will come from this source.

R. E. Hellmund: During the early days of electrical machinery, a great deal of attention was paid to the measurement of the insulation resistance of new machines. However, the results obtained were so irregular that they did not seem to be of real practical value and therefore less attention was paid to these insulation measurements as time went on. More recently, however, the question has again been agitated, and Mr. Wieseman's paper as well as the study indicated by the discussions of Messrs. Henderson and Calvert and others are evidence of a somewhat renewed interest in this subject. Unfortunately, however, there does not seem to be available even now sufficient data and knowledge for formulating any rules that would be sound from an economical or operating point of view.

Mr. Wieseman in his paper makes an attempt to eliminate some irregularities by a uniform test procedure and to include some variables in his formulas, such, for instance, as a rough measure of the entire insulating surface. Although there is some logic in this, all the test data available plainly indicate that several other variables are of much greater practical importance than this insulating area; in fact, the test data indicate that there is practically no relation between such area and the results obtained. The formulas given take care of other variables by the proper choice of coefficients; these coefficients, however, vary over an exceedingly wide range. The amount of variation of these coefficients is entirely out of proportion to the variations introduced by the remainder of the formulas. It therefore would hardly seem advisable to introduce complications which at the present state of the art are not justified. With reference to the influence of the size of the insulating area, on the one hand it may be true that, everything else being equal, a lower resistance should be expected with increased area; on the other hand, it should also be considered that the larger the machines and the corresponding investment, the more desirable it is to increase the factor of safety. If some weight is given to this consideration and if it is fully appreciated that there are many uncontrollable variables, it seems that for the present there is a good deal of merit in the very simple rule suggested by Messrs. Henderson and Calvert for a-c armatures.

On the whole, however, I feel that before formulating any definite rules, we should establish a definite objective and devise a plan working toward such objective. If the insulation resistance is of any practical value in some or in all cases of machine windings, it is because it may indicate the possibility of breakdown and service interruption. Therefore, if it can be established that there is a relation between these factors, both manufacturers and operators should be willing and anxious to make practical use thereof. The only possible way of arriving at any conclusion in this manner is through a collection of statistical data definitely inter-

relating insulation resistance measurements and breakdowns as well as the nature of the breakdowns. The latter item is of utmost importance. The data given by Messrs. Henderson and Calvert, for instance, seem to indicate that in the case of new a-c armatures, which usually have no exposed conductors, it is relatively easy to obtain a minimum insulation resistance of one megohm; it is furthermore quite likely that statistical data would show the danger of breakdown if the resistance of such windings reaches lower values. On the contrary, it is quite probable that statistical data relating to machine parts having a great many exposed conducting parts, and which therefore depend largely upon creepage distances, would show that the tested insulation resistance is of practically no value in giving any indication of the condition of the winding proper, although it may indicate the advisability of cleaning the creepage distances. In so far as the exposure of conducting parts cannot be eliminated in the case of commutators and slip rings, it may always be impracticable in these cases to resort to insulation tests for sizing up the operating reliability of the windings. Exposed conducting parts are also quite commonly used in connection with various types of field windings, and through facilitating ventilation and simplifying the insulation structure they have resulted in appreciable economies in design. The purchaser of these machines certainly would not be willing to pay higher prices for such machines, which he would have to do if such economies were eliminated, unless he could be definitely shown by statistical data that the lower insulation resistance which is likely to result from such designs actually indicates increased danger of breakdowns.

In view of these facts, I wish to emphasize again that the collection of statistical data, or the submission of such data by those who may have them available, and an analysis thereof should be the first step toward clarifying the issue. Unfortunately the manufacturers are not in a position to collect data of this nature and therefore must depend upon others for them.

W. B. Creagmile: There has been some feeling for a long time that A.I.E.E. Standards for insulation resistance of electrical machines were inadequate and in many cases gave too low a value for the resistance. Mr. Wieseman is to be congratulated on having developed workable formulas which take into account type, rated capacity, voltage, speed, and kind of insulating material of electrical machines. It is to be hoped similar research can soon be extended to other types of electrical equipment.

The following comments and criticisms may help to clear up what we believe to be a few rather important details, and in that way to stimulate a more extended practical use of insulation resistance tests for detecting and diagnosing insulation weakness.

Under the heading "Measurement of Insulation Resistance," p. 1011, it is stated:

"Insulation resistance of an armature winding may be measured with an instrument such as a megger, 'megohmer,' etc.; or with a voltmeter or a microammeter connected in series with the winding and a direct voltage. The megger has been used for many years, and it gives reliable readings if it is calibrated periodically and if it is operated long enough to eliminate the electrostatic capacity effect of the winding. With the voltmeter method, the maximum resistance that can be measured with reasonable accuracy is about 10 megohms when an ordinary voltmeter is used and about 100 megohms when a high resistance voltmeter is used. From the operator's viewpoint, however, a resistance above 100 megohms for any machine is considered satisfactory. The microammeter method is very accurate for measuring high insulation resistances if a storage battery furnishes the voltage."

We believe the author's reference to need for frequent calibration of megger instruments may be based on the use of instruments which have been in service for many years without recalibration, whereas voltmeters and microammeters are likely to be recalibrated frequently. It has been our experience that megger instruments hold their calibrations remarkably well, and do not need to be checked frequently.

Reference is made to an insulation resistance of 100 megohms being satisfactory from the operator's viewpoint. Accordingly, in practically all cases of testing the insulation resistance of electrical machines, a megger instrument having a range to 100 megohms will cover the requirements. Such an instrument has zero as the first point on the scale, with the highest numbered mark 100 megohms, and with infinity also marked. Such an instrument is self-checking at zero and infinity by operating on short and open circuits. If correct at these points, there is little chance for error throughout the scale. If it is possible to check the instrument on a resistance of 1 megohm and it is correct at this value also, there is almost no chance of error at any point on the scale.

The effect of electrostatic capacity on the testing instruments is not confined to the megger but appears also if any other type of ohmmeter, voltmeter, or microammeter is used. The megger will charge the electrostatic capacity at a slower rate than a storage battery, because of the small size of its generator and the use of a ballast resistance in series with the test circuit within the instrument. However, by shunting the ballast resistance of the megger during the first few seconds the voltage is applied the charging rate may be quickened very much. A 500-volt storage battery is seldom available, and for this reason, as well as convenience, etc., megger instruments have come to be considered standard for the testing of insulation resistance.

It is not intended to discuss values assigned to coefficient k as to whether they give too high or too low a value of resistance. The coefficients set down for conditions 1 and 2 of Table I at top of p. 1014 can be determined by tests on comparatively few machines. Coefficients for condition 3 and more particularly condition 4 must be determined by a long series of tests on many machines, and depend largely on the judgment of those who assign the proper values for insulation resistance. Condition 4, under which a machine should be cleaned and/or overhauled, is the one of greatest interest to the man who operates the machine.

We suggest that many plant electricians may find difficulty in working out the formulas given or in applying nomographs correctly, and we believe that recourse will be had to requesting the proper value of insulation resistance from the manufacturer, or failing in that, to resort to some relatively practical value such as one megohm. A "one megohm standard" has been set by many electrical engineers and plant electricians as sufficiently high for safe operation and not too difficult of attainment. It is higher than most values determined by the A.I.E.E. Standards except for high-voltage synchronous machines, and appears to have worked out very well in practice. Should one megohm prove to be too low in view of the values determined by the formulas given in the paper, a readjustment upward will probably follow in due time.

In the summarization of the paper (p. 1016), it is stated:

"The trend or slope of the curve of insulation resistance will indicate the condition of the insulation better than insulation resistance values themselves. If an insulation resistance curve of a machine is not available, insulation resistance obtained by the formula for conditions 3 and 4, Table I, can be used as a basis for comparison."

We understand the reference to be to what the author calls elsewhere an insulation resistance-time curve, extending over 10 to 15 minutes and similar to Figs. 1, 2, and 3 of the paper. These curves are very interesting, and the author's suggestion of how to use them in diagnosing the flow of current, whether due principally to moisture in the insulation and surface leakage, or absorption (see column 1, p. 1012), appears to be new and highly commendable. We would point out, however, that the curves shown are for very high values of insulation resistance—far higher than any values given in Tables II, III, IV, and V. Unfortunately, as illustrated in Fig. 2, the curve tends to become quite flat if the conduction and leakage currents are large compared to the absorption current. This is the case for such values of resistance as are determined by the formulas given in the paper, and the absorption current has relatively little effect. Consequently such curves are of little practical value to the man who wants to know if trouble is brewing.

Another sort of curve which is likely to prove even more useful (and which we thought at first the author might have had in mind) is a curve plotted for insulation resistance taken at periodic intervals such as one week or one month. Brief mention of such tests is made at the end of the author's summarization.

We believe thoroughly in periodic tests of insulation resistance and are backed up by the practice of many engineers who make such tests and record and plot values on cards properly ruled. Insulation tests are made only that we may know the condition of our machines. Consider the following cases:

Insulation resistance so low that operation is unsafe and something must be done to raise the resistance.

Insulation resistance low but well maintained. Machine is probably all right for operation, but an effort should be made to locate and remedy the cause of the low resistance.

Insulation resistance of fair or high value and well maintained. Machine should give little cause for worry.

Insulation resistance of fair or high value but showing a constant tendency toward lower values. An effort should be made to locate and remedy the cause and check the downward tendency.

Insulation resistance of fair or high value and previously well maintained but showing a sudden lowering in resistance. When this occurs, the machine should be watched carefully, and insulation resistance tests made at short intervals until the cause of the lowered value is located and reme-

died, or the resistance becomes steady at a lower value safe for operation, or reaches so low a value that the machine is unfit to be kept in service.

The paper recommends reading insulation resistance at the end of one minute electrification. It is worth noting, as shown in Figs. 1, 2, and 3, that there is an apparent increase in resistance for several minutes. Consequently, if in less than one minute the resistance of any machine is more than the value set for that machine, there is no necessity to wait until the end of any stated time interval before taking the reading unless records are to be kept for comparison, in which event all readings should be taken at the end of the same time interval.

E. J. Rutan: The paper on insulation resistance of armature windings is of particular interest in that the author is making an attempt to develop a suitable formula which will result in an insulation resistance higher than that at present required by the A.I.E.E. Standards. It is well known and considered rather peculiar that the formula at present approved results in a required insulation resistance far below that usually attained. The author's efforts are therefore to be commended in that he would require insulation resistances more in line with normal manufacturing practice on new machines. Although the formulas as developed may not be the most desirable way of expressing the limits to be attained, they are at least a start.

In connection with the constants for machines in service, I would like to speak with particular reference to synchronous converters. The formulas proposed still allow too low an insulation resistance for what would be considered safe operation. In general, the larger synchronous converters are used on systems where it is very undesirable to have failures from lack of proper maintenance. When insulation resistances as low as one megohm are permitted, there is considerable uncertainty as to when the resistance may suddenly become so low as to cause a flashover or failure. This is mentioned because on converting apparatus low insulation resistance is usually due to the collection of dirt or dust between exposed live parts and ground. A thorough cleaning and blowing out of the machine will usually eliminate this condition and bring the insulation resistance well above one megohm. Accordingly, in my estimation, any formula which provides a standard below that figure, is not suitable.

Of course it is known that insulation resistance is not a true measure of the condition of the insulation, but if regular tests are made and the trend is obtained the operator is well able to decide when the machine needs the necessary cleaning and maintenance.

The last paragraph of the author's summary gives the necessary information for determining the condition of insulation and the desirable method of using insulation resistance information.

J. L. Rylander: Mr. Wieseman's paper is a desirable addition to the subject of insulation resistance, on which comparatively little information has been published. The curves showing the variation of resistance with the time of appilcation are new and

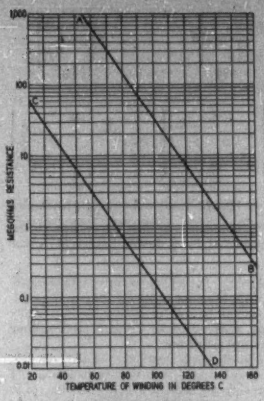


Fig. 1. Variation of insulation resistance with temperature

bring out clearly another of the several variables encountered when dealing with this subject.

However, the suggested formulas with their different fractional exponents and their different values and the nomographs do not eliminate any one of the major variables. Furthermore, these formulas are complicated, whereas the present formula is quite simple and probably more accurate.

The constants chosen by Mr. Wieseman for his formulas are so different from each other that it would be difficult to have confidence in them. For example, the constant for class *B* insulation in Table I is 188 times as great as for class *A* insulation for No. 4 condition. It would be difficult to choose a constant for those machines which have a mixture of class *A* and class *B* insulation materials, such as those that use class *A* insulation plus mica. There does not appear to be any consistent relationship among the many different "constants."

Although the value of insulation resistance is affected by the size of machine, the kind of insulating materials and their quantity, the variations due to these factors are comparatively small when compared to the 3 major factors that are always involved. These 3 are: (1) the temperature of the insulation; (2) the moisture or solvent that is present in the insulation; and (3) the conducting dust and moisture on the surface of the insulation. Any one of these factors is such as to change the insulation resistance value 10 times or 100 times and in some cases even 1,000 times. As the chief purpose of insulation resistance is to determine the extent to which the insulation has been affected by these latter 2 conditions, it seems quite logical that the other great variable (temperature) should always be given the chief consideration when using insulation resistance values.

The straight line curves shown in Fig. 1 of this discussion, obtained from test data, show the manner in which insulation resistance changes with temperature on a particular line of general purpose squirrel cage induction motors. The upper line *AB* shows what the insulation resistance usually is on clean and very dry windings, and the lower line *CD* shows about what the same windings measure if they are filled with unbaked varnish with solvent in it, or if the windings have been soaked in water for a certain time. Intermediate stages of dryness are shown by straight lines parallel to and between these 2 lines.

The formula as proposed by the A.S.A.,

$$R_i = \frac{\text{Rated voltage}}{\dfrac{\text{Rated kva}}{100} + 1{,}000}$$

gives the same values for all ratings up to 1,000 kva as the more simplified rule often used by many:

$$R_i = \frac{\text{Rated voltage}}{1{,}000}$$

Even for a 10,000-kva machine this simplified rule gives practically the same value as the A.S.A. formula. A 100,000-kva machine only doubles the value and that is only a trifling quantity when discussing insulation resistance. It is desirable to have a larger factor of safety on the larger machines. A formula $R_i = \dfrac{\text{Rated voltage}}{1{,}000}$ at a definite temperature such as 75 deg C and a chart like the curve in Fig. 1 of this discussion to make corrections for all other temperatures at which the measurements were taken would be a very decided improvement over the existing formula and methods.

Split Winding Transformers

Discussion and author's closure of a paper by D. D. Chase and A. N. Garin published in the June 1934 issue, p. 914–22, and presented for oral discussion at the electrical machinery session of the summer convention, Hot Springs, Va., June 27, 1934.

P. L. Alger: It appears to me that Messrs. Chase and Garin's paper is particularly interesting as a specific example of progress in a field that has yet been relatively little developed. Since the first important application of the split winding idea in the design of double winding turbine generators some 6 years ago, this scheme has also been employed extensively in starting synchronous motors. Many special winding arrangements have been developed for this purpose. In general, the winding is arranged in 2 or more similar circuits, only one of which is thrown on the line at a time so that the motor can start on full voltage with low current and then be put into operation in one or more additional steps by successively throwing on the other winding sections in parallel with the first. This scheme avoids opening the motor circuit at any time during the starting period, and also avoids the use of any compensator or reactor.

As yet, however, the system has not been used for generators aside from the turbine type. It seems probable that in some of the older low voltage systems the existing

generators could be advantageously reconnected for double winding operation, obtaining increased reliability of operation and reduction of switching capacity requirements. A review of the advantages of split winding transformers described in this paper and those for generators previously described, together with the realization that these advantages can often be obtained in existing systems by relatively inexpensive changes, may lead to a desirable expansion of the split winding system's usefulness.

H. L. Cole: The paper by Messrs. Chase and Garin is particularly interesting to the transformer designer because it points out some of the natural limitations of this type of transformer, as well as a summary of its general application.

In the early days of transformer design it was common practice to split a high capacity or unusually heavy current winding into 2 or more parts and carry the separate circuits to the outside of the case through separate pairs of terminals. This was advantageous because it simplified the coil design and permitted the use of a smaller and less costly terminal arrangement. In extending the separation of the circuits farther than the outside of the transformer terminals, into the station bus and outside the station on separate lines, 2 things must be considered by the transformer designer: (1) the effect of transfer reactance and load unbalance on the losses and heating of the transformer; and (2) the necessity for completely insulating each circuit and making insulation tests (including impulse tests) on each one.

Seven years ago a 94,000-kva bank of transformers for the Colfax station, Duquesne Light Company, was supplied with the split winding type of circuit, to reduce the size of breakers required.

An interesting installation made in 1930 of a 90,000 kva bank, at the Roseland switching station of the Public Service Electric and Gas Company, is described in the Feb. 21, 1931, Electrical World. ("Design Features of the World's Largest Transformers," H. L. Cole and F. J. Vogel.) In these transformers the split windings are for 138,000 volts; they have a high ratio of transfer reactance to through reactance and a comparatively high permissible load unbalance. Various methods of obtaining interlacing and interleaving of windings are described in this article. Many other transformer installations of the shell-type interleaved-coil design, which is particularly suitable for obtaining desired reactances, have been made with split windings.

A. Boyajian: Steinmetz used to lecture on "the serious problem of huge concentrations of energy in short circuits." Little is heard on the subject nowadays because the problem has been solved to a large extent by the split winding generator suggested by Mr. Chase and Mr. Barton, the split winding transformer suggested by Mr. Brand and Mr. Gay, and improved breakers.

As the authors have covered the split winding transformer very thoroughly, I wish to add a few words on how transformer windings or busses and transmission circuits

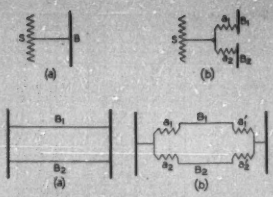


Fig. 1(top). Transformer secondary feeding bus

Fig. 2(bottom). Sending and receiving busses connected by a double transmission circuit

which were not originally split or sectionalized can be split or sectionalized externally by what might be called a sectionalizing autotransformer.

In Fig. 1*a* is shown the one-wire diagram of an unsplit transformer secondary S feeding an unsplit bus B. In Fig. 1*b* is shown this system sectionalized with the aid of a sectionalizing autotransformer having the windings A_1 and A_2 wound so that "through" currents (i. e., from S to B_1, B_2, or from B_1, B_2 to S) flow through A_1 and A_2 noninductively, but "transfer" currents between B_1 and B_2 flow through A_1 and A_2 inductively. Thus, with such an arrangement, the "through" reactance of the system need not be materially affected, but the "transfer" reactance may be adjusted to any desired value. The magnetic circuit of A_1 and A_2 should not saturate under short circuit, neither should the "transfer reactance" be excessive at normal load unbalances. This means that the core should either have an airgap or be altogether nonferrous.

In Fig. 2*a* are shown sending and receiving busses connected by a double transmission circuit. In Fig. 2*b* is shown the transmission system sectionalized by 2 sectionalizing autotransformers, one at each end. Power flowing in lines B_1 and B_2 in the same direction flows noninductively through the autotransformers, but any exchange power between B_1 and B_2 encounters high "transfer" reactance through the autotransformers, and thus short circuits in either transmission circuit are limited to far smaller magnitudes than what would otherwise correspond to the system impedance for normal currents. If power can be fed from only one end of the system, sectionalizing need be done at only that end, but if power can be fed from either or both ends, than both ends are preferably sectionalized.

The size of the sectionalizing unit as a 2-winding transformer in per cent of the base kva will be of the order of a quarter of the per cent transfer reactance, if the base kva for the percentage value of the reactances is the total output of the busses and each section is rated at half of the total. Thus, in Fig. 1*b* let S be a 100,000-kva source, and B_1 and B_2 each 50,000-kva loads. If the transfer reactance contributed by the autotransformer is 50 per cent based on 100,000 kva, the physical size of the autotransformer as a 2-winding transformer will be of the order of 12,500 kva—a pretty husky fellow. This shows that if the transformer or generator is originally sectionalized by proper foresight, a large portion of the cost and losses of the external sectionalizing device would be saved. We say "a large portion" and not "all" advisedly, inasmuch as the addition of this large extra duty on the transformer may not be obtained without increased complication and cost.

An advantage of the external sectionalizing autotransformer is that with it any desired ratio of "transfer" to "through" reactance can be obtained without serious design difficulty, whereas in a split winding transformer, as this ratio increases beyond a value of 4, design difficulties increase with it.

Of course, if the source of power consists of a number of generators or transformers operating in parallel, sectionalizing can be accomplished in simple well-known manners, with or without bus sectionalizing reactors.

A. N. Garin: The "sectionalizing autotransformer" proposed by Mr. Boyajian may be appropriately called a "split winding reactor." It possesses all the reactive characteristics of a split winding transformer; its "through," "transfer," and "one circuit" reactances are readily identified and must satisfy eq 2 of our paper.

It is more convenient, however, to deal with overall impedances of the power transformer and the "sectionalizing autotransformers" taken together, in which case all the formulas and curves of our paper will become applicable.

It has been stated in our paper that when 2 separate lines are connected through reactors to the same terminals of an ordinary transformer the total theoretically possible range of values of the ratio of "transfer" to "through" reactance is contained between the limits of zero and 4. These limits apply when separate reactors are used. The upper limit can be raised, however, by providing inductive coupling, of proper sign and magnitude, between the 2 reactors. This can be done either by means of auxiliary coupling windings on the 2 separate reactors, or by interwinding the 2 reactors together. The latter method would give us a device proposed by Mr. Boyajian under the name of "sectionalizing autotransformer."

The practicability of "sectionalizing autotransformers" for moderate voltages and in moderate sizes is demonstrated by their frequent use in load ratio control transformers under the names of "preventive autotransformers" and "circulating current limiting reactors." The ratio of "transfer" to "through" reactance required for load ratio control application is, however, usually less than one. This explains the difference in size, and consequently cost and losses, between the modest load ratio control reactor and the "husky fellow" visualized by Mr. Boyajian.

H. L. Cole has given a very interesting historical review of the development of split winding transformers beginning with "the early days of transformer design when it was common practice to split a high capacity or unusually heavy current winding into 2 or more parts and carry the separate circuits to the outside of the case through separate pairs of terminals." We might begin perhaps with a still earlier date—the date when multiple connected strands were first used

in transformer windings. I should like to point out, however, that neither transformers with windings consisting of several strands connected in multiple below the transformer cover, nor transformers with windings consisting of several circuits brought out separately through the cover, but connected in multiple at the bus, are split winding transformers in the modern meaning of this term. With parallel circuits, as with parallel strands, the only problem confronting the designer is to obtain approximately equal current division—and as a rule this does not require either large or, as pointed out in the paper, symmetrical reactances.

In regard to the early installations of true split winding transformers, I was interested to learn of the 7-year old Duquesne Light Company transformers. Another early installation is a 66,667 kva autotransformer of the Buffalo General Electric Company which was installed in 1926.

I regret having overlooked the very interesting *Electrical World* article by Messrs. H. L. Cole and F. J. Vogel. From its title one would not expect it to contain the information on split winding transformers it does contain. This article shows that Roseland transformers have a ratio of transfer to through reactance equal to 8.7 and the maximum permissible load unbalance is given by the load division of 40//60 per cent. As Mr. Cole has stated, the permissible load unbalance is comparatively high, considering the high ratio of transfer to through reactance. That still higher values of reactance ratio can be obtained, when necessary, together with still greater permissible load unbalance is shown by the 66,667 kva Brooklyn Edison autotransformers mentioned in our paper, which have a reactance ratio of 13.1 and 34//66 per cent permissible load division.

Mr. Cole's endorsement of statements in our paper concerning the effects of transfer reactance and load unbalance on load losses and concerning the necessity of insulating the circuits of a split winding as if they were separate windings is highly gratifying. Mr. Cole would hardly expect me to agree, however, that shell type construction, which limits the designer to interleaved coil groupings, can possibly be more suitable for obtaining desired reactances than the core type construction, which offers the designer the choice of interleaved, concentric, and mixed interleaved and concentric coil groupings.

P. L. Alger's discussion is valuable in pointing out the spread of the "split winding" principle of construction among various types of electrical machinery. The process is far from being completed and undoubtedly new and unexpected applications will be found. It would be interesting to survey the fields of steam, hydraulic, and other nonelectrical machinery with a view to introducing the "split system" principle. We might learn, however, that mechanical engineers were the first to apply this principle.

Returning to electrical engineering, the concepts and methods developed for the study of split winding transformers may be found applicable and illuminating in apparently unrelated fields. As an example, a symmetrical 3-phase system may be considered as a system split into 3 circuits. The "through" load, with definition modified to permit the angular displacement of the 3 phase currents, is given by the positive phase sequence currents. There are 2 "transfer" loads, represented by negative and zero phase sequence currents respectively. The 1 "through" and the 2 "transfer" impedances are readily identified as the impedances offered to the flow of positive, negative, and zero sequence currents. Thus the ability of the 3-phase system to carry unbalanced loads, its performance under unsymmetrical faults, etc., are seen to be analogous to the characteristics of split winding transformers.

Encouraging Initiative in the Engineering Student

C. L. Dawes, June 1934 issue, p. 910–4.

Industry Demands and Engineering Education

L. W. W. Morrow, April 1934 issue, p. 518–22.

Engineers of the Next Generation

C. F. Hirshfeld, June 1934 issue, p. 857–9.

Discussion of a group of papers (and author's closure of one paper) presented for oral discussion at the session on education at the summer convention, Hot Springs, Va., June 26, 1934. (Discussion and closures of individual papers of this group are given under separate headings on later papers.)

P. L. Alger: These 3 papers seem to me most significant of a fundamental change that is taking place in technical education. Each of them expresses in a different way the broad conception that we must seek out and teach the fundamentals of engineering knowledge.

Professor Dawes emphasizes the necessity for developing initiative and self-reliance of students. Self-reliance, however, comes only from ability to handle new situations, which implies a thorough grasp of the fundamentals of knowledge common to most engineering problems.

Mr. Morrow stresses the need for giving the business man an understanding of engineering, so that the broad planning which he is responsible for will be more intelligently done. This again requires the selection and presentation to the students of the essence of engineering knowledge.

Mr. Hirshfeld appeals for common action in defining the requirements for engineering proficiency and evaluating the existing curricula. Here also the first step must be to define the fundamentals of engineering knowledge.

Dr. Steinmetz once said that early in the process of learning, each additional fact is more difficult to retain than the last one. Finally, however, some favored people reach a stage where new knowledge becomes successively easier and easier to acquire, due to their appreciation of the interrelations of facts, and to such analogies as those suggested by the periodic table of elements. I believe we have now reached this critical stage in engineering education as a whole. We should teach knowledge as a single subject, not as a series of disconnected courses carried to widely different degrees of refinement.

So far as possible, knowledge should be acquired in the same manner that the successive terms of an infinite series are developed, each term being logically developed from the preceding one, and each representing a higher degree of specialization. We do not learn to swim by taking a lecture course on the proper arm motions and then waiting a couple of years before entering the water. Nor should we take a mathematics course without concurrently putting the mathematics to practical use.

I think that the mathematics should be taught as though it were nothing more than a shorthand for describing the physical realities, the same expressions being representative of a wide variety of natural phenomena. By training the student at each step to translate from the mathematics to physics and back again, most of the basic essentials of all types of engineering should be acquired in a single course.

Also, economics should be so taught that the student will regard all history as a laboratory report of the results of a series of experiments, by analysis of which he must determine the causes and effects of all human actions. The laws of ethics as well as those of finance may be developed by study of economic data just as the laws of gases have been developed by physical and chemical experimentation.

If these 2 subjects of mathematics and economics can be so intimately related to the student's own observations and actions that he instinctively collects all available information and arranges it in mathematical form before reaching a conclusion, that student will be well fitted for an engineering career.

E. E. George: In this most interesting symposium on engineering education nothing has been said about costs or economics. It seems to be generally assumed that an engineering education is always worth what it costs, and that we need not consider whether or not the cost of production is reasonable and whether or not the selling price is at least equal to the cost of production. Yet the cost of education of all kinds has risen with great rapidity, and recently there have been wide-spread and well justified criticisms of the cost of schooling, even in the grammar school grades. Certain educators have seemed to think that parents should pay anything requested for tuition, textbooks, or school taxes, so long as the request was made in the name of *education*. Perhaps these current discussions about engineering education will result in the engineering student getting more nearly the worth of his money.

However, the suggestion to add another

year or 2 to the present 4-year technical courses seems to the writer to be a step in the wrong direction. Such a move tends more and more to restrict education to the children of the wealthy, yet very few argue that boys from families of wealth would make the best engineers or would be more satisfied in their profession. The coöperative engineering courses offered by certain schools have considerable value, enabling each student to earn part of the cost of his education, aside from their value in orienting his perspective of engineering work in general. Some course should perhaps be set up whereby the student could attend school for 2 or 3 years and then, after a year or 2 of work in the field to replenish his finances, go back and finish his professional course. This would mean less rearrangement of class schedules and courses than in the present coöperative courses in which students change every 6 weeks.

There are today many occupations where some technical knowledge is essential but where a limited amount may be reasonably satisfactory. There should be courses of 2 or 3 years which would give a man some practical technical information, even though they do not qualify him as a professional engineer. At present the engineer who completes only part of the 4-year course has no definite standing, no diploma, and has not acquired any correlated technical education of consequence. The manual training school idea has never taken hold much in this country, but there are lots of men with some practical experience who would be worth much more to themselves and to their employers after a year or 2 of technical engineering education in fundamental principles. Because the educational system of today offers nothing of this kind, many large employers try to train their own men. This in itself indicates that the educational system is falling down on the "industrial" end of the job.

The Institute was favored with some very fine addresses on the duties of the professional engineer, and of the attitude which the successful engineer should have, but one cannot help wondering if these idealistic professional concepts would be received in the proper spirit by those engineers just out of school who are out of jobs or who are working at meager wages in the name of "getting experience." Those of us further along in our professions, who belong to the A.I.E.E. and come to the conventions, undoubtedly approve of the ideals outlined by some of the able speakers who addressed us on professional education, but it is a recognized fact that material prosperity must precede cultural advancement. Much has been said about getting the young engineer properly started off in his career, about giving him the right outlook upon life, and about raising the prestige of the engineering profession, but nothing would do quite as much toward raising the prestige of the engineering profession as an organized effort toward giving each young engineer interesting technical work at a rate of pay commensurate with the value of his work and with the investment he has made in his education. As long as certain of the older engineers regard it as unethical for an engineering society to discuss salary levels and working conditions, just so long will the younger engineer regard his profession with some doubt and lack of confidence. Instances have been reported in certain sections of the country where technical engineers never had a Saturday afternoon off, until the NRA code came along, and other instances where young engineers' weekly pay was increased by NRA minimum wage requirements, yet the NRA was intended to help only the unskilled and uneducated. Some of the worst offenders among employers have been engineers who hold responsible positions and who are in a position to effectively determine salaries and working conditions for younger engineers reporting to them.

Perhaps the Engineers Council for Professional Development will give earnest consideration to some of these things and acquire enough publicity that engineers in general may know what is being done. Until this is done the engineers will continue to be split into 2 distinct groups: a few conservative "elder statesmen," deans, professors, and consulting engineers, who believe in unrestricted competition among engineering graduates and a "closed corporation" for professional engineers; and a large number of young engineers more or less dissatisfied with the organization and operation of the engineering societies, with some of them entirely radical in their economic views and likely to support any movement or organization that promises to improve their economic condition, regardless of technical achievements, social ideals, or other long-range interests, of which the A.I.E.E. is justly proud.

R. W. Sorensen: The 3 papers relating to the subject of an engineer's education are, indeed, most interesting. Taken together, they present thoroughly the many ideas which bear upon what we, as electrical engineers, are trying to do to keep abreast of the progress in today's civilization and to train the younger men who will carry on the torch of our profession in ways which we think will best enable them to attain the results we so much desire. We, naturally, are trying to develop our ideal engineer; and in so doing have set standards which, if met completely, will produce supermen who will push all of us out of our jobs. As engineers, we have learned to write specifications for everything with which we have to deal; and we are now writing a specification for an engineer.

In the preparation of this specification we are, I gather from these papers, doing very well, but are encountering 2 major difficulties, namely: insufficient attention to the raw material of which the engineer is to be made; and the endeavor to make our specification an all-inclusive one, covering in the one specification all the general and special requirements of engineers. The first difficulty must, of course, be overcome largely by our educational institutions, many of the professors from which are with us this morning, by the simple process of paying more attention to the prospective student in his pre-college work and the application of more rigorous selective methods through which the candidate must pass to be admitted to our engineering colleges. The use of rigorous selective methods for entrance to college is, of course, very difficult if we consider an engineering course as a part of our regular public educational program and work on a basis that every one who completes a high school course is entitled to admission to some engineering college. Practicing engineers can give much aid to those of us who are doing the teaching and are advocating rigorous selection for entrance to engineering colleges by spreading the gospel of what E.C.P.D. plans to do among the youth of pre-college days, and by recognizing the fact that no college can make an engineer who will come up to the specifications we are discussing this morning if the material with which the college must work is not of the very best quality. In our specification for an engineer, about which I am not at all pessimistic because I have great hopes that we are rapidly approaching a time when the members of our profession will very closely meet it, we are, as I have mentioned, setting very high standards because, as you will note, we have demanded that, first of all, the engineer be a highly qualified specialist in any line of engineering endeavor that may come his way even though he is assigned, perhaps by chance, to some phase of engineering work to which, previous to the assignment, he has paid little attention. In doing this there is grave danger that we are too forgetful of the fact that each year we are adding new developments which we expect the young engineer to know, even though we have kept him busy during his college course cramming into him the accomplishments incidental to the past history of our profession. Again, we are demanding that the young engineer must know how to converse intelligently with his fellow citizens concerning art, literature, music, health, biology, geology, religion, and many other things of interest to human beings. We expect him, in his conversation, to show that he is a thorough master of at least one language and, better, he should know several. In addition to meeting these requirements, we expect him to be a good dancer, a good bridge player, good at golf and badminton, with perhaps a few extras thrown in, and, above all, he should have in his make-up enough of the soul of a researcher and love for pure science to make him willing, after having become qualified in all the things named and many more, to forget them and retire to a sub-basement room in some laboratory and toil many hours per day, day after day, week after week, and month after month on a pet research problem.

Then, because our engineer must live and may have a desire to support a family, we expect him to come out of his sub-basement laboratory with his research problem applicable to some practical need. With this accomplished all he had to do is find a way to finance and secure patents which will protect his findings and contact some industry that will find a market for what he has developed. Of course, to do this and be sure he has good patent protection, he must develop, incidentally, a fine knowledge by patent procedure.

You may say these comments are exaggerated and visionary, nevertheless they are practically the demands which we are setting up in our specification for an engineer and which we hope to have met to a considerable degree. Moreover, remarkable as it may seem, these demands are met to a very large degree; and so great is our expectation of having them met that

I know of college groups which rather recently have spent many hours discussing ways and means of enabling students to meet all these demands. The magic words which initiated these discussions were: "Their technical training is most excellent, but they are failing in the broad knowledge of human qualities including social relationships and in economics," which words are almost the same as one phrase in the paper by Professor Dawes.

After a committee consisting of very able business men, faculty members, members of a board of trustees, alumni members, and students of the college in question had devoted much time and thought to the analysis of these problems, a few minor changes in the program carried on by the college under discussion were made. These changes may be summed up in 2 recommendations: the appointment of a committee to plan more opportunity for students to participate in social functions; and a change in academic rules permitting to continue and remain in good standing seniors who, at the end of the first or second term of their senior year, have not made the usual minimum requirements for continuation in college. It is understood, of course, that these seniors must bring all their work up to the required minimum standard before graduation.

Perhaps the puzzling question as to length of course will be decided some day by a new arrangement whereby the better students in a group being trained for certain routine engineering work will be moved on to courses involving theory and mathematical applications, and the better ones from this group in theory will be moved on to a course of more advanced work including research. Until that time has arrived, it would seem to be rather dangerous for us arbitrarily to divide engineering schools into groups as suggested by Mr. Morrow, some colleges devoting their entire time to training for routine work, whereas other colleges would be devoting their entire attention to the courses more theoretical in nature.

Specifically, Professor Dawes's paper is largely of value in a psychological presentation of choice to the student as I find that his so-called wholly elective curriculum is, after all, very similar to the curriculum at California Institute of Technology, with which I am most familiar and which, for undergraduate work, is almost wholly prescriptive. That is, it seems to me that Mr. Dawes's plan as outlined, is very much like the modern kindergarten and grade school courses which are advertised as being arranged to allow the pupil full freedom of choice as to what will be done. For example, recently I have been made aware of the fact that one morning a certain group of children in a school of this kind suddenly decided that they would like to visit a dairy, and on another morning they suddenly decided they would like to visit a dining car to see how meals were served on a train. On both these occasions, within a very few minutes after the children had reached their decision, automobiles for transporting them to the place they wished to see were on hand and, when the children arrived at the dairy and at the dining car, respectively, they found the most interesting operations of these 2 institutions at just the right phase to be most interesting to them. Moreover, suitable refreshments in the way of cookies, fruits, etc., were on hand in order that each child might take away some pleasing souvenir of the trip.

In conclusion, my opinion therefore is that whether we consider our courses prescriptive or wholly elective, we have, for the most part, in all our better colleges, arranged courses which represent the best composite methods of engineers and teachers alike for teaching those who will, in the next generation, solve engineering problems in a way best suited to the convenience and service of mankind.

W. H. Timbie: Mr. Morrow presents a most timely discussion of the question that is of utmost importance not only to engineering educators, but to every one interested in higher education in all fields. Although he has not stated it in so many words, the whole import of his analysis is that engineering education is rapidly becoming, if in fact it has not already become, the liberal education of today.

By liberal education I mean that kind of an education which sets as its goal the development of the latent interest and potentialities not only of each individual, but also of the social organism of which he is a member. In other words, it is an education which will give him a correct understanding of the spirit of his own generation, and will best enable him to fit into the era in which he is to live, and to take his part in advancing civilization.

This has been called the Machine Age, or the Power Age, but in spite of all the machinery and the power, the spirit of the age is scientific, and in the highest degree, idealistic. Mr. Morrow's paper is a well founded plea further to liberalize engineering education by seeing to it that not all the student's time is devoted to the study of machinery and power, but that some time is devoted to the study of "what it is all about" . . . of history, philosophy, and economics. I heartily agree with him as to this need, but a word of caution should be introduced at this time to emphasize the fact that the greatest care must be used as to *what* history, *what* philosophy, and *what* economics should be taught, and the manner in which they should be taught.

For example, Latin and Greek used to be considered as liberalizing subjects. Sometimes they were, but more often they were merely mental exercises. The subjects of history, philosophy, and economics are particularly susceptible to the use of poor material and to wrong viewpoints and methods of presentation. To my mind there is little that is liberalizing in historical exposition that deals almost exclusively with less than 10 per cent of the people of a given generation—its kings, queens, and military leaders—or in philosophy that is merely a history of the different philosophies of the world, but does not develop in the student a wholesome philosophy of his own, or in economics that is deductive and speculative rather than social and factual. To be truly liberalizing a course in economics should be "social economics," and I believe it should be taught by an engineer—one who has analyzed modern engineering problems from their social and economic aspects, and who uses on these aspects the same rigorous scientific thinking and methods of attack that he employs in the solution of so-called technical problems. History should be studied for the light it will throw upon the path of civilization up to the present time. One of the surest guides for the future is the knowledge of how we arrived at our present position. For this reason history should be taught not in detached units, but as a comprehensive whole. It should not be military history, civil history, and economic history, but a synthesized study which presents the combined effect of all factors, foreign and domestic, upon successive eras of the world's history. Here again the teacher and the method of presentation are fully as important as the material studied.

Finally, while I agree that there is need of liberalizing all engineering curricula by the introduction of these important subjects, properly taught, there is also, I believe, an equal need to add to the little groups of Mr. Morrow's specialists still another group whose tastes and abilities lie in this field of social economics. The members of this "economics" group should receive intensive training in the art of navigating the "ship of industry." They should be given all the preliminary training possible to enable them eventually to reach their place on the "bridge." The increasingly large number of "captains of industry" who have been drawn from the ranks of these other groups of specialists proves that the type of training which these groups are receiving is conspicuously effective in preparing them for positions of leadership and responsibility. To add this other group would only be adding another possible route to the top. However, to train members of this new group for their positions of leadership, there is needed not a curriculum in which a few milk-and-water courses in economics, business methods, and industrial management are superimposed upon a smattering of engineering subjects, but rather a thorough and rigorous engineering training, with special emphasis on an equally rigorous application of scientific habits of thought and engineering methods of analysis to modern social and economic problems. If Mr. Morrow's plan contemplates this latter type of course, I believe it is right in line with the present trend of engineering education.

Professor Dawes's paper on "Developing Initiative in the Engineering Student" is also timely. The idea of putting a student more on his own, especially in the laboratory, as to what he will do and as to how he will do it has been in operation at M.I.T. with gratifying results for several years. It was first tried out on selected groups of students and gradually introduced as our regular practice. We go even much further than this. We believe that every part of a student's career should be so conducted as to develop not only his initiative and originality, but also a proper sense of his own responsibility in planning out not only his laboratory work but his entire career. For this reason, in the electrical engineering department we really have no standard curriculum but each student has his own individual program of studies of an exacting character and in logical sequence. This means that we have about as many curricula in electrical engineering as we have students. The cur-

riculum printed in the catalog is merely a guide to show the student how to build up his own course of studies. Eight times a year a student officially presents his program to his registration officers for their criticism and advice. Unofficially, I imagine, the student at all times is seeking information and advice not only at the Institute, but also in industry and in business, concerning everything that pertains to an engineering career. In other words, each student must be aiming at some definite goal and must give serious consideration to a plan for getting there. Of course as he gets more acquainted with the industrial and commercial fields, and with his own special abilities and individual preferences, he may from time to time make slight changes in his objective and in the method of arriving at it.

This means that a student has a wide choice in the subjects which he may study, but it does not mean that he can scatter all over the field and get only a superficial knowledge of engineering as a whole. There is a main stem of mathematical physics related to electrical engineering which he must follow, but he has a wide choice as to the field in which he chooses to study the application of these principles, and as to what subjects he wishes to take in order to buttress and strengthen his main stem. For instance, a student who wishes to specialize in electronics will study exactly the same theory as the student who is specializing in electromagnetic machinery. He would, however, choose his courses so that the applications of the theory were to electronic devices rather than to rotating machinery. Similarly a student who is interested in the economic aspects of engineering has an opportunity to select courses which emphasize this aspect. By this procedure, students are not only encouraged but actually compelled throughout their entire course to give thoughtful consideration to their objects in being at M.I.T. and to the methods of obtaining their objectives.

Finally, I cannot resist the temptation to question Professor Dawes's reasons for selecting the titles which he has included in the bibliography at the conclusion of his paper. To be sure they are pertinent and well worth reading, but why pick out these few articles which deal more or less with the details of administration and instruction rather than with the larger fundamental considerations? Probably, these fundamental principles having been laid down as far back as Plato and Aristotle, it was because the literature concerning them extends from classic times down through Pestalozzi, Ascham, and Bacon, to John Dewey of our own day, and a comprehensive list would have been altogether too long.

C. F. Hirshfeld: The discussion offered by Mr. E. E. George touches a subject to which I have given a great deal of thought, particularly during the past 5 years. What he says about the economic value of an engineering education and about the economic status of the engineer represents a viewpoint and state of mind that is very common at present.

I think it necessary that we first distinguish clearly between temporary phenomena due to the existing depression and more permanent phenomena which are characteristic of both boom and depression periods. It is natural that during a depression there should be a surplus of engineers. A large part of the profession is necessarily employed in the creation of capital goods as against consumer goods and it is characteristic of a depression that the production of capital goods reaches a very low ebb. Men thus thrown out of normal employment are necessarily going to work for what they can get at any job that they can get. We must not allow such conditions to befog our thinking when considering the broad question of the economic status of the engineer. This would be just as foolish as would be the determination of normal farm incomes by studying the present incomes of farmers in the drought stricken areas of this country.

It is possible to speak with some knowledge of what may be called the normal economic status of the engineer. The A.S.M.E. has had a committee studying that subject for some years and several comprehensive reports have been published. One outstanding finding is the tremendous range of annual earnings among engineers. The committee found that those engineers whose activities indicate that they combine a knowledge of engineering with business or executive or administrative abilities receive by far the largest incomes as a class, while those who are capable of doing only routine technical work are as a class most poorly paid.

My own interpretation of the findings of the committee is that they represent exactly what one would expect. There is in this country a comparatively small number of outstanding men with engineering training. Those men can command, in one way or another, large annual incomes. At the other end of the scale there is a very large number of individuals with engineering training who do not possess any outstanding characteristics. Any one of them can be replaced easily and quickly with another man of equal training and ability. These men cannot earn large annual incomes because of the ease with which they can be replaced. They are really in a marginal position. Between these 2 classes lies a widely spread third class, the best members of which touch the upper class and the poorest of which touch the lower class.

I feel that we must recognize such a distribution in the engineering profession not only as fact but as a natural fact which cannot be changed. It parallels the conditions in all other walks of life. To rail against it is futile and to attempt to change it by law or otherwise is fruitless. It simply represents the general distribution of abilities in the human race.

There is the possibility that the incomes of engineers can be shifted upward as a class. This is indeed the only real hope for improving the economic status of those in the lower earning groups. But, if this is to be done, the engineers must so improve themselves as servants of the public that that public recognizes the fairness of higher compensation. This is one of the thoughts that lies back of E.C.P.D. which, as a matter of fact, is an outgrowth of one of the recommendations of the A.S.M.E. committee on the economic status of the engineer. It is thought that as engineers as a class succeed in adding to their present technical engineering knowledge that further insight into human affairs, economic and social, which E.C.P.D. is providing for, these better equipped, more rounded, and more human engineers will automatically command greater incomes because of their greater degree of usefulness. Even then, there are bound to be some for whom such disciplines are too severe. These will unfortunately remain as a dissatisfied substratum whose heritage, through no fault of their own, does not fit them to rise above that level. This reads like a hard philosophy. It is a hard but a pragmatic one and, if the engineer stands for any one thing, it is a recognition of facts as demonstrated by experience.

I believe that it is also necessary that we recognize another set of facts. We are all inclined to form false estimates of the earnings in other professions. We look at the successful lawyer, the successful doctor of medicine, or the outstanding religious leader; we visualize their probable incomes and we compare these exceptions with our averages or even our lowest. Seldom do we compare like levels or true averages.

If we believe that as engineers we are in an unfortunate economic position, we can certainly derive comfort, if not satisfaction, from properly made comparisons. For example, the graduates of the better schools of medicine are now required to spend 8 years in college and then to work as internes for 2 years without compensation other than room, board, and laundry before they are in position to begin practice. Is the young engineering graduate who starts at $25.00 to $35.00 a week after 4 years of college so badly off as he thinks when compared to the young medical practitioner? Moreover, statistics show the same sort of spread of annual earnings in the medical profession as we find in engineering. The average annual earnings of doctors of medicine have been shown to be small indeed when compared to the investment in preparation for a medical career.

I think we must conclude that in the long run that which one is paid represents very closely one's worth to the community and, if we do so conclude, it follows that our pay as a class can be increased only as we not only prepare ourselves to be of greater value to the community but actually comport ourselves so that that greater value is realized.

Encouraging Initiative in the Engineering Student

Discussion and author's closure of a paper by C. L. Dawes published in the June issue, p. 910–4, and presented for oral discussion at the education session of the summer convention, Hot Springs, Va., June 26, 1934. (Discussions of the group of papers of which this was a part are given under the group heading on an earlier page.)

H. W. Bibber: While most of us who teach electrical engineering recognize the desirability of taking steps to develop initiative in students, we have difficulty sometimes in visualizing new ways in which this can be

accomplished, so binding are the effects of our established routines. We often feel that no way other than that which we now use would work. When those who have tried new schemes that have proved successful report on them as Professor Dawes has done in this paper, it provides a valuable stimulus to engineering teachers. It is to be hoped that others will follow his example. Not all schools now have the teaching staff or laboratory facilities needed to carry out his suggestions with the number of students they are handling. The time required for conferences to adequately supervise individually initiated work of students far exceeds that of the usual classroom exercises where groups number 20 or 30 students. One of the most significant inferences to be drawn from this paper, therefore, is that *the ratio of students to teaching staff must be lowered, and additional laboratory facilities made available if more initiative is to be developed in students at many of our colleges.*

R. E. Hellmund: Although I have previously stressed the necessity for developing initiative in the engineering student in various talks and discussions, Professor Dawes's paper with the plan he describes therein is such an interesting effort in this direction that some further comments seem justified.

As mentioned in the paper, the idea of developing initiative in the student was strongly emphasized in the paper on "The University of Pittsburgh-Westinghouse Graduate Program," presented by Professor Dyche and myself at the winter convention. However, there was no intention of suggesting that the development of initiative should be limited to graduate programs; on the contrary, it was pointed out in the closing discussion in particular that efforts for developing initiative should form an important part of the undergraduate program as well. In fact, there should be no doubt whatsoever as to the correctness of the broad fundamental that any engineering education should give as much emphasis to the development of habits, such as initiative, as it does to the acquisition of knowledge, and, furthermore, there should be no doubt as to the advisability of making efforts in this direction as early as possible in the program. The only questions which might be raised are those of how far such efforts can be carried at any one time without interfering too much with other objectives and which methods are the best for accomplishing the desired results. Depending upon the ability of the student during the various stages of his training to take the initiative in solving his problems, it is of course necessary at all times to strike the proper balance between the extremes of assisting him too much and of assisting him so little that he makes obviously wrong decisions or becomes discouraged in his work. This can be worked out only through experience and study of the individual cases.

It further must be determined which of the college activities can best be utilized for developing initiative. In the plan described by Professor Dawes, the planning of the student's program, certain laboratory work, and reading periods are used for this purpose—and no doubt to good advantage. As a matter of fact, the ideal teacher will use practically every course for this purpose. However, it is probably too much to expect that all teachers will stress this point, and frequently it may be overlooked entirely on account of the many other objectives, particularly that of imparting the required amount of knowledge in a limited period of time. For this reason, the selection of courses with this particular purpose in mind should prove of assistance. I personally have always felt that a certain amount of design or similar engineering work carried on during the entire course by engineering students would be very effective. (This is covered more fully in a paper on the subject, "Fundamental Principles in the Design of Electrical Engineering," read before the S.P.E.E. and published in the *Journal of Education*, April 1929, p. 819–33.) It would develop not only initiative but also the habit of doing creative work, which is so important in the engineering profession, and it would furthermore serve to exemplify the practical application to engineering work of the material given in the various science courses and thereby maintain the student's interest in these courses.

I am fully aware of the fact that many teachers are rather skeptical of the possibility of carrying on design or engineering tasks in the freshman year, and from my personal contact with quite a number of engineering students during that period I am willing to grant that it may be somewhat difficult. Nevertheless, I believe that it can be done, and done advantageously, if sufficiently simple subjects are selected and a certain amount of guidance given. I have observed that some of the science courses assign rather difficult tasks during the freshman year, such, for instance, as the writing of themes on the psychology of leadership, psychology of advertising, etc., and finding that the students with some guidance handle these subjects in a rather creditable manner, I am quite convinced that they could handle some of the simpler engineering or design problems equally well. If they were obliged to do so, it would certainly go a long way toward developing in them the habit of taking the initiative, of doing creative work, etc., and in addition would give them during the early part of their course a general idea of what engineering is all about, which I am sure would be very encouraging and stimulating throughout their course.

Although some of these latter remarks do not relate directly to the development of initiative, they illustrate how efforts along this line can be combined with other important objectives, which, of course, is desirable on account of the limited time available during the course.

C. L. Dawes: It is most gratifying to us who are attempting to adapt our methods of teaching engineering to meet better the needs of present day conditions to find such widespread interest in the subject as is evidenced by the number of teachers and practicing engineers participating in this session. A number of us have just come from the more extended educational convention (S.P.E.E.) at Cornell University and found similar intense interest there. Not only teachers but practicing engineers as well came from distant parts of the country to devote an entire week to the consideration of the current problems in engineering education. Although, naturally the subject was discussed in much greater detail there than here, the general tenor of the ideas expressed there was almost identical with those exemplified by the 3 papers presented at this session and the ensuing discussion. A number of schools have already liberalized their curricula, permitting wider choice of subjects, yet insisting that the program shall be unified and substantial. Some schools are already offering opportunity for emphasis on the economic and administrative aspect of engineering with less stress on highly analytical and research work for those students who have not high technical ability, but who do show aptitude for industrial and occupational work. This is along the general plan advocated by Mr. Morrow. I was also very much impressed there, as I am here, at the unanimity of opinion; not only as to the requirements which engineering education must now meet, but also that a number of schools were making changes with the object of meeting these requirements and many of the changes were similar to those suggested by these 3 papers.

Mr. Alger's statement that knowledge should be taught as a single subject is in accord with our own policies, as is indicated in my paper where it is stated that we give the degree for the satisfactory completion of a coördinated program of study. Also, in the electrical engineering department and in other departments, we emphasize the close correlation among the laws of electricity, hydraulics, heat flow, and mechanics. In fact we demonstrate electrical oscillations with mechanical models, and many mechanical problems are solved by equivalent electrical circuits. It is not easy, however, to persuade the mathematics department to teach mathematics as shorthand for describing physical realities. Usually the department also must adapt its courses to other students who have interests other than engineering and science, so that the plan usually is not practicable. However, it is my experience that students actually come to know their mathematics only after they have used it extensively in the problems of engineering and science. The engineering teacher may well do as Mr. Alger suggests, and many of us, I know, attempt to follow his suggestion.

In reference to Mr. George's discussion, the economics of engineering education is a paradoxical one. The majority of students have difficulty in meeting expenses and on the other hand, in my own institution as in most others, the tuition fee pays for only from 40 to 50 per cent of the cost of educating the student, and this cost does not include any overhead charges on buildings and equipment. Also, a large proportion of the students do not pay the full tuition but receive scholarships and other aid. As is well known, educational institutions are not extravagantly operated but actually the reverse is true. Economies that are sometimes to the detriment of the purposes of the school are frequently necessary, and certainly the teachers are not overpaid. The college and university of today can offer so much of educational value that it is really the fault of the student if he does not obtain his money's worth.

However, the economic problem of the student is a serious one and is not easy of solution. Many students of ability find it necessary to restrict their educational opportunities because of lack of funds. My own institution is attempting in part to meet the problem by awarding to a limited number of students of demonstrated ability a sufficient amount each year to meet all their educational expenses throughout the 4-year course. In addition to scholarships, loans and other aids are available to other students. A number of fellowships with stipends more than sufficient to meet living expenses are awarded to outstanding graduate students so that they can continue their studies. Also, we have increased the number of half-time assistantships so that engineering students can continue their studies after graduation, and still be earning something over actual living expenses. However, even with all these aids, there is a large number of deserving students who have insufficient funds, and as Mr. George intimates, this is a real problem.

His statement that adding another year or 2 to the present 4-year course is in the wrong direction is contrary to the opinions of many of us engineering teachers and also of many practicing engineers. The many recent developments in science and engineering and the complexity of our present day social system, which is emphasized by Professor Sorensen, necessitate a longer period than 4 years for adequate training to meet these conditions. Attempting to train students within a 4-year period has led to the many criticisms of engineering education that we so frequently hear.

Experience has shown that the plan which Mr. George advocates of a student leaving for a year or 2 to earn money for expenses does not work out well in the majority of cases. The students find it difficult to give up a paying position to resume studying again, even though it may be to their future advantage; some become married. With the usual salary which such men receive, it is difficult to save a sufficient amount over living expenses to pay for a year or 2 more at college. Also, when the continuity of study is interrupted, it is not easy to resume again after such a long period. There are many opportunities for those who wish only 2 or 3 years training without qualifying for a professional engineer. In many schools it is possible to select a group of courses which are suited to such needs. There are, however, many excellent technical institutes which offer just this type of technical training.

No one regrets more than we engineering teachers the conditions which Mr. George deplores of the young engineering graduate having difficulty in finding a position or of obtaining a salary which is at all commensurate with his engineering training. Present day economic conditions are undoubtedly in a large measure responsible for this condition and let us hope that the situation, therefore, is only temporary. There is no doubt that even in normal times, in the beginning, numbers of young engineering graduates were underpaid, but in the past those who have shown outstanding ability have as a rule been able to push up and obtain some measure of success. Professor Sorensen's enumeration of the many qualifications which are expected of the engineering graduate are in accord with the experience of many of us. Furthermore, if the graduate is in any way found deficient in any of these numerous qualifications, his engineering training has been inadequate and the methods of engineering teaching accordingly should be improved. I cannot, however, agree with his statement that the program which I describe is almost wholly prescriptive, like that at the California Institute of Technology. The entire paper emphasizes the opposite, that is, our program is entirely elective.

In answer to Professor Timbie's query as to the manner of the selection of the titles in the bibliography, these were not selected by me, but are given as submitted by the respective authors. To my mind, these references have focused attention on our present day engineering education problems as no other writings have done. With all due respect to Plato and Aristotle, it is really asking too much of these 2 ancient Greek philosophers, who have been dead some 2,200 years, to solve the many current problems of this complex machine age.

As is stated by Professor Bibber, with our plan it may require more time on the part of the instructing staff for individual conferences. However, there are compensating factors which tend to offset this. For example, the reading period at the end of each term relieves the staff of 3 weeks classroom time although some preparation for the reading period is necessary. The project method of conducting laboratory work compresses the time in the laboratory into a very few sessions and hence reduces considerably the time of laboratory supervision. Moreover, as the students become accustomed to depending on themselves, the time that they require for consultation becomes less. Before seeking advice, they of themselves have developed their plans almost completely and need advice only on some minor factors. However, as Professor Bibber states, in teaching it is an advantage when the ratio of students to instructing staff is low.

We all welcome the views of Mr. Hellmund, a practicing engineer, who not only comes in contact with large numbers of our engineering graduates but who also is instrumental in having developed an educational plan. As he states, it is necessary to strike the proper balance between assisting the engineering student too much and too little. We urge our students to come to us for assistance after they have exhausted a reasonable amount of time in the solution of a problem. It is desirable to do this for the usual student has considerable pride and does not like to admit that he cannot extricate himself from the difficulty.

The suggestion that a certain amount of design be carried on throughout the course is one well worth our consideration. Most of us do give, from time to time, some relatively short problems of a design nature. If a comprehensive design problem could be coördinated with the other subjects in the curriculum, I have no doubt that it would be well worth while and would also develop initiative and perspective in the student.

In conclusion, I feel that we electrical engineering teachers and the electrical profession as a whole have benefited mutually by the friendly interchange of the many ideas which have been expressed at this session.

Industry Demands and Engineering Education

Discussion and author's closure of a paper by L. W. W. Morrow published in the April 1934 issue, p. 519–22, and presented for oral discussion at the education session of the summer convention, Hot Springs, Va., June 26, 1934. (Discussions of the group of papers of which this was a part are given under the group heading on an earlier page.)

C. D. Backus: This paper presents a careful analysis of the subject covered, particularly of underlying conditions, and should leave no room for discussion that a remedy is necessary. There is, however, a strong probability that there will arise doubts regarding the proposed remedy in the minds of many who take a deep interest both in broad educational lines and also those which affect the engineer, not only as an engineer but as a human element in our social fabric.

In the first place, the educational requirements presented solely by industry are not alone to be considered in any final solution of the problem. The fitness of the man having a strictly engineering education for the management of industry is one question; the fitness of those who have managed, or will manage, our industries, to perform that function is quite a different subject.

Now, whence comes the assurance that a training based on proposed "course No. 1" will produce a better qualified manager for industry, when looked at from a social point of view, than those who have functioned in that capacity, whether their education be based on engineering fundamentals or on strictly non-engineering curricula, or none at all? Recent developments clearly show that plenty of our industrial managers, from the point of view of their own industries, had sufficient qualifications for the immediate purpose. Yet industry could not keep going under such management.

Where does one look for an explanation for this condition of affairs? It seems that 2 fundamental requirements have to a large extent been overlooked.

First, the engineer, and more particularly the research worker, acquires a habit of forming conclusions based only on observed facts. This is true even though as an intermediate step he formulated and used a hypothesis. Such a general course leads to sound reasoning and if followed in practice in business management and social and political affairs, it cannot fail to be helpful, in the opinion of many, in developing a saner industrial organization from the social aspect. Mr. Morrow does not overlook this feature but appears not to stress it enough. This scientific method as a desirable aspect of educational development is already receiving attention from leaders of our educational institutions and elsewhere, as especially pointed out by Secretary of Agriculture Wallace ("The Social Advantages and Disadvantages of the Engineering-Scientific Approach to Civili-

zation." *Science*, v. 79, Jan. 5, 1934). It is a reasonable expectation that pursuance of such methods will tend to minimize those results occurring because some one or some group of citizens, or even some coterie of stockholders, wishes them, or because they can be effected through mere forensic persuasion, or for similar reasons characterized in general by the fact that either the fundamentals were insufficiently ascertained or that the reasoning applied thereto was faulty, or both.

Second, the other fundamental qualification relates to the humanistic side. This subject is a large one and deserves more extensive treatment than can be given in these comments. A mere outline calls to attention that the concept of the individual's conduct toward or behavior relationship to all others jointly, that is, to the social state, should be comparable to the relationship between individuals themselves. With a low standard for the latter relationship it would be natural to consider that that of the former would be still lower. Now, it is a matter of common observation that there is much room for improvement in the relationship between individuals, in the proper development of which forces such as home training, religious training (whether regarded favorably or indifferently), and ethical or other cultural agencies no longer exert the required influence in this direction. The very complexities themselves of modern life may be partly responsible for the inadequacy of such building-up forces. However this may be, and in spite of the disclaimer that attempts made by those who would improve our economic conditions do not envision an improvement in human nature, it still remains rather obvious that society will not improve much even on its economic side so long as human nature remains static or declines in its assessable value.

Now the question arises, will society as a whole find its engineers, when confronted with these conditions, any better trained for industrial management after pursuing the courses suggested by Mr. Morrow than have been our recent industrial managers, who have been merely developed, as it were, or were more or less specially trained, but without engineering training? Recent investigations have shown plenty of instances of mismanagement in connection with control banks, holding companies, and the like (to cite one field merely for illustration) where there could be no gainsaying that the mismanagers had sufficient ability or that they knew their business. They knew their economics also, from the practical viewpoint. One sometimes wonders whether such individuals, in case they had not already had any special education in political economy, would have been improved upon from a social point of view if they had had such education. Let the economists make the answer. It seems almost certain that little or no social improvement is to be expected merely by adding to an abridged engineering education further training along the lines indicated in the suggested course, unless real and visible stress is laid on those lines of effort which will have for their effect to improve man's understanding of what his attitude shall be toward other men individually and collectively. One concrete objective, for example, might be inculcation of those ideas underlying coöperative efforts. While broad cultural education has been advocated and possessed by many leading engineers, it does not appear that either such a qualification in itself, or its prevalency, has been sufficient to produce perceptible results.

It is believed that many of our real universities already present curricula of the scope indicated by the proposed "course No. 1," also curricula which could be adapted to include deficiencies pointed out herein. It is true that much of the work as given in those curricula may not be presented in a manner to meet the object contemplated by "course No. 1." This, however, is a matter of suitable educational direction as is also the supervision of selection of that combination of subject courses adapted to meet the prospective needs of the individual student. Such a selection is fairly presupposed since existing managerial functionings obviously are different and would require different trainings.

Finally, an interesting question arises: What sort of a capacity status as citizens, or as leaders in their own expert line, will those engineers have who have been educated according to "course No. 2?"

H. W. Bibber: Those of us who are engineering teachers should, it seems to me, feel very grateful to Mr. Morrow for the very definite conclusion which he presents at the end of his paper. Others less articulate than Mr. Morrow may have felt the demands of the situation we face at present but few have set them forth as clearly. Dean Doherty of Yale expressed a somewhat similar view at the S.P.E.E. convention at Ithaca, N. Y., June 21.

Mr. Morrow seems to feel that a realignment of organization in existing institutions would have to be made before the results he describes in his conclusion could be achieved. I wonder if this would be necessary in most schools. Rather limited experience and observation on my part tends to make me feel that in many institutions it would not be necessary to create new departments or a new college. The possibility of achieving the results which Mr. Morrow describes hinges on: (1) the use of the "honors" plan and (2) the revision of the usual electrical or other engineering curricula along lines that have been rather widely discussed recently, and mentioned in part in this paper. I refer to the inclusion of more electives and the requirement of more nontechnical subjects in the course, with the accompanying omission of specialized courses. May this paper help speed the day of liberalization of engineering curricula!

The general concept I have of the modern plan which takes care of the students Mr. Morrow would have follow his course No. 1 is that an engineering course would be built up around a core of required fundamental physical science, mathematics, and social science, with basic technical courses in whatever the description of the course implies, mechanical, civil, or electrical. There would be a considerable portion of the whole curriculum free for electives and there would be options in advanced technical courses, none of which would be of the type which Mr. Morrow speaks of as "specialized." "Honors courses," such as those which have been operating with apparent success at the Massachusetts Institute of Technology and other places, rather than a special curriculum would form the means of taking care of Mr. Morrow's course No. 2 group, the future professional engineers.

My reason for believing that the men to staff and operate mechanized industry can best be obtained from the regular engineering courses of the improved type I have described is that all responsible work in the operation of modern industry consists of problem solving of one sort or another. The function of the school is, therefore, to teach the student how to solve problems, and give him some familiarity with the few principles that can truly be called fundamental. This is a trite statement but one sometimes overlooked in the heat of discussion. To teach young men how to solve problems, we can proceed most effectively if the subject matter used in the beginning is simple enough to permit the instructor's attention being concentrated on improving the students' method of attack. We should not at first burden the teacher with a discussion of the validity of assumptions, reliability of data, variations in conditions, etc., all of which are inherent in any social science material. In addition, methods of attack on physical problems by pencil and paper can be supplemented and complemented by appropriate laboratory work. Laboratory work in the social sciences requires tremendous expenditure of time. The results are often open to different interpretations and much experience is required to draw reasonable conclusions.

I may seem to imply here that a good preparation for success in a social science field is a study of applied science. I believe this to be absolutely true. Those who have great native ability succeed in the study of the social sciences in spite of the obstacles and difficulties involved in trying to learn how to attack social problems by working on the variable material presented by economic and social phenomena. Is it not easier and more logical to learn the technique of problem solving by first working with physical problems and then applying the experience thus gained to the economic or social field? Obviously the techniques of solution are not the same, but the factual approach and analytical spirit are identical. Another way of putting this whole matter is to say that to successfully solve the problems of a mechanized business a man does not have to start off his apprenticeship on the solution of business problems. He may do so, of course, but his time will be more effectively spent by beginning with the solution of engineering problems of a fundamental character, and learning the general art of problem solving first.

I quite agree with Mr. Morrow that a course to prepare men to staff and operate mechanized industry must be a welded whole and not a composite. I believe this welding process can best be carried out by the previously described broadening of existing courses in civil, mechanical, or electrical engineering. It may well be that new personnel would be required in college staffs, men with industrial experience, able to stimulate students to creative effort. With such teachers the engineering dominance which Mr. Morrow mentions would be a beneficial influence rather than a bane, if the men chosen from industry

were engineers whose experience had been as much in economic and social matters as in technical engineering. Surely there are such men.

Mr. Morrow's statement "present faculties in engineering and arts are like water and oil. They do not mix" merits comment. It was remarked by Prof. D. C. Jackson that there are such things as emulsions. Many of these are relatively stable, and extraordinarily serviceable to mankind. The value of emulsions comes precisely from the fact that the oil and water particles always retain their separate identity, but come into very intimate contact. No doubt many would agree with Mr. Morrow that some universities need an emulsifying agent. My own limited experience is that faculties in engineering and arts can mix if they are well chosen and then encouraged to do so. Putting them together and shaking them up vigorously is the logical way to accomplish the desired emulsification. It will usually work if tried, I believe. I wonder, too, how many arts college instructors in these days "teach orthodox economics." The last 4 years of depression have caused repercussions that have penetrated into even the most cloistered academic circles.

Mr. Morrow says "the ideal business course . . . is broader than engineering and requires a new perspective." If the engineering schools are preparing men for the direction and operation of mechanized industry it would seem that the definition of civil engineering as given in the charter of the Institution of Civil Engineers (London) in 1828, "the art of directing the great sources of power in nature for the use and convenience of man," is sufficiently broad and encompasses everything that Mr. Morrow mentions. With the revised type of civil or electrical engineering course there would be no lack of balance in content or lack of purpose in viewpoint, if it gave students the ability to tackle new problems effectively and familiarized them with the fundamental principles of physical and social science.

I must confess that I do not understand the first 3 pages of Mr. Morrow's paper very well. If I could grasp what Mr. Morrow had in mind I would not feel that some of his observations ought to be challenged. Mr. Morrow says that the professional engineer should do his part in social matters "largely as a citizen and not as a professional man." There will be many who will not agree with this statement. For example, the definition of "professional engineer" in the Encyclopaedia Brittanica reads in part as follows: "the engineer is under obligation to consider the sociological, economic, and spiritual effects of engineering operations and to aid his fellowmen to adjust wisely their modes of living, their industrial, governmental, and commercial procedures."

At times, as one reads the paper, it seems as if Mr. Morrow did not take cognizance of the recent tendency to employ graduates in pure science such as physics or chemistry to do more of the very highly theoretical work of research. There are, of course, engineering graduates who are doing similar work, but should they be called "engineers" any more than those engineering graduates who are now "business men?" I should like to apply the title of "engineer" rather strictly in accordance with the definition given above.

In past years the engineering graduate who later became a professional engineer picked up a good amount of his knowledge of economics and social science after graduation. Then, the physical or technical problems connected with engineering projects were so pressing that most of the attention of engineers had to be devoted to these aspects. Now, so much progress has been made in overcoming the physical difficulties and in charting the proper technical courses of action, it is but natural that the economic and social problems, heretofore somewhat neglected by the engineer but always in his domain, should be a subject for increased attention on his part professionally, and hence become matters for formal instruction in the colleges.

Another aspect possibly worth mentioning is the modern trend in education in which school is conceived to be a part of life, not an area of artificial experience. The present endeavor seems to be to make the transition from school to outside life simply another step in progress and not a radical change. Outstanding educators have long held this view I believe, but in recent years it is becoming more general. Experiments are being tried in which industrial conditions are being rather closely duplicated in the last years of the college course, in some places even to the extent of providing each student with a regular desk in the manner of engineering offices, and with stenographic service.

I cannot let the statement that "applied science or engineering is little different" [from pure science] pass unnoticed. I must refer again to the definition of engineering that I have previously quoted, and insist that engineering as widely defined over a long period of years has included a very considerable recognition of social and moral values.

Mr. Morrow and I are in most hearty agreement that the engineer has no Messianic rôle in our civilization, and I am glad to see Mr. Morrow's criticisms of the efforts that have been made to put the engineer in that false position. This does not mean however, that it is erroneous to conceive of an engineer as having some rather definite notions as to the social values of his professional work, nor that it is impossible to develop future engineers who may be more socially minded.

C. L. Dawes: In his paper Mr. Morrow specifies 2 types of engineering courses which he believes will best develop students to meet the demands of industry. One course, for the majority of students, is designed to train men as industrial executives. It will include courses in science and engineering in which these subjects are taught from the broader point of view in contrast to the highly analytical method. Also, the course as a whole will include economics, humanities, banking, and similar courses. The other course is designed particularly for a small number of selected and highly trained technical men, the object being to prepare them as specialists for technical engineering and research work.

I can heartily subscribe to these 2 objectives, for the Harvard Engineering School for some few months has had an almost identical plan under consideration. Moreover, just as Mr. Morrow's paper appeared in Electrical Engineering, Dean W. B. Donham of the graduate school of business administration at Harvard, at a meeting of the engineering faculty advised the engineering school to develop a broader engineering course, including business subjects, for the majority of students and a specialized, highly technical course for selected students. His ideas were almost identical with those given in Mr. Morrow's paper, although he had not seen it. He also stated another important fact. Of the large number of graduates of the business school, it was found that practically 300 had had engineering training, either as a formal engineering course or else had elected a sufficient number of engineering and scientific courses to give them an engineering background. The records showed that not one of these men was unemployed. Inevitably a few had lost their positions due to business changes, but they were almost immediately placed elsewhere. Hence an educator in business has come to the same conclusions as Mr. Morrow, who follows closely the teaching of engineering. Also, the statistics substantiate Mr. Morrow's statement that men with this combined type of training are in demand.

Mr. Morrow's statement that the present courses in administrative engineering do not measure up to the proposed course is in accord with our experience. For a number of years we offered a 5-year course in engineering and business administration in which the student was required to take all the specialized technical engineering courses and a number of business subjects. A limited number of men took the course and after graduation have been very successful. However, since the course apparently had unusual merits, we were surprised that it was not elected by large numbers of students. It was found, however, that after having taken the highly technical courses in which most of the problems had but a single precise solution, the students found the working of the more generalized and statistical problems and the humanitarian problems of the business world unbearable, and so lost interest. Later, many of these technically trained men entered positions in which they were obliged to meet these same types of industrial problems and were thus obliged to adapt themselves to the more general point of view. This experience confirms Mr. Morrow's statement that the engineering courses should be broader and more general than the orthodox engineering courses. Also, there is no doubt that the teachers of business and economic subjects could well modify their points of view so that they are more nearly in accord with those of the technical engineer.

Another element which is necessary to the success of such a plan is that there should be some one responsible for the plan as a whole. As Mr. Morrow states, oil and water do not mix. Unless coördinated in some way, the engineering faculty and the business and liberal arts faculty tend to remain in water-tight compartments. It is therefore necessary that some person with an engineering background and economic experience who is sympathetic to the plan be placed in charge so that adjustments and proper coördination between the different faculties can be obtained.

In the many conferences held at the recent S.P.E.E. Convention at Cornell University, the trend toward injecting economic and business subjects into the engineering curriculum was very noticeable, but many teachers seemed puzzled as to the proper procedure. Mr. Morrow's paper, coming as it does from one who has had educational experience and who is also in intimate contact with the business world, will be very helpful to such teachers in planning both the technical engineering and the administrative engineering courses.

C. Francis Harding: Such criticisms and concrete suggestions as those offered by Mr. Morrow in this paper, particularly on the part of those not immediately associated with technical education but yet familiar with the needs of industry and the shortcomings of its applicants, are greatly appreciated. I am sure that all industrial executives and technical educators will agree with Mr. Morrow in his conclusion that 2 types of engineers and of engineering training are desirable, particularly in the larger technical colleges. The problem at issue is that of the best method of classifying and training these 2 types without lowering the standards and prestige of either.

Recent studies of the problem of the possible establishment of a separate course in engineering administration at Purdue University resulted in an overwhelmingly negative vote of the engineering faculty of that institution. This vote favored the present flexible elective courses which are more readily adjustable to the needs of the individual student. As the result of such studies it is believed that the reactions of the faculty and certainly that of the writer to the following forceful statements quoted from the paper are as indicated in the comments following each quotation:

"Social sciences are not formulistic or calculable for the reason that they deal with human actions and emotions. At best they permit only the use of a statistical analysis and at worst they deal with only the social and moral averages of a mob of irrational human beings.

"But the engineer, the scientist, and the educator are called upon to apply their scientific methods of analysis and their finite solutions to the *social sciences;* to apply the cool-headed objectiveness whereby they are accustomed to reach quantitative conclusions, and yet they must retain the intelligent emotion that is necessary to motivate all human action." (p. 519)

To this we heartily agree and beg to submit that *engineering training*, plus such sociological electives as are necessary and applicable to establish the proper contact with the future problems "on location," is the proper solution of such preparation.

"The foregoing analysis indicates that the present demands from industry reduce to the possibilities of training 2 types of men: (1) a large number of men with a broad training that includes some fundamental engineering and science to fill the functional positions of a large part of industry; and (2) a small but very highly trained group of technical men who can be developed into technical specialists. . . . Yet in very few instances have the schools faced these 2 demands honestly in order to satisfy them or refuse them." (p. 521)

The latter sentence we deny at Purdue University unless we be classified among the "very few instances." We recognize both the demands and the indicated proportions of our students available for each group but we submit that individual student analysis and adaptation of sociological and economic electives are preferable to the opening of a necessarily "snap course" into which some of group No. 2 might be tempted to enter to their ultimate sorrow. Better more rigorous training for *several* future executives than superficial training for *one* potential research worker and specialist.

"Why not make a new course that incorporates the best elements of both the engineering and arts courses to prepare the large majority of college students for business life and relegate both of the older courses to more highly specialized types of education? . . . It is evident that the present courses in administrative or industrial engineering do not measure up to the requirements and possibilities of the proposed course, although they attempt to do this in some degree. These courses are unsatisfactory because present facilities in engineering and arts are like water and oil. They do not mix. In some instances the economics department dominates and in others the engineering department keeps control." (p. 521)

Again we submit that the new course is not necessary, at least in our situation. The engineering schools at Purdue University are in the vast majority and there are no colleges of arts, law, and medicine. The non-engineering and service departments are dealing primarily with engineering students and naturally assume the engineering method of attack.

"The course must be a welded whole and not a composite of courses already given in 2 departments. It must have a content, a method, an administration, and an identity of its own to be successful. It should be a separate college in the typical university organization." (p. 522)

This we believe to be unnecessary at our institution for reasons stated above. The course for *each individual student* should be a "welded whole" but such does not necessarily imply a separate curriculum and college for all.

"An essential part of this conception of a technical course is a careful selection of the students and the instructors. They must be high in quality although relatively few in number and their capacities must be measured by technical yardsticks."

To this we heartily subscribe. In fact it is recognized as an endorsement of our *individual student selection* and elective course recommendation adopted for both types of students. The technical yardstick is applied to instructors in other than engineering departments as well.

E. J. Rutan: This paper is of considerable interest at this time. I would like to draw attention to a portion of the paper which has a particular significance. Page 520, beginning with the paragraph "Occupational records of engineering graduates . . ." down to the section beginning "The Day of the Specialist Is Here" should be carefully considered.

As judged from the comments made by many educators, they express a willingness to give general business courses as part of a new engineering course, or they may already be giving such instruction under the head of "industrial engineering" or "administrative engineering." I would like to focus attention on the preparedness of industry to absorb men with this type of training in the regular way in which they have in the past handled men for technical positions. You will note that the author says those men in non-engineering work, who represent 60 to 70 per cent of the engineering graduates, apparently arrive there in a hit or miss fashion.

We are all acquainted with the program that exists in the larger companies for assimilating engineering graduates. This program, however, was built up over a period of years until it reached the stage where its functioning was well known to the various educators and was apparently satisfactory to the men employed. It is thought that it will be necessary to develop a similar program for men going into these so-called administrative or directive positions. The task will present more difficulties than that for the strictly technical men and it is well to mention some at this time.

In order to place men in directive or supervisory positions, it is necessary that they have considerable knowledge of the business. Provision must be made for obtaining this training. The qualifications for occupying supervisory positions are much more diversified than those for strictly technical work. These qualities can be determined only after careful observation and trial. The placing of men in supervisory positions supposes that they are more suitable than men in the ranks. This idea, I do not believe, will be readily accepted by most of the men in the ranks.

When technical graduates are employed for engineering work, most of the other employees are ready to consider that the engineering field requires a specialized training which the graduate has, and do not look upon him as a competitor. When the engineering graduate with the general training attempts to enter supervisory fields where men in the ranks feel they also are competitors for the position, difficulty may be expected. It is not anticipated that they will be ready to agree that the engineering graduate has those qualities which make him peculiarly fitted for the position instead of themselves. In order, therefore, to adapt the technical men to the positions which, we hope, they will be able to fill in better fashion, it will be necessary to give attention to suitable methods of introducing them into the organization and directing them through channels so that they may arrive in positions of responsibility without causing unrest among those who work for them.

This problem was brought up in my work several years ago but, due to business conditions, was dropped at that time. It has recently come up again in connection with a study of the men occupying supervisory positions. In some instructions by my superior regarding the study of this problem, a statement was made which can well be repeated as a warning that this program cannot be organized as quickly as some may think. The statement was along the following lines:

In introducing these engineering men into supervisory positions, you must be careful not to set up an aristocracy.

R. E. Hellmund: For the last few years I have followed with interest the many discussions on engineering education, stressing the necessity for broadening the curriculum to include non-technical subjects to a greater extent. A broad education for an engineer seems, of course, very desirable and one therefore hesitates to contradict statements to that effect. However, I have never been convinced that it is desirable to delete from the curriculum some of the

subjects absolutely essential for engineering and now generally included in the 4-year courses, nor am I very much in favor of extending engineering courses beyond the 4-year period. In general, I rather feel that as far as preparation for actual engineering work is concerned, the 4-year courses should primarily attempt to turn out efficient engineers and devote just enough time to a number of non-technical subjects to arouse an interest in such subjects. Where post-graduate work is possible for an engineer while he is practicing his profession, the inclusion of some of these broadening subjects is undoubtedly of advantage. In view of this opinion on my part, I rather welcome Mr. Morrow's viewpoint, which frankly recognizes the practical limitations and suggests one type of course which is primarily devoted to subjects needed for engineering work.

In analyzing this whole question, we realize that much of the discussion relating to the broadening of an engineering education has sprung from conditions created by the depression. Since our unemployment problems have been caused to a certain extent by engineering activities directed toward labor saving, the feeling has developed that it is the responsibility of the engineer to broaden his activities and to direct his attention toward solving this problem which he is accused of having created. As an engineer engaged purely in engineering work, I have therefore often wondered what I and my associates similarly engaged could possibly do about it. Assuming, for the sake of argument, that the education of these engineers was broad enough to include all such subjects as enter into the depression and unemployment problems, I was forced to conclude that such knowledge would be of little value to these engineers or anybody else unless they were willing to step out of the engineering profession and take up activities along entirely different lines. As far as the engineer who is engaged in regular engineering work in industry is concerned, his opportunities for exerting his efforts in broad activities are distinctly limited. He can, of course, take part in general educational work and he can, individually or through his activities in the various professional societies, assist in disseminating correct information regarding engineering and industry. In connection with the unemployment situation, he can support any movements for adjusting working hours to meet the demands of the times, appreciating that a gradual shortening of working hours will be a more or less natural development, as it has been in the past.

In addition to these incidental activities, he has, however, one major possibility to contribute toward the correction of the situation, and that is by creating through his engineering activities greater demands for industrial products. This he can do by devising entirely new products which will be useful in some way or other, by making existing products better and more useful, or by making such products available to a greater number of people through further reduction in cost. In other words, his principal opportunity to contribute effectually toward the problems of the day is through more and better engineering, or, in other words, in more efficient work in his own particular line.

All of this simply indicates that courses intended to prepare students for engineering work should have as their primary aim the production of efficient engineers. This in turn means that they should include thorough training in such subjects as physics, chemistry, mathematics, etc. Since the engineer's work should be directed principally toward the production of something of use to the human race and toward satisfying human needs and desires, the curriculum should preferably include some well selected course in psychology and, obviously industrial and engineering economics (not national or international economics and finance) should receive attention. Last, but not least, engineering courses should be directed toward developing interest in and ability to carry out typical engineering tasks.

Regarding the other type of course advocated by Mr. Morrow, there is no doubt that it will fill a real need. The designation "industrial engineering" seems to be quite appropriate for this course, but as pointed out in the paper, present courses going by this name do not entirely cover what the author has in mind. This is possibly due to the fact that the industrial courses are comparatively new in most schools, but I believe that their further development along the lines suggested in the paper is not only desirable but entirely feasible.

In general, after looking over typical curriculums of engineering colleges, I believe that with few exceptions the subjects listed are entirely as they should be. On the other hand, there frequently seems to be room for improvement in the way of a more careful selection of the material to be presented in such courses, and a method of presentation more suitable for engineering students. There also seems to be a need for better correlation of the various courses and for the choice of a better time for their presentation. The present quite common practice of turning the engineering student over to the college of arts and science for the greater part of the first 2 years of his course and of not giving him during that period even an inkling of what engineering is does not appeal to me. As a matter of fact, I consider it hardly fair to a student who has embarked in training for engineering to keep him practically in the dark as to what engineering work is really like for almost 2 years of his training, and up to a time when it is usually of great disadvantage for him to make a change to some other line of work.

Mr. Morrow's suggestion to weld the pure science courses and the engineering courses into one college has a great deal of merit. However, even if it is not possible to bring about this major change, it seems essential that the engineering schools should govern and take part to a greater extent in the training of the student during the first 2 years, which in turn may of course make it necessary to extend some of the science course into the third and fourth years. With the present arrangements, the engineering schools seem to have but little influence upon the work given to the students in other departments, and if an English teacher sees fit to teach an engineering student old English instead of training him in the best use of the English language in modern industry, there seems to be little that the engineering school can do about it. The study of old English is most interesting, but in my opinion it has no place in an already very crowded course for engineers.

Unfortunately the time available does not permit comment on many of the ideas given in Mr. Morrow's paper, most of which I can, however, heartily endorse.

L. W. W. Morrow: It is stimulating to hear so many constructive comments or suggestions for improving engineering education. We all agree that what is desired is an educated man and that education only starts in the colleges. It is also apparent that the majority agrees that engineering education is valuable because of its method and technique in addition to the contents of the courses. The trained engineer is an analyst and he is taught to seek facts in order to arrive at logical conclusions.

But the form of university organization and the types of courses to be taught are debated. Engineers in the field are well agreed that 4 years is sufficient time for the majority of students to spend in college. The addition of another year or 2 in order either to broaden or to narrow the college training is not economic and not practical. Therefore the general discussion reduces to plans for 4 years in college.

In my opinion the introduction of any great amount of cultural or economic course content in an engineering course designed to train men for professional engineering is inadvisable and impracticable—it weakens the professional training and is insufficient to give any appreciable element of broad training. In other words, with elevated technical standards for engineers, the 4 years in college should be devoted to technical training just as is the case with students in law and medicine. The infiltration of economic and cultural courses or the use of the optional method weakens rather than strengthens the present courses which are already below standard in technical content. I prefer the approach that modernizes and elevates the present technical courses.

For the large mass of young men who expect to enter upon business careers, as pointed out in several discussions, there is a possibility of developing an organization and a course that will be an improvement upon the present engineering courses or those in business and commerce. Such a course would use the engineering method and technique in instruction. It would not be a "snap" course. It can be developed to give a training in technology, economics and business more adequate and more rounded than those now available.

I agree with the comments that all educated men should have social consciousness and the broadest possible knowledge. But we are speaking of what is possible and practicable in the undergraduate period of life and in the present educational organizations. The present engineering schools are doing excellent work and their graduates are finding their places in all types of industry activities. The suggestions therefore that were made were general and not formulistic or rigid and were presented to the end that present trends in industry and in education might develop along logical lines to a culmination that appears to be an improvement upon present practices.

News

Of Institute and Related Activities

Salt Lake Convention Upholds Coast Reputation

OPENING on Labor Day, Monday, September 3, 1934, the 22d Pacific Coast convention of the Institute held forth during the week at the Hotel Utah in Salt Lake City. Enthusiasm at the technical sessions and during the entertainment features remained high throughout the week.

B. C. J. Wheatlake, chairman of the general convention committee, called the opening session to order at 2 o'clock Monday afternoon, with more than 140 members and guests present. Paul F. Keyser, president of the Salt Lake City chamber of commerce, in his welcoming address cited the long electrical history of the state of Utah, dating back to the historic initiation of high voltage transmission by the Telluride Power Company in Provo Canyon. Acting on behalf of President J. Allen Johnson, who was unable to attend, Vice President R. W. Sorensen of Pasadena, Calif., responded for the Institute, reëmphasizing some of the principal aims and objectives of the Institute, and urging engineers in general and electrical engineers in particular to stop "waiting for something to happen," and to proceed with the development of projects that will be of service to mankind. Turning his remarks to the younger engineers, Professor Sorensen urged that they should extend their activities into the fields where the products of engineering skill are used, and not limit their activities to the fields of development and production; he urged that activities and influence be extended through direct participation in the social and economic problems of community and state. By way of offsetting the tendency for the younger engineers to feel that there is no place for them, Professor Sorensen emphasized for one thing the "replacement market" throughout the industries in whose services electrical engineers are now indispensable, as well as the new industrial and other activities that now offer the enterprising electrical engineer an opportunity to reëstablish himself.

Attendance

A fitting testimonal to the unremitting efforts of the various convention committees was the fact that the total registration was 232 persons, and the fact that the attendance at the various technical sessions averaged above 100 and went as high as 140-odd. The territory considered as contributory to the Pacific Coast convention includes Districts 8 and 9, and the western portion of District 10; there were members and delegates present at Salt Lake City from 13 out of the 14 student Branches in this territory, and from most of the 7 Sections. National officers of the Institute present included Vice Presidents R. B. Bonney of Denver, Colo., R. W. Sorensen of Pasadena, Calif., and F. O. McMillan of Corvallis, Ore.; past vice presidents of the Institute present included: Dean H. V. Carpenter, Pullman, Wash., A. W. Copley, San Francisco, Calif., and C. R. Higson, Salt Lake City, Utah. The attendance is analyzed in the accompanying tabulation.

Analysis of Attendance at 1934 Pacific Coast Convention

Classification	Location: Salt Lake City	Dist. No. 9*	Dist. No. 8	Misc.	Totals
Members	26	15	33	25	99
Men Guests	10	7	4	7	28
Women Guests	27	13	16	11	67
Students	10	14	14	—	38
Totals	73	49	67	43	232

* District No. 9 outside of Salt Lake City.

Technical Sessions

The 5 technical sessions were held Monday afternoon, and Tuesday, Wednesday, Thursday, and Friday mornings, featuring the 25 papers listed in the convention program as published on p. 1128–29 of ELECTRICAL ENGINEERING for July 1934. As to subject matter and general interest, the sessions were devoted respectively to communication, management and protective devices, lightning, transmission, and a selected group of special research papers. Presiding over these meetings, respectively, were George T. Royden, of San Francisco, Calif., A. LeRoy Taylor, of Salt Lake City, Utah, Vice President F. O. McMillan of Corvallis, Ore., national transmission and distribution committee chairman D. M. Simmons, of New York, N. Y., and Past Vice President A. W. Copley of San Francisco.

Taking advantage of the unified publication plan, the committee in charge of the technical program for the Salt Lake City convention was able to schedule for discussion at the 5 sessions 25 papers instead of the previous limit of 14 or 16. Consequently the scope of interest was noticeably broadened and the discussion was particularly active and widely participated in, both by those present and by absentees through the medium of written discussion. Subject to the review and recommendation of the technical program committee, this discussion will be published in an early issue of ELECTRICAL ENGINEERING.

Student Activities

In addition to the general technical program, 2 entire afternoon sessions were devoted to the presentation of 12 student papers. The Tuesday afternoon session was presided over by Robert Ingebretsen of Stanford University, and the second student session was presided over by Don Pugsley, of the University of Utah, Salt Lake City. The student papers presented were as follows:

THE PERIODICITY ANALYMATOGRAPH, S. Hansen and G. K. Barger, University of Washington.

A NEW ILLUMINOMETER, Warren Patton, California Institute of Technology.

TRANSMISSION OF SOUND ON A BEAM OF LIGHT, W. H. Flanse, James W. Gilmer, and J. M. Kennedy, University of Montana.

SAN FRANCISCO-OAKLAND BAY BRIDGE CONSTRUCTION RADIOTELEPHONE SYSTEM, D. Reginald Tibbetts, University of Idaho.

AN AUDIO OSCILLATOR PIANOTRON, D. J. Ward, University of Idaho.

AUTOMATIC SYNCHRONIZATION, M. G. Lewis, University of Santa Clara.

ELECTRICAL MEASUREMENT OF WATER VELOCITY, J. K. Moore, Oregon State College.

THE GENERATING ELECTROSTATIC VOLTMETER, E. A. Schuchard, University of Washington.

A STUDY OF THE HIGH-TENSION MAGNETO IGNITION SYSTEM WITH SPECIAL REFERENCE TO THE SOURCE AND ELIMINATION OF RADIO INTERFERENCE, W. B. Smith, University of British Columbia.

FLASHOVER TESTS IN OIL, Ray Kidd, California Institute of Technology.

CORONA ATTENUATION WITH ARTIFICIAL LIGHTNING WAVES OF SHORT DURATION, P. DeK. Dykes, Stanford University.

ECONOMIC COMPARISON OF INCANDESCENT LAMPS, Max Llewellyn and Edward Hardley, University of Utah.

In addition to the student technical sessions already mentioned, the Enrolled Students and their counselors participated in a luncheon meeting Tuesday, September 4, and in the annual student conference that was held in part as a luncheon meeting after the close of the general session Friday afternoon. The latter meeting was presided over by Vice President Sorensen, who opened the session with a brief address emphasizing the importance of student activities in the further development of the Institute, and urging full coöperation of all concerned.

Of the 14 Student Branches in Districts 8, 9, and the western part of 10, all were represented by student chairmen or vice chairmen, and all but one were represented

Membership—

Mr. Institute Member:

By this time you have received a letter asking you to help your Section membership committee by sending in the name of one person who you feel should be invited to join the Institute. Your willingness to do this in the past has helped us to record a considerable increase in membership applications. If you have not yet replied to the letter, will you not do so promptly?

Very truly yours,

Chairman National Membership Committee

also by the student counselor. Branch counselors present included: A. L. Albert, Ore. State Col., E. F. Peterson, Univ. of Santa Clara, W. A. Hillebrand, Univ. of Calif., R. H. Hull, Univ. of Idaho, G. R. Shuck, Univ. of Wash., S. G. Palmer, Univ. of Nev., F. C. Lindvall, Calif. Inst. of Tech., O. E. Osburn, State Col. of Wash., and J. A. Thaler, Montana State Col.

The Branch chairmen present included: J. C. Garrett, State Col. of Wash., John V. Kelly, Univ. of Ariz., M. G. Lewis, Univ. of Santa Clara, T. M. Libby, Univ. of Wash., T. B. Lyman, Univ. of Calif., Donald Odell, Univ. of Nev., A. E. Opdenweyer, Ore. State Col., O. E. Osburn, State Col. of Wash., E. F. Peterson, Univ. of Santa Clara, E. E. Simmons, Calif. Inst. of Tech., and G. L. Stancliff, Jr., Univ. of Southern Calif.

One of the subjects most widely discussed at the student conference was the relative advisability of planning Student Branch programs on the basis of having outside speakers in the persons of practicing engineers, as against building such programs on the basis of entirely student presentations. Some favored one, and some favored the other, but the final general consensus of opinion seemed to be that a proper balancing of the 2 in the light of the peculiar conditions that may affect any one Branch produces the best over-all results.

At a group conference of the counselor-delegates for District No. 8, Prof. F. C. Lindvall, student counselor at California Institute of Technology, Pasadena, was chosen to act as District student counselor chairman for the ensuing administration year. A similar conference of the counselor-delegates from District No. 9 resulted in the choice of Prof. O. E. Osburn, student counselor at State College of Washington, Pullman, to act as District student counselor chairman for the ensuing administration year.

Entertainment Program

The entertainment program, judging by the general comments of those present, was pleasant in its variety, and satisfying in its quantity and quality. The program was formally initiated at the reception held Monday evening at the Hotel Utah, followed by dancing, although the enterprising local women's entertainment committee gathered all the women guests in attendance Monday afternoon and took them on a delightful automobile tour to points of scenic interest in the vicinity of Salt Lake, followed by tea at a popular rendevous. Other features presented especially for the entertainment of women guests in attendance at the convention were the bridge luncheon and the approaching and putting contest on the golf course, both of which were held Thursday afternoon at the Salt Lake Country Club. First prize in contract bridge went to Mrs. R. W. Sorensen of Pasadena, Calif.; for auction bridge to Mrs. W. B. Clark of Salt Lake City. In the putting contest, first honors went to Mrs. H. N. Raymond of Boise, Idaho; second honors to Miss Helen Rockwell of Los Angeles, Calif. Honors for the best approach shot were divided between Mrs. A. H. Brolly of San Francisco, and Mrs. D. K. Brake, Butte, Mont.

Most of those attending the convention took the opportunity of listening to the Tuesday noon organ recital at the Mormon Tabernacle, and later in the afternoon participated in a general excursion to Saltair where they disported themselves in the 28-per cent salt solution of the Great Salt Lake. The lake is at its lowest point in history, and the water has receded so far that it requires the services of a half-mile tramway to carry the bathers from the end of the pier out to the present actual water's edge.

The principal technical inspection trip, and excursion combined, was out to the mine and mills of the Utah Copper Company in Bingham Canyon, where many enjoyed themselves profitably Wednesday afternoon. Other parties were conducted to other points of mining and industrial interest, according to their choice.

An informal dance held at the Old Mill Club, in the vicinity of Salt Lake Wednesday evening, drew a large crowd, and the capstone of the convention entertainment program was represented by the convention banquet held Friday evening at the Salt Lake Country Club where some 150 or more of those attending the convention gathered for the final celebration and the awarding of golf prizes.

Acting at the request of J. A. Kahn who presided at the head table, Vice President Sorensen awarded the 1933 technical paper prizes for District No. 8: best Student Branch paper, to John H. Genzenhuber, of the University of Southern California, Los Angeles; best initial paper to A. H. Albrecht, Standard Oil Company of California, La Habra; best paper for the year, Lloyd F. Hunt and Alex A. Kroneberg, of Los Angeles. Final decisions on similar awards for District No. 9 had not been reached, and announcement consequently was deferred.

Golf

The annual golf tournament drew an entry list of 29 golfers and aspirants who had looked at the display of prizes, including the prized and coveted Fisken Cup. The affair was held on the beautiful and challenging course of the Salt Lake Country Club, Thursday, September 6.

The Fisken Cup, named for John B. Fisken (A'03) of Spokane, Wash., was won by H. W. Flye of San Francisco, Calif. For low net honors, Mr. Flye, M. M. Keneally of Mansfield, Ohio, and H. M. Ferguson of Salt Lake City, Utah, were tied; Mr. Ferguson won the toss to break the tie. The best fundamental golfer of the day proved to be E. W. Rockwell of Los Angeles, whose gross 86 topped the records.

Among the special awards were the following: for high gross score, Past Vice President H. V. Carpenter, of Pullman, Wash.; for the longest drive on No. 3 hole, E. W. Rockwell; for the best third shot on No. 18, Chester Coon of Oakland, Calif.; fattest golfer, M. M. Keneally; thinnest golfer, E. H. Martindale, Cleveland, Ohio; for the best No. 2 tee shot, S. L. Case of Oakland, Calif.; for blind bogey J. A. Kahn of Salt Lake City, and H. W. Flye and H. M. Ferguson were tied.

Committees

The general convention committee in charge of this most successful convention was: B. C. J. Wheatlake, *chairman;* R. W.

Future AIEE Meetings

Winter Convention,
New York, N. Y., Jan. 22–25, 1935

South West District Meeting,
Oklahoma City, Okla., Apr. 24–26, 1935

Summer Convention,
Ithaca, N. Y., June 24–28, 1935

Pacific Coast Convention,
Los Angeles vicinity, Fall 1935

Great Lakes District Meeting,
Indianapolis—Lafayette Section territory (Date to be determined)

Sorensen, A. C. Kelm, W. R. Barrett, A. LeRoy Taylor, J. A. Kahn, C. A. Malinowski, L. E. Brown, C. R. Higson, W. L. Winter, J. A. Hale, J. Hugh Hamilton, Mrs. L. B. Fuller, F. O. McMillan, H. T. Plumb, L. B. Fuller, A. H. Hull, A. P. Hill, J. A. Thaler, V. B. Wilfley, W. C. Smith, G. L. Hoard, W. M. Allen, and L. R. Stacey. The chairmen of the various subcommittees working with the general convention committee were as follows:

Entertainment—W. L. Winter, *chairman;* P. P. Ashworth, A. W. Copley, R. J. Corfield, H. H. Kroeger, and F. E. Young, Jr.

Finance—J. A. Kahn, *chairman;* W. R. Barrett and A. C. Kelm.

Golf—J. A. Hale, *chairman;* W. L. Winter and J. Hugh Hamilton.

Hotels and Registration—L. B. Brown, *chairman;* H. B. Waters and C. A. Wolfrom.

Publicity—L. B. Fuller, *chairman;* M. L. Cummings, Elwood Backman, and Harvey Hancock.

Reception—C. R. Higson, *chairman;* S. D. Packard, A. C. Kelm, and H. B. Waters.

Technical Program—A. LeRoy Taylor, *chairman;* C. R. Higson, H. T. Plumb, Fred Lundberg, and John A. McDonald.

Student Activities—J. Hugh Hamilton, *chairman;* J. Hugo Johnson, Nathan C. Clark, and F. C. Lindvall.

Transportation—C. A. Malinowski, *chairman;* D. L. Brundige, Frank E. Young, Jr., Sigurd A. Bloomquist, and Fred Lundberg.

Ladies' Entertainment—Mrs. L. B. Fuller, *chairman;* Mrs. J. A. Hale, Mrs. C. R. Higson, Mrs. B. C. J. Wheatlake, Mrs. J. A. Kahn, Mrs. H. T. Plumb, Mrs. W. L. Winter, and Mrs. C. A. Wolfrom.

Nomination of A.I.E.E. Officers for 1935 Election; Members Invited to Submit Suggestions by Nov. 15

FOR THE nomination of national officers to be voted upon in the spring of 1935, the A.I.E.E. national nominating committee will meet between November 15 and December 15, 1934. To guide this committee in performing its constituted task, suggestions from the membership are, of course, highly desirable. To be available for the consideration of the committee, all such suggestions must be received by the secretary of the committee at Institute headquarters, New York, N. Y., not later than November 15, 1934. In accordance with the provisions of the constitution and by-laws, quoted herewith, actions relative to the organization of the national nominating committee now are under way.

Constitution

28. There shall be constituted each year a national nominating committee consisting of one representative of each geographical district, elected by its executive committee, and other members chosen by and from the board of directors not exceeding in number the number of geographical districts; all to be selected when and as provided in the by-laws. The national secretary of the Institute shall be the secretary of the national nominating committee, without voting power.

29. The executive committee of each geographical district shall act as a nominating committee of the candidate for election as vice president of that district, or for filling a vacancy in such office for an unexpired term, whenever a vacancy occurs.

30. The national nominating committee shall receive such suggestions and proposals as any member or group of members may desire to offer, such suggestions being sent to the secretary of the committee.

The national nominating committee shall name on or before December 15 of each year, one or more candidates for president, national treasurer, and the proper number of directors, and shall include in its ticket such candidates for vice presidents as have been named by the nominating committees of the respective geographical districts, if received by the national nominating committee when and as provided in the by-laws; otherwise the national nominating committee shall nominate one or more candidates for vice president(s) from the district(s) concerned.

By-Laws

Sec. 22. During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical district that by November 1 of that year the executive committee of each district must select a member of that district to serve as a member of the national nominating committee and shall, by November 1, notify the secretary of the national nominating committee of the name of the member selected.

During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical district in which there is or will be during the year a vacancy in the office of vice president, that by November 15 of that year a nomination for a vice president from that district, made by the district executive committee, must be in the hands of the secretary of the national nominating committee.

Between October 1 and November 15 of each year, the board of directors shall choose 5 of its members to serve on the national nominating committee and shall notify the secretary of that committee of the names so selected, and shall also notify the 5 members selected.

The secretary of the national nominating committee shall give the 15 members so selected not less than 10 days' notice of the first meeting of the committee, which shall be held not later than December 15. At this meeting, the committee shall elect a chairman and shall proceed to make up a ticket of nominees for the offices to be filled at the next election. All suggestions to be considered by the national nominating committee must be received by the secretary of the committee by November 15. The nominations as made by the national nominating committee shall be published in the January issue of ELECTRICAL ENGINEERING, or otherwise mailed to the Institute membership during the month of January.

(*Signed*) H. H. HEELINS,
National Secretary

October 1, 1934.

A.S.M.E. Annual Meeting. The technical program for the 55th annual meeting of The American Society of Mechanical Engineers, to be held in New York, N. Y., Dec. 3–7, 1934, is well under way. Among the sessions being planned are the following: domestic heating; industrial power, and central station power; heat transfer; vibration, materials, stress analysis, and bearing analysis; aeronautics; machine design,

A Group at the Institute's Recent Pacific Coast Convention

This group, showing about half of those registered at the Institute's 22nd Pacific Coast convention, held this year at Salt Lake City, Utah, September 3–7, was photographed on the Temple Grounds Tuesday noon, September 4

Repairing a Conductor Carrying 38,000 Volts

THE above reproduction of a photograph received from H. L. Talbot (A'14, M'25) Bolivian Power Company, Ltd., Oruro, Bolivia, South America, shows men performing work which is believed to be quite original and which may be of interest to engineers in other countries. According to information received from Mr. Talbot, their single circuit steel tower transmission line of 4/0 aluminum conductor steel reinforced cable has developed serious conductor breakage due to crystallization of the aluminum strands at the suspension ears. The remedy for this recommended by the manufacturer of the cable was the installation of tapered aluminum armour rods twisted around the main conductors at each ear. The line is 3 phase, 38,100 volts, 50 cycles, and cannot be shut down for repairs. As no hot-stick equipment has as yet been developed for doing this kind of work, it must be performed by hand with actual personal contact. The work is being carried out successfully by the special method developed in the field for its performance. Mr. Talbot states that if any member of the Institute is interested in knowing how this work is being done he would be very pleased to give him all details. With the exception of the foreman in charge of the work, they do not have a single man on the job who has had previous line or even electrical experience, as the war between Bolivia and Paraguay has drafted all physically fit men in the working ages.

metal cutting, broaching, and welding; management; and prevention of occupational disease disability. Papers will also be presented on education, training in the industries, fan design, and research on steam, mechanical springs, boiler feedwater, and fluid meters.

Refrigerating Machinery Association Meeting. The annual meeting of the Refrigerating Machinery Association will be held October 22, 1934, at the Stevens Hotel, Chicago, Ill. At this meeting, officers will be elected and activities will be planned for the coming year. The past year has been especially productive in the cooperative exchange of technical information, standardization of equipment, and the promotion of a high standard of trade practices.

Radio Engineers to Meet at Rochester. The program for the Rochester fall meeting of the Institute of Radio Engineers, to be held at the Sagamore Hotel, Rochester, N. Y., November 12–14, 1934, has been announced. Among the subjects to be discussed are iron core tuning systems, high fidelity reproducers with acoustical labyrinths, automatic reactance control systems, applications of ultra-high frequencies, diode coupling considerations, centimeter waves, cathode wave tubes in receiver distortion measurements, converter tubes at high frequency, input losses in vacuum tubes at high frequencies, detector distortion, inductive interference, and new equipment. Brief discussions on the desirability of the reduction of radio interference from several different viewpoints also will be presented.

Standards

Membership Increase Reported by A.S.A.

According to an announcement made by Dr. P. G. Agnew (A'12, M'19) secretary of the American Standards Association, that association has reached an all-time peak in membership, in spite of present business conditions. The A.S.A. now has 42 member-bodies and associate members, and 1,233 company members. Since January 1934, 9 associations have become member-bodies or associate members. During this period, 11 other companies have joined the association, and 4 corporations have voluntarily increased their dues.

The A.S.A., national clearing house for standards and safety codes, was formed in 1918 by 5 technical societies which felt the need of developing inter-industry standards out of their own technical standards. More than 260 codes have been developed by the association and nearly 200 are under development or are being devised. More than 3,000 engineers, scientists, and industrialists, representing manufacturers, technical societies, consumers, and government departments, serve on its numerous committees.

Engineering Foundation

Second Volume of Arch Dam Report

The extensive 10-year field and laboratory research on problems of constructing and designing arch dams, which was carried on by The Engineering Foundation, was completed in 1933. (See ELEC. ENGG. for July 1933, p. 511–2.) Volume II of the report on the investigation of arch dams is now being printed, and completes the reports on this work. This volume, of 550 pages, approximately twice as many as either Volume I or Volume III, records the study of models of dams, and of materials therefor, and special studies of portland cement concrete. A copy will be supplied to each contributor to the fund for the research. Members of the 4 national societies of civil, mining and metallurgical, mechanical, and electrical engineers may purchase copies from The Engineering Foundation at $3 each; other persons at $4 each.

American Engineering Council

Prominent Engineers Named on Federal Aviation Commission

A practical approach to the aviation problem has been made by the appointment of 2 outstanding aeronautical engineers on the new 5-member board which will develop national policies for civilian and military aviation, according to a statement made recently by F. M. Feiker, executive secretary of American Engineering Council. The President recently named, as members of the federal aviation commission, Edward P. Warner, recognized as a leading authority on heavier-than-air craft, and Jerome C. Hunsaker, who is of similar prestige in the lighter-than-air field.

Mr. Warner, formerly a professor of aeronautical engineering in Massachusetts Institute of Technology, served as assistant secretary of the Navy for aeronautics from 1926 to 1929, and is now editor of the magazine, *Aviation*. Mr. Hunsaker also instructed in aeronantical engineering at M.I.T., where he has returned to head the mechanical engineering department. He was a commander in the Navy in charge of aircraft design. He is an officer of Goodyear-Zeppelin, International Zeppelin, and other companies.

Both men are members of American Engineering Council's committee on aeronautics of which Mr. Warner is chairman. Through this committee, Council is seeking to bring to bear the advice of organized engineers upon problems of the aviation industry along lines followed for the past decade.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Engineering Service

To the Editor:

President J. A. Johnson in his message in the August 1934 issue of ELECTRICAL ENGINEERING, p. 1142, said that he expected to do considerable thinking about the Institute's position in the "New Deal" and invited comment. He mentioned 9 definite movements which somewhat confuse the situation.

I have had to do some deep thinking myself as my friends know that I left Westinghouse last March and opened a consulting office in the Gulf Building in Pittsburgh. I believe that any effort the engineer makes for his own benefit must be based upon the fundamentals of service that is of direct value to some going organization. The "trade union" idea of combination to increase salaries and benefits is not the way to start. The engineer must command respect and a fair return for his services but first he must do things that will justify this respect and remuneration. Much more can be accomplished by coöperation through organization than by individual effort. Few men have that "all round" ability and experience necessary to handle the complicated situations in our present social order. Each of us has definite abilities and experiences which can be combined into a strong group which is mutually supporting and capable of wonderful accomplishments. Many commercial groups have commercial limitations that restrict engineering activities to definite channels. The A.I.E.E. is one of the few national groups that is free from such limitations where engineers can work for the common good which is the best way to advance our profession.

We need this kind of coöperative effort now more than ever. When it is necessary for individuals to reduce their society activities it is better to concentrate on our national society because of its broader possibilities. Individual members directly benefit largely in proportion to the efforts they put into their society. The profession as a whole is helped through the combined effort of the membership. During a depression like this one it may be necessary for us to do as many business enterprises have done, namely, to concentrate our efforts.

A lack of business has given many groups an opportunity to do some careful thinking and investigation, with the results that new things and new results will be available when business comes back and the time is ripe to release them. Engineers and business executives should be alive to this situation. The publications of the national societies are full of new things that should stimulate the engineering imagination. Many of these ideas and deductions are still in the theoretical stage and require the application of business judgment to make them commercial. Business men will not disclose their plans before they are ready to enter the market but the A.I.E.E. is an open forum for the exchange of engineering information; it is a good place to go for ideas.

Very truly yours,

H. D. JAMES (A'98, F'12)
(Consulting Engineer, Gulf Building, Pittsburgh, Pa.)

Graphical Solution of Delta-Star Resistance Transformations

To the Editor:

In solving networks it is frequently desirable to replace a delta combination of resistances or reactances by an equivalent wye which will give the same terminal voltage and current conditions. This well-known relationship is (see Fig. 1):

$$a = \frac{BC}{A + B + C} \text{ and } aA = bB = cC$$

As a mathematical recreation it is interesting to prove that these wye values can be found by the following graphical construction (see Fig. 2):

1. Construct a triangle with sides proportional to the delta resistances.
2. Draw the angle bisectors.
3. From their intersection draw lines parallel to the sides. These lengths are proportional to the desired wye resistances.

PROOF (see Fig. 3):

1. Draw lines parallel to the sides through the intersection of the angle bisectors.
2. From the similar triangles cxa and ABC

$$\frac{c}{a} = \frac{A}{C} \text{ and } \frac{x}{a} = \frac{B}{C}$$

3. $B - c - a = x$
4. (Substituting) $B - \frac{A}{C} \cdot a - a = \frac{B}{C} \cdot a$
5. $CB = Aa + Ca + Ba$
6. $a = \frac{BC}{A + B + C}$
7. The other relationships are found by using the appropriate triangles.

EXAMPLE

The example shown by the figures has the following proportionate values:

$A = 10$	$a = 3.2$
$B = 8$	$b = 4.0$
$C = 12$	$c = 2.6$

Very truly yours,

WILLIAM W. EDSON (M'25)

(Electrical Engineer, Construction Dept., Edison Electric Illuminating Co. of Boston, Mass.)

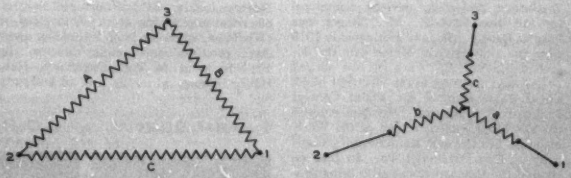


Fig. 1

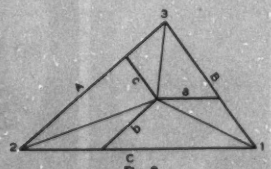


Fig. 2

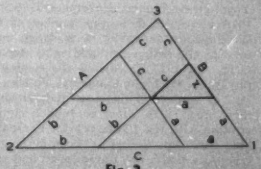


Fig. 3

Personal Items

C. O. Bickelhaupt (M'22, F'28) assistant vice president, American Telephone and Telegraph Company, New York, N. Y., has been appointed chairman of the Institute's publication committee for 1934–35. He was born at Roscoe, S. D., in 1888, and received the degrees of B.S., in 1911, and E.E., in 1914, from the University of Wisconsin. During several summers preceding graduation in 1911, he was employed by the Dakota Central Telephone Company. In the latter year he entered the American Telephone and Telegraph Company as an engineering assistant, becoming general commercial problems engineer in 1920, toll traffic engineer in 1922, and later in that year commercial engineer. From 1925 to 1930 he was vice president, director, and member of the executive committee of the Southern Bell Telephone Company, and during 1925–26 also held these offices in the Cumberland Telephone and Telegraph Company. Since 1930 he has been an assistant vice president of the American Telephone and Telegraph Company and a director of the Bell Telephone Securities Company. He has been a vice president and a director of the Institute, and has served on a number of committees. He has been reappointed as chairman of the committee on economic status of the engineer, and in addition is a member of the following committees: award of Institute prizes; constitution and by-laws; coördination of Institute activities; and technical program. Mr. Bickelhaupt also is the Institute's representative on the American Engineering Council and the Engineers' Council for Professional Development. He is a member of the New York Electrical Society and of the American Engineering Council, of which he is a vice president and committee member and chairman.

H. P. Sleeper (A'22, M'30) Public Service Electric and Gas Company, Newark, N. J., has been appointed chairman of the Institute's protective devices committee for the year 1934–35. Mr. Sleeper was born at Bangor, Me., and graduated in 1915 from the University of Maine with the degree of B.S. in E.E. Until 1917 he worked as assistant foreman in the electrical block signal department of the Maine Central Railroad at Brunswick. He then entered the advanced student course of the Westinghouse Electric and Manufacturing Company at East Pittsburgh, Pa. In 1917 he entered the U.S. army, and after being promoted to the rank of captain, was wounded in action in France, November 1918. In 1919 he returned to the employ of the Westinghouse company as a design engineer in the instrument and relay department. In 1923 he entered the employ of the Duquesne Light Company, Pittsburgh, Pa., as protection engineer and remained there until 1925 when he took a similar position with the Public Service Company. Since 1929 Mr. Sleeper has been in the general office under the transmission and substation engineer in charge of the operation of substations and switching stations. He has developed many new schemes of relay protection, and has been especially interested in perfecting operating procedures for high voltage electrical equipment, with particular reference to personnel safety. Mr. Sleeper holds 12 patents. He has presented several papers before the Institute, and has written various articles in technical magazines. He was the editor-in-chief of the N.E.L.A. relay handbook supplement published in 1931. He has served on various technical committees of the Institute, and has been a member of the protective devices committee since 1926.

J. Allen Johnson (A'07, F'27, and president) chief electrical engineer, Buffalo, Niagara, and Eastern Power Corporation, Buffalo, N. Y., has been appointed chairman of the executive committee of the Institute for 1934–35. He is also a member of the following: board of directors; Edison medal committee; and Charles A. Coffin fellowship and research fund committee. He is also representative on the American Engineering Council. A biographical sketch of Mr. Johnson appears on p. 230 of the January 1934 issue of Electrical Engineering in connection with his nomination for the presidency, and a photograph on p. 1038 of the July 1934 issue.

L. W. W. Morrow (A'13, F'25) editor, *Electrical World*, New York, N. Y., has been appointed chairman of the committee on coördination of Institute activities for 1934–35. He was born at Hammond, W. Va., August 7, 1888, and was educated at public schools in Fairmont, W. Va., Fort Worth, Texas, and Amarillo, Texas, followed by preparatory schooling at Marshall College, Huntington, W. Va. In 1907 he entered Cornell University and graduated in 1911 with the degree of M.E., remaining for 2 years as an instructor. He then went to Norman, Okla., as assistant professor of electrical engineering at the University of Oklahoma, where he later became an associate professor and acting director. In 1918 he went to Yale University, New Haven, Conn., where he was an assistant professor of electrical engineering until 1922, when he became affiliated with the McGraw-Hill Publishing Company, Inc., of New York, on the editorial staff of *Electrical World*, of which he became editor in 1928. Mr. Morrow is a director of the Institute and has served on many committees. He is now a member of the board of examiners, and of the following committees: finance; legislation affecting the engineering profession; applications to marine work; membership; production and application of light; and technical program. He also is Institute representative on the Engineers' Council for Professional Development.

R. H. Tapscott (A'18, F'29, and vice president) vice president, New York Edison Company, New York, N. Y., has been appointed chairman of the finance committee of the Institute for 1934–35. He is also a member of the following committees: board of directors; coördination of Institute activities; executive; and headquarters. A biographical sketch of Mr. Tapscott appears on p. 231 of the January 1934 issue of Electrical Engineering in connection with his nomination for a vice presidency, and a photograph on p. 1038 of the July 1934 issue.

H. M. Hobart (A'94, F'12, and member for life) consulting engineer, General Electric Company, Schenectady, N. Y., has been appointed chairman of the Institute's committee on electric welding for 1934–35. He was born at Boston, Mass., in 1868, and graduated from the electrical engineering course at Massachusetts Institute of Technology in 1889. He then entered the employ of the former Thomson-Houston Company at Lynn, Mass., transferring to Schenectady, N. Y., with the formation of the General Electric Company, but later returning to Lynn. From 1900 to 1911 he was in Europe, principally in London, England, where he practiced consulting engineering for 8 years. During this time he was a lecturer at English educational institutions. Upon his return to this country he became associated with the General Electric Company as a consulting engineer. He has been particularly interested in electric welding, and was a member of the welding committee of the Emergency Fleet Corporation. Mr. Hobart has served on a number of Institute committees, and is now

H. P. SLEEPER

C. O. BICKELHAUPT

Kaldm-Kasanian Studios

L. W. W. MORROW

E. B. MEYER

V. M. MONTSINGER

H. M. HOBART

a member of the research committee, and also is Institute representative on the American Bureau of Welding. He is a member of the Institution of Civil Engineers, Institution of Mechanical Engineers, and Institution of Electrical Engineers, all of Great Britain; and of The American Society of Mechanical Engineers and American Welding Society, and a fellow of the American Association for the Advancement of Science.

E. B. Meyer (A'05, F'27) vice president United Engineers and Constructors, Inc., Newark, N. J., has been appointed chairman of the Institute's committee on constitution and by-laws for 1934–35. He was born in Newark, and in 1903 graduated from the Pratt Institute, Brooklyn, N. Y. He entered the employ of the Public Service Corporation of New Jersey and remained with that organization until he was appointed chief engineer of the Public Service Production Company in 1922. He became a vice president of that company in 1929, and of United Engineers and Constructors, Inc., in 1930 when the 2 companies merged. Mr. Meyer has been very active in Institute affairs and has served on many committees. He was a director 1927–31 and a vice president 1932–34. He is now a member of the following committees: coördination of Institute activities; Edison medal; publication; and transfers; and is representative on the Engineering Societies monograph committee.

V. M. Montsinger (A'14, F'29) research engineer, General Electric Company, Pittsfield, Mass., has been appointed chairman of the Institute's electrical machinery committee for 1934–35. He was born at High Point, N. C., and graduated from the University of North Carolina in 1909 with the degree of B.S. He entered the transformer department of the General Electric Company in January of the following year. From that time until 1922 he devoted most of his time to the study and development of practical thermal laws relating to the heating of transformers and to improved methods of cooling transformers. Since 1922 his time has been devoted mostly to the study and development of simple and workable dielectric laws for insulations, and means for insulating transformers to withstand high voltage stresses, particularly of the transient type. He has been a member of the Institute's electrical machinery committee since 1926, and he has been reappointed as a member of the standards committee, on which he has served since 1928, where he has been active in keeping the Institute Transformer Standards up to date in reflecting the latest practice. He has written numerous technical articles for engineering journals.

W. T. Ryan (A'07, M'12) professor, department of electrical engineering, University of Minnesota, Minneapolis, was elected a member of the council of the Society for the Promotion of Engineering Education at the annual meeting in June at Ithaca, N. Y. Professor Ryan has served on 2 Institute committees, production and application of light, 1928–30, and education, 1929–33, and was a vice president, 1928–30.

F. W. Smith (A'05, M'12) president, New York Edison Company, United Electric Light and Power Company, and Brush Electric Illuminating Company, has been elected a member of the board of trustees of the Northwestern Mutual Life Insurance Company, Milwaukee, Wis. He has participated in committee work of the company, and was a pioneer in advocating the investment of insurance company funds in public utility bonds.

H. C. Dean (A'12, F'30) general superintendent, New York and Queens Electric Light and Power Company, Flushing, N. Y., has been elected a vice president of the company. He has been identified with the utility since 1916, becoming general superintendent in 1917. He has served on the Institute's power transmission and distribution committee, 1929–32, and the board of examiners, 1933–34.

L. M. Klauber (A'11, F'23) vice president in charge of operation, San Diego Consolidated Gas and Electric Company, San Diego, Calif., is a director of the Pacific Coast Electric Association. Mr. Klauber was a member of the Institute's power transmission and distribution committee, 1921–25, and its representative on the American Association for the Advancement of Science council, 1931.

T. S. Taylor (M'21) director, T. Smith Taylor Laboratories, Caldwell, N. J., has been appointed head of the physics department at Washington and Jefferson College, Washington, Pa., but will continue his consulting service. Doctor Taylor was a member of the committee on research, 1928–30, and is the Institute's representative on the committee on heat transmission of the National Research Council.

C. E. Magnusson (A'05, F'13, and Life Member) head of the electrical engineering department of the University of Washington, Seattle, has been named permanent chairman of the Washington State Planning Council's technical advisory committee. Dr. Magnusson was an Institute vice president 1920–21, and has served on a number of committees.

C. C. Curtis (M'23) who recently succeeded A. M. Chitty (M'22) as district manager, Puget Sound Power and Light Company, Olympia, Wash., has been transferred to Stone and Webster, Inc., as personnel director for that organization. He has been connected with Stone and Webster enterprises since 1907.

Sidney Hosmer (A'97, F'12, and member for life) vice president and general manager, Edison Electric Illuminating Company of Boston, Mass., was honored by his associates on July 11, 1934, the 40th anniversary of his association with this utility. Mr. Hosmer became a vice president in 1926 and general manager in 1932.

E. F. Scattergood (A'08, F'13) chief electrical engineer and general manager, bureau of power and light, Los Angeles, Calif., has been named the first national chairman of the newly organized National Municipal Utilities Association. He was a member of the power stations committee of the Institute 1914–17.

A. S. Moody (A'09) northwestern manager, General Electric Company, Portland Ore., has been elected a member at large of the executive committee of the Northwest Electric Light and Power Association. He was Institute representative on the U.S. national committee of the International Electrotechnical Commission, 1919–22.

George Sutherland (A'20, F'27) formerly assistant general superintendent, New York and Queens Electric Light and Power Company, Flushing, N. Y., is now general superintendent. He was a member of the board of examiners 1929–30, and of the standards committee 1927–34.

Gerard Swope (A'99, F'22) president, General Electric Company, New York, N. Y., has been named to membership on the advisory committee of the American Standards Association. He has been on the Iwadare Foundation committee of the Institute, 1931–34.

J. E. Royer (A'15) vice president and general manager, Washington Water Power Company, Spokane, has been elected a member-at-large of the executive committee of the Northwest Electric Light and Power Association.

J. H. McGraw (A'01 and member for life) chairman of the board, McGraw-Hill Publishing Company, New York, N. Y., has been named to membership on the advisory committee of the American Standards Association.

H. R. Stewart (A'26) formerly general engineer, Westinghouse Electric and Manufacturing Company, Boston, Mass., has become protection engineer for the New England Power Engineering and Service Corporation, Boston.

W. S. Gifford (A'16) president, American Telephone and Telegraph Company, New York, N. Y., has been named to membership on the advisory committee of the American Standards Association.

L. A. Grettum (A'24) Eastern Oregon Light and Power Company, Baker, Ore., has been elected state vice president for Oregon of the Northwest Electric Light and Power Association.

M. S. Oldacre (A'13) has been appointed equipment planning engineer in the equipment section of the Commonwealth Edison Company, Chicago, Ill.

L. I. Anderson (A'25) has been appointed equipment standardization engineer in the equipment section of the Commonwealth Edison Co., Chicago, Ill.

Obituary

Walter Wood (A'04) partner, R. D. Wood and Company, Philadelphia, Pa., died April 20, 1934. He was born at Philadelphia on Dec. 6, 1849, and received the degree of A.B. from Haverford College in 1867 and from Harvard University in 1868. In that year he entered R. D. Wood and Company, an organization which was founded in 1803. Mr. Wood was treasurer of the Millville Gas Works and president of the Florence Iron Works. He was also a director of the Burlington (N. J.) City Loan and Trust Company, and a trustee of Haverford College. He was a member of The American Society of Mechanical Engineers, the American Institute of Mining and Metallurgical Engineers, the American Society for Testing Materials, and the American Waterworks Association. His club membership included: Union League, Manufacturers', Art, University, and City, all of Philadelphia; Machinery, Engineers', University, Harvard, and City of New York.

Paul Bernard Selden (A'08, M'13) industrial tests and layouts, Springfield, Mass., died on December 12, 1933. He was born at Hallsport, N. Y., January 21, 1878. After graduating from the Bliss Electrical School in 1900 he worked for short periods of time for the Union Telephone and Telegraph Company, Bradford, Pa., and the New York Edison Company, New York. In 1904 he went to Springfield as superintendent in the meter department of the United Electric Light Company. He became chief electrician in 1908, with charge of all additions to electrical station equipment. In 1917 he engaged in consulting engineering, and 4 years later became electrical engineer for McClintock and Craig, Springfield, which position he held until recently.

Richard Little Wilson (A'22) wire chief, Braden Copper Company, Rancagua, Chile, was accidentally killed there some 2 years ago, according to word just received at Institute headquarters. He was born at sea aboard the British sailing vessel "Primrose Hill" on July 13, 1889. His education was received at schools in Altrincham and Bowden, in Cheshire, England. In 1905 he joined the Wardle Engineering Company in Manchester as an electrician, and for short periods subsequently was employed by engineering firms in Edinburgh, Scotland, and Belfast, Ireland. In 1914 he became telephone foreman for the Braden company in Rancangua, and assumed the position of wire chief in 1921.

Edward Marc Duvoisin (A'23) lightning arrester engineering department, General Electric Company, Pittsfield, Mass., died on July 6, 1934, after a short illness. He was born at Grandson, Switzerland, May 21, 1894. He graduated from the University of Lausanne in 1917, and from then until 1922 was engaged in work at Geneva and Lausanne, Switzerland. In that year he came to the United States and entered the test department of the General Electric Company in Schenectady, N. Y., and after 2 years there he was transferred to the lightning arrester department in Pittsfield.

Foster D. Keesi (A'20) instructor and textbook writer, International Correspondence Schools, Scranton, Pa., died on Aug. 14, 1934, from gangrene. He was born at Rome, N. Y., Aug. 7, 1889. Upon completion of the electrical engineering course at Syracuse University in 1910 he entered the test course of the General Electric Company at Schenectady, N. Y., and remained with that company until 1914, when he became an instructor for the correspondence school. He was engaged in this work until his death with the exception of a year in the radio branch of the U.S. signal corps at the time of the war.

Mitchell Aaron Kreindler (A'32) maintenance man, Union Gas and Electric Company, Cincinnati, Ohio, died in a New York hospital on August 10, 1934, and was buried in Cincinnati. He was apparently recovering from an illness but suffered a relapse. He was born at New York on August 28, 1908. He was a graduate of the electrical engineering course at the University of Cincinnati, class of 1931, and had been employed as maintenance man since January 1929.

Membership

Recommended for Transfer

The board of examiners, at its meeting held September 19, 1934, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Member

Coulthard, Wm. B., asst. prof. of E.E., Univ. of British Columbia, Vancouver.
DuBois, N. W., supt. of distribution, Dominion Elec. Pwr. Ltd., Estevan, Sask.
Evans, Haywood W., asst. system relay engr., Va. Elec. & Pwr. Co., Richmond.
Geiger, James M., E.E., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Gray, John L., electrolysis engr., Louisville Gas & Elec. Co., Louisville, Ky.
Hodges, Ralph C., E.E., Titanium Pigment Co., Spotswood, N. J.
Holden, Omar W., Jr., E.E., Bureau of Pwr. & Lt., Los Angeles, Calif.
Johnson, Kenneth H., relay engr., Niagara, Lockport & Ontario Pwr. Co., Jamestown, N. Y.
Kronenberg, Alex A., tech. asst. to operating engr., So. Calif. Edison Co. Ltd., Los Angeles.
Levy, Mortimer N., 40 West 72 St., N. Y. City.
Milbrye, Joseph H., gen. supt., Niagara, Lockport & Ontario Pwr. Co., Olean, N. Y.
Presley, Evans E., supt. of lines, Tonawanda Pwr. Co., No. Tonawanda, N. Y.
Sawyer, Mark A., protection engr., So. Calif. Tel. Co., Los Angeles.
Schlaikjer, Hugo C., asst. engr., Bklyn. Edison Co. Inc., Bklyn., N. Y.
Smith, Farquhar W., asst. gen. engr., Va. Elec. & Pwr. Co., Richmond, Va.
Smith, Harry B., elec. pwr. trans. engr., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Tennant, George B., engg. asst., The Syracuse Ltg. Co. Inc., Syracuse, N. Y.
Wilkinson, B. J., dist. commercial mgr. and pwr. engr., Niagara, Lockport & Ontario Pwr. Co., Olean, N. Y.
Wilson, Dean, supervising draftsman, Pacific Gas & Elec. Co., San Francisco, Calif.
Wright, Sherwin H., elec. engr., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.

20 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before Oct. 31, 1934, or Dec. 31, 1934, if the applicant resides outside of the United States or Canada.

Adashko, J. G., Ford Instr. Co., L. I. City, N. Y.
Alfred, G. E., Gibbs & Hill, N. Y. City.
Allen, A. S., Tonawanda Pwr. Co., N. Tonawanda, N. Y.
Babcock, G. S., Drake Hotel, Chicago, Ill.
Bailey, W. F., Stevens Inst. of Tech., Hoboken, N. J.
Bobier, F. C., Gen. Elec. Co., Schenectady, N. Y.
Bonacio, T. J., 11 Main St., Cold Spring, N. Y.
Castle, D. McC., Calif. Portland Cement Co., Colton.
Curry, A. R. (Member), Buffalo, Niagara & Eastern Power Corp., Buffalo, N. Y.
Egan, F. D. (Member), Bethlehem Steel Co., Lackawanna, N. Y.
Freudenberger, W. J. (Member), Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Fuller, D. C. (Member), Bd. of Pub. Util., Jamestown, N. Y.
Greene, H. G. (Member), Bethlehem Steel Co., Lackawanna, N. Y.
Harris, C. H., Va. Elec. & Pwr. Co., Richmond.
Hawke, R. S., Louisville Gas & Elec. Co., Ky.
Heffner, C., Okla. Gas & Elec. Co., Oklahoma City.
Heinz, C. A., 1925 Cecil Ave., Baltimore, Md.
Heston, W. S. (Member), Gen. Elec. Co., Buffalo, N. Y.
Isbister, E. J., 1126 84th St., Bklyn., N. Y.
Jasnecke, L. E., Tonawanda Pwr. Co., N. Tonawanda, N. Y.
Jochnck, K. M., Gen. Elec. Co., Schenectady, N. Y.
Jolliffe, C. B. (Member), Federal Communications Commission, Washington, D. C.
Keller, C. L., Toledo Edison Co., Toledo, Ohio.
Leidy, H. B., Westinghouse Elec. & Mfg. Co., Wilkes-Barre, Pa.
Marvin, G. S., Central Ill. Lt. Co., Peoria.

Noble, T., Bureau of Pwr. & Lt., Los Angeles, Calif.
Ochsner, W. W., Southwestern Lt. & Pwr. Co., Lawton, Okla.
Parker, J. A. (Member), Niagara, Lockport & Ontario Pwr. Co., Jamestown, N. Y.
Plant, W. L., Tonawanda Pwr. Co., N. Tonawanda, N. Y.
Podowitz, S., 1920 Walton Ave., Bronx, N. Y. City.
Pollock, R. B., So. Calif. Edison Co., Ltd., Los Angeles.
Randall, H. L. (Member), Buffalo Gen. Elec. Co., N. Y.
Rankin, O. T., Toledo Edison Co., Toledo, Ohio.
Samuel, A. L. (Member), Bell Tel. Lab., N. Y. City.
Sieminski, E., 420 Sawyer St., New Bedford, Mass.
Smith, J., Canada Wire & Cable Co. Ltd., Regina, Sask., Can.
Stankevich, P. A., Bklyn. Edison Co., Bklyn., N. Y.
Thompson, R. E. (Member), Trinidad Elec. Trans. Ry. & Gas Co., Trinidad, Colo.
Thornton, W. N. (Member), U. S. Navy, Navy Yard, Boston, Mass.
Towle, J. M. (Member), Buffalo Gen. Elec. Co., Buffalo, N. Y.
Turner, H. R. (Member), Bethlehem Steel Co., Lackawanna, N. Y.
Vivian, J. H., So. Calif. Edison Co., Ltd., Los Angeles.
Voelkner, G. A. (Member), C. & W. I. R. R. & Belt Ry. Co., Chicago, Ill.
Walker, R. A., Tufts Col., Medford, Mass.
Warner, J. C. (Member), R. C. A. Radiotron Co., Harrison, N. J.
Williams, D., Toledo Edison Co., Sylvania, Ohio.
Yerger, L. K. (Member), Buffalo Gen. Elec. Co., Buffalo, N. Y.

47 Domestic

Foreign

Aristarov, A. V., Research Inst. of Shipbuilding, Leningrad, U.S.S.R.
Colwell, H. F. (Member), Victorian Rys., Melbourne, Victoria, Australia.
Haase, D. A., Lago Oil & Transport Co., Ltd., Aruba, D. W. I.
Howell, W. F., San Fernando Borough Council, San Fernando, Trinidad, B.W.I.
Lamm, A. U., Allmanna Svenska Elektriska Aktiebolaget, Vesteras, Sweden.
Marlatia, R. M., Indian Inst. of Sci., Bangalore, India.
Mehta, J. J., Bombay Municipality, Municipal Workshops, Bombay, India.
Raman, P. N., Chlittoor Elec. Supply Corp., Ltd., Mylapore, Madras, India.
Watkins-Ball, C. G., Metropolitan-Vickers Electrical Co. Ltd., Manchester, Eng.

9 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Adams, William C., 801 S. Lynn St., Champaign, Ill.
Baloocian, Levon M., 776 N. Cass St., Milwaukee, Wis.
Handley, Wilbur H., 4416 Loren Ave., Los Angeles, Calif.
Jordan, Henry, 7408A Christopher Colombus, Montreal, Que., Can.
Losonoy, William A., 14067 Cherrylawn Ave., Detroit, Mich.
Mexal, J. Rene, 86-03 Britton Ave., Elmhurst, L. I., N. Y.
Moellendick, K. F., L. A. Automotive Works, 1010 Towne Ave., Los Angeles, Calif.
Schultz, Carl H., 15 Cook St., Jersey City, N. J.
Simpson, Sidney, Deputy Loco. Supt., Eastern Bengal R. R., Kanchrapara, Bengal, India.
Stuntz, Hans, 106 Peck Ave., Newark, N. J.
Villegas, Lucio P., Tacoma General Hospital, Tacoma, Wash.
Wagoner, K. S., 320 Wisconsin, Oak Park, Ill.

12 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

APPLIED ACOUSTICS. By H. F. Olson and F. Massa. Phila., P. Blakiston's Son & Co., 1934. 430 p., illus., 9 x 6 in., lea., $4.50. The principles of acoustical engineering and discussion of the design, construction, operation, and analysis of modern acoustical and electro-acoustical apparatus; fundamental acoustic equations, systems of sound transmission, fundamental acoustical measurements, laboratory apparatus, microphones, telephone receivers, loud speakers, architectural acoustics, noise, physiological acoustics, and miscellaneous applications of acoustics.

CIVIL ENGINEERING HANDBOOK. By L. C. Urquhart. N. Y. & Lond., McGraw-Hill Book Co., 1934. 885 p., illus., 9 x 6 in., lea., $5.00. A compact, comprehensive book to which the practicing engineer can refer when confronted with a problem outside a specialized field. Civil engineering is covered in 10 sections each by a well-known authority: surveying, railway and highway engineering; mechanics of materials, hydraulics, stresses in framed structures, steel design, concrete, foundations, sewerage and sewage disposal, water supply and purification. Much tabular matter usually incorporated in handbooks is omitted and attention is given especially to fundamental theory.

COST ACCOUNTING for CONTROL. By T. H. Sanders. 2 ed. N. Y. & Lond., McGraw-Hill Book Co., 1934. 517 p., illus., 9 x 6 in., cloth, $4.00. A revised and enlarged edition of the author's "Industrial Accounting," brought up to date and in line with the new problems introduced by government control of industry. As in the previous work, emphasis is upon the meaning of costs and their uses in management, rather than upon matters of technical procedure.

ENGINEERING DRAFTING. By W. G. Smith. N. Y. and Lond., McGraw-Hill Book Co., 1934. 236 p., illus., 9 x 6 in., cloth, $2.25. A course for the beginner which aims to develop, in addition to skill as a draftsman, independent thinking and initiative. Part 1 presents the fundamentals of the subject; part 2, its applications to machine, airplane, and pictorial drafting.

ENGINEER'S SKETCH-BOOK of MECHANICAL MOVEMENTS, Devices, Appliances, Contrivances, and Details. By T. W. Barber. 6 ed. London, E. & F. N. Spon, Ltd.; N. Y., Engineers Book Shop, 1934. 355 p., diagrs., 9 x 5 in., $4.50. Collection of mechanical movements popular with designers and mechanics for nearly 50 years. The present issue contains almost 3,000 sketches of machines and machine elements of all kinds, classified and indexed.

50 JAHRE BERLINER ELEKTRIZITÄTSWERKE 1884-1934. ed. by C. Matschoss, R. Schulz, A. T. Gross, in Kommission with VDI-Verlag. Berlin, 1934. 247 p., illus., 12 x 8 in., cloth, 6 rm. A contribution to the history of electrical engineering, issued on the fiftieth anniversary of the founding of the Berlin Electric Works and tracing the development of the municipal electric system from then to the present day. Both economic and engineering features are described in detail. A chronological table is included, as well as a bibliography.

KINEMATICS of MACHINES. By G. L. Guillet. 3 ed. New York, John Wiley & Sons, 1934. 276 p., illus., 9 x 6 in., cloth, $3.00. In this college text the author has kept in mind the knowledge of physics and mathematics to be expected of the sophomore student, and the amount of time usually allotted to the study of kinematics. The book does not attempt to cover the field completely but gives a selection of material of decidedly practical interest. Fundamental mathematical analyses of motions in machines and useful graphical constructions pertaining to these have been given preference over purely descriptive matter.

MACHINE DRAWING. By E. F. Tozer and H. A. Rising. N. Y. and Lond., McGraw-Hill Book Co., 1934. 317 p., illus., 9 x 6 in., cloth, $3.00. A text and problems in accordance with good drafting-room practice which will bridge the gap between the fundamentals of freshman drawing and advanced treatises on machine design. The problems trace the production of a machine from the conception of the idea to its completion.

MATHEMATICAL TABLES, reprinted from Searles and Ives' Field Engineering with additions. Compiled and arranged by H. C. Ives. 2 ed. N. Y., John Wiley & Sons, 1934. 160 p., illus., 7 x 4 in., lea., $1.50. A collection of the mathematical tables most frequently wanted is presented in a volume small enough to be carried easily in the pocket. The type is clear and great care has been taken for accuracy. The new edition has been enlarged from 14 to 18 tables.

NEW BACKGROUND OF SCIENCE. By Sir James Jeans. N. Y., Macmillan Co., 1933. 301 p., illus., 8 x 5 in., cloth, $2.50. A discussion of the discoveries of Einstein, Bohr, Heisenberg, and others, and explanation of how these have led to a new philosophy. As in previous books, Sir James has kept in mind the general reader, as well as the student of physics, and the book is eminently clear and readable.

(The) KINETIC THEORY of GASES. By L. B. Loeb. 2 ed. N. Y. & Lond., McGraw-Hill Book Co., 1934, 687 p., illus., 9 x 6 in., cloth, $6.00. The aim of this work is to provide students and investigators with a book presenting the classical and more modern aspects of the kinetic theory in a form suitable for use as a college text and handy reference work. The new edition has been thoroughly revised and largely rewritten in the light of developments since the first publication.

Great Britain. Dept. of Scientific and Indus. Res. Illum. Res. Tech. Paper No. 15. INDUSTRIAL LIGHTING, Pt. 2. LIGHTING for CRANES. Lond., His Majesty's Stationery Office, 1934. 8 p., diagrs., 10 x 6 p., paper, 3d. (Obtainable from British Library of Information, $.10.) This paper, the second of a series upon dock lighting, considers the methods of fitting lighting units to shore cranes and makes recommendations concerning the best systems.

POWER PLANT TESTING, a Manual of Testing Steam Generating Equipment, Engines, Turbines, Pumps, Refrigerating Machinery, Fans, Fuels, Lubricants, etc. By J. A. Moyer. 4 ed. enl. N. Y. & Lond., McGraw-Hill Book Co., 1934. 614 pp., illus., 9 x 6 in., cloth, $5.00. This volume gives in some detail the generally approved methods of testing engines, turbines, boilers and power-plant auxiliary machinery, accompanied by descriptions of the apparatus used and the calibrations required for accurate work. This edition has been rewritten and enlarged, particularly with reference to the codes for testing approved by various engineering societies, and again represents up-to-date practice. The book is intended as a laboratory manual for students and a reference book for the engineer of tests.

PRACTICAL BUSINESS STATISTICS. By F. B. Croxton and D. J. Cowden. N. Y., Prentice-Hall, 1934. 529 p., illus., 9 x 6 in., cloth, $3.50. The collection, tabulation, graphic presentation and interpretation of statistics are here discussed in a clear manner. The treatment is concerned only with elementary statistical procedures, but includes those commonly wanted in business. The text seems well adapted for students of business methods.

Engineering Societies Library

29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

Thyrite Protects Meters From Lightning.—Safe, convenient protection against failure due to lightning is provided for polyphase watthour meters by a new device, the Thyrite meter-protector, recently introduced by the General Electric Co. The device, designed to be mounted as part of the meter installation, is intended for use on relatively long and exposed secondary circuits of 650 volts or below. An installation of 500 of these new protectors has been made by the Consumers Power Co., Jackson, Mich., on a three-phase 480-volt secondary for industrial-customer service. Previously, lightning failures were numerous. However, with most of the new protectors in operation during the major part of the lightning season, failures due to normal causes have been practically eliminated on protected meters. The device consists essentially of three single-pole protectors each of which is made up of a Thyrite disk and a small series gap. The whole is contained within a steel enclosing case, 5 $^1/_2$ in. high, 4 $^1/_2$ in. wide, and 2 $^1/_4$ in. deep. Thyrite is a non-porous, inorganic, ceramic material, which General Electric has used successfully for years in the manufacture of lightning arresters.

Bakelite Laminated "Sandwiches."—Meeting a need for a product that must be "as soft as rubber and long-wearing as Bakelite Resinoid," Synthane Corp. of Oaks, Pa., is manufacturing, under Bakelite Corp. patents, a new material consisting of layers of soft rubber "sandwiched" between sheets of Bakelite Laminated. An infinite number of combinations are possible, since the layer thicknesses may be varied, as well as the number of alternating layers of rubber and laminated material. Uses suggested are gasket applications where a combination of axial resiliency with strength and rigidity is required and for vibration-absorbing machine mountings.

New Heavy Duty Blower.—The Ideal Commutator Dresser Co., Sycamore, Ill., has announced an addition to its line of portable cleaners in the Jumbo model designed for the most extreme heavy-duty dust, dirt and lint cleaning work. The new machine blows, suctions and sprays. It is powered by a full horsepower G-E motor. It may be used to blow or vacuum all dirt from motors and machinery or to clean irregular surfaces before painting. An attachment sprays paint, varnish or any liquid or powder.

New Compact Circuit Breaker Interrupts 20,000 Amperes.—The Westinghouse Electric & Mfg. Co. announces a new low voltage "De-ion" breaker, similar in general to the standard 600-ampere, 600-volt AB breaker brought out several years ago, with the major exception that the new breaker has an interrupting capacity of 20,000 amperes. The new AB-20 is totally enclosed, being mounted in the standard 600-ampere molded case. It is available in all ratings from 50 to 600 amperes, complete with standard tripping accessories and motor mechanism. To secure a heavy duty AB-20 breaker it was necessary to double the interrupting capacity of the standard AB breaker. This was accomplished by a complete redesign of the contact structure and major modifications in the "De-ion" chambers and operating mechanism. The cold cathode principle of arc extinction, which has been successfully used in the standard duty breakers, has been retained.

Additions to Square D Switch Line.—The addition of 100- and 200-ampere switches to the new Square D 50,000 line of type A switches has been announced by Switch & Panel Division, Square D Co., Detroit, Mich. The new catalog numbers are now in production. This completes the line up to and including 200-ampere switches in either standard sheet metal boxes or cast aluminum enclosures, with cast iron enclosures optional, if specified. The new 100- and 200-ampere numbers include all the features of the 30- and 60-ampere switches of this line, with some added points necessitated by the higher capacities. They are quick-make, quick-break, with interlocked covers and elevated removable bases for easier wiring. The enclosures are considerably smaller than those of the conventional type of knife switch due to the compact design of the interiors. Among other features are double-break contacts with steel spring reinforcements assuring constant pressure on the contacts for reduced heating and Square D positive pressure contacts.

Trade Literature

Insulators.—Bulletin 28 pp. Describes a comprehensive line of switch and bus type insulators. Complete specifications are included. Locke Insulator Corp., Baltimore, Md.

Transformers.—Bulletin 300, 4 pp. Describes a line of distribution transformers in which it is announced many valuable improvements have been introduced. Pennsylvania Transformer Co., 1701 Island Ave., Pittsburgh, Pa.

Electrically Operated Valves.—Bulletin 1, 2 pp. Describes the Hoppe electro-hydraulic valve designed for pressures up to 250 lb. The line pressure opens and closes this valve. Bulletin 2, 2 pp. Describes an electro-magnetic valve for remote control of oil, gas, air, and water lines. A. F. Hoppe Engineering Co., 246 S. Meridian St., Indianapolis, Ind.

Aluminum Paint.—Booklet, 64 pp. Describes the uses and applications of aluminum paint in a wide range of industries, including the electrical; profusely illustrated. Specifications as to the composition and the use of the paint on various surfaces are included. Aluminum Company of America, Gulf Bldg., Pittsburgh, Pa.

Broadcasting Equipment.—Bulletin 15A, 20 pp. Describes Western Electric speech input equipment, a self-contained unit for use with a radio transmitter situated at a distance from the studios. Bulletin 701A, 28 pp. Describes studio speech input equipment and control panel. Bulletin, 10 pp. Describes type 618A dynamic microphone and 80A amplifier. Graybar Electric Co., 420 Lexington Ave., New York.

Thyrite Lightning Arresters.—Bulletin GEA-1304C, 12 pp. Describes Thyrite form D lightning arresters, station-type, in which many new refinements have been developed. Potential stresses resulting from lightning are reduced to an extremely wide margin below the dielectric strength of the apparatus, a feature of great importance in extending the service life of apparatus. General Electric Co., Schenectady, N. Y.

Illumination.—Bulletin, 24 pp. Recommended Standards of Illumination. Comprises a new set of recommended foot-candle standards for illumination design, divided into distinct classifications depending upon the visual tasks to be considered, and offering recommended values for each and every duty common to stores, offices, factories, schools, and outdoors. General Electric Co., Inc., Nela Park, Cleveland, O.

Control and Distribution Apparatus.—Catalog 34, 64 pp. Describes the Bull Dog line of controlling and distributing apparatus for electric light and power, including safety and meter service switches, SAFtoFUSE range switches, Fusenters, lighting and metering panels, SAFtoFUSE convertible distribution panels and switchboards, circuit breaker apparatus, Trol-e-duct and electro BUStribution systems. Bull Dog Electric Products Co., Detroit, Mich.

Geared Reduction Motors.—Bulletin. Describes the "Syncrogear" motor, offering variations in speed from 2 rpm up to 10,000 rpm. The new machine is a self-contained motor with a single base, embodying a geared transmission foundationed on a heavy gear pedestal base, which supports the unusual torque strains in high torque geared reductions. The complete assembly occupies practically no more space than an ordinary electric motor. U. S. Electrical Manufacturing Co., 1510 So. Western Ave., Chicago, Ill.

Magnetic Contactors.—Bulletin 1901, 4 pp. Describes d-c magnetic contactors, 1- and 2-pole, designed for continuous duty operation, 2- or 3-wire control. They can be used as control contactors for direct current motors, for disconnect purposes in conjunction with suitable auxiliary switches, battery charging circuits and for special control panels. Bulletin 4401, 4 pp. Describes a-c magnetic contactors, 2-, 3-, and 4-pole, designed for continuous duty operation, 2- or 3-wire control. They are applicable for starting motors directly across the line, for disconnect purposes in conjunction with suitable auxiliary switches, and for special control panels. Ward Leonard Electric Co., Mt. Vernon, N. Y.

Published Monthly by

American Institute of Electrical Engineers

(Founded May 13, 1884)

Electrical Engineering

Registered U. S. Patent Office

November 1934
Volume 53
No. 11

The Official Monthly Journal and Transactions of the A.I.E.E.

J. Allen Johnson, President
H. H. Henline, National Secretary

Publication Committee

C. O. Bickelhaupt, Chairman
J. W. Barker — L. F. Hickernell
R. N. Conwell — E. B. Meyer
L. A. Doggett — L. W. W. Morrow
W. S. Gorsuch — I. M. Stein
H. H. Henline — H. R. Woodrow

Publication Staff

G. Ross Henninger, Editor
C. A. Good, Advertising Manager

PUBLICATION OFFICE, 20th and Northampton Streets, Easton, Pa.

EDITORIAL AND ADVERTISING OFFICES, 33 West 39th Street, New York, N. Y.

ENTERED as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918.

SUBSCRIPTION RATES—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii and the Philippine Islands, Central America, South America, Haiti, Spain and Spanish Colonies; $13 to Canada; $14 to all other countries. Single copy $1.50.

CHANGE OF ADDRESS—requests must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered due to incorrect address cannot be replaced without charge. Be sure to specify both old and new addresses and any change in business affiliation.

ADVERTISING COPY—changes must be received by the fifteenth of the month to be effective for the issue of the month succeeding.

STATEMENTS and opinions given in articles appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters.

REPUBLICATION from "Electrical Engineering" of any Institute article or paper (unless otherwise specifically stated) is hereby authorized provided full credit be given.

COPYRIGHT 1934 by the American Institute of Electrical Engineers.

ELECTRICAL ENGINEERING is indexed in Industrial Arts Index and Engineering Index.

Printed in the United States of America. Number of copies this issue—

18,500

This Month—

Front Cover

Looking up through the interior of the new 3,000-kv impulse generator with helical mounting at the Ohio Brass Company's high voltage testing laboratory, Barberton, Ohio. (See description in ELEC. ENGG., v. 53, 1934, p. 1255–9.)

Educational Series—No. 11

Fundamental Electrical Properties of Mercury Vapor and Monatomic Gases 1435
By ALBERT W. HULL

Special Articles

Vapor Conducting Light Sources . . . 1447
By R. D. MAILEY

Diesel Electric Rail Cars and Locomotives 1461
By N. W. STORER

A.I.E.E. Papers

Lightning Performance of 220-Kv Lines 1443
AN A.I.E.E. COMMITTEE REPORT

Limits to Amplification 1449
By J. R. JOHNSON and F. B. LLEWELLYN

High Velocity Streams in the Vacuum Arc 1454
By E. C. EASTON, F. B. LUCAS, and F. CREEDY

Power Losses in Induction Machines . 1466
By PAUL M. NARBUTOVSKIH

A New Method of Ground Fault Protection 1472
By F. M. STARR

Vibration Analysis—Transmission Line Conductors 1478
By W. B. BUCHANAN

Theory of Multielectrode Tubes . . . 1485
By H. A. PIDGEON

Dielectric Properties of Cellulose Paper—II 1498
By J. B. WHITEHEAD and E. W. GREENFIELD

Vacuum Tubes as High Frequency Oscillators 1504
By M. J. KELLY and A. L. SAMUEL

The "Thyratron" Motor 1517
By E. F. W. ALEXANDERSON and A. H. MITTAG

News of Institute and Related Activities 1542

The Institute Budget for 1934–35 1542

1935 Winter Convention. . . . 1543

What Place the Engineer in the Changing Economic Scene? . 1546

Engineering Foundation Pays Tribute to Founder Swasey 1552

Letters to the Editor 1553

Membership 1558

Engineering Literature. 1559

Industrial Notes 1560

Employment Notes (See Advertising Section)

Officers and Committees (For complete listing see p. 1339–6, September 1934 issue of ELECTRICAL ENGINEERING)

——Turn to Next Page

Discussions of A.I.E.E. Papers

Automatic Stations

A Compensated Automatic Synchronizer—Seeley 1528

Load Totalizing in the New York Metropolitan Area—Zogbaum 1529

Electronic Regulator for A-C Generators—Gulliksen 1530

Electrical Machinery

Insulator Resistance of Armature Windings—Wieseman . . . 1524

Insulators

Flashover Voltages of Insulators and Gaps—An A.I.E.E. Committee Report . . . . . 1531, -37

Selection and Performance of Suspension Insulators—Sporn, Peterson, & Mulford . . . . . 1531, -38

High Voltage Insulators—Smith & Lusignan . . . . . 1531, -36

The Suspension Insulator—Hawley . . . . . 1531, -36

Radio Influence Insulator Characteristics—Gilchrest . . . 1531, -39

Recent Developments in Suspension Insulators—Barrow . 1531, -39

A New Porcelain Post Insulator—Lapp . . . . . 1531, -40

Power Generation

Voltage Regulation and Load Control—Forbes & Searing . . 1525

1935 TRANSACTIONS

TO secure the A.I.E.E. TRANSACTIONS for 1935, your advance subscription must be on file at A.I.E.E. headquarters not later than Friday, December 21, 1934; that is, unless you entered last year your advance subscription for the 1934 volume and "for future editions until countermanded."

NOW a more comprehensive reference volume than ever before, the annual TRANSACTIONS contains the entire contents of the 12 issues of ELECTRICAL ENGINEERING for the current year, excepting only the advertising pages. In fact, the sheets for TRANSACTIONS are printed month by month while the forms for ELECTRICAL ENGINEERING are on the press. This economical means of production enables the continuance of the members' price of $4 per year for the cloth bound volume (paper bound volumes no longer are issued). However, inasmuch as the edition must be determined before the January issue goes to press, it is essential that subscriptions be entered in advance—and it is advisable to enter them "for future editions until countermanded"—although payment will not be required until the volume is ready for distribution.

IF you desire to maintain a permanent file of A.I.E.E. papers and discussions in this permanent form, you are requested to forward your subscription at once; otherwise, there can be no assurance that volumes will be available. For your convenience, an order blank is provided on p. 18 of the advertising section of this issue.

Act Now!

Fundamental Electrical Properties of Mercury Vapor and Monatomic Gases

By ALBERT W. HULL, Member Am. Phys. Soc.
General Electric Co., Schenectady, N. Y.

GASES in their normal states are electrically neutral. A discussion of the electrical properties of gases therefore must deal with abnormal states. The 2 abnormal states of atoms are *excitation* and *ionization*.

When an electron collides with an atom, one of 4 things may happen: nothing at all, deflection, excitation, or ionization. In the inert gases, nothing at all happens at low electron energy, less than about one volt. (Electron energies are measured in "equivalent volts" or "electron volts"—energy = eV = charge of electron × accelerating voltage—and generally are given, for brevity, in volts.) The electron passes through the solar system of the atom with no loss of energy and only slight probability of deflection. This transparency to slow electrons is a unique property of the inert gases.[1] It usually is expressed in terms of the small "cross section" that the atom presents to a colliding electron, as shown in Fig. 1. The cross sections to be expected from the kinetic theory of gases are shown at the right.

With increasing electron velocity, the "effective cross section" of the atoms becomes larger, several times as large as the kinetic theory value; this means that collisions are very frequent. However, these are deflecting collisions only, involving no loss of energy,* provided the electron velocity is less than a critical value. This is intelligible on the basis, now well established, that atoms can exist only in discrete states. The atom cannot take energy from an electron unless it can do something with the energy, *viz.*, store it in some form; and an atom cannot store energy unless there is enough to raise it to its next higher state, namely, to one of the excited states, or the ionization state. For the inert gases the lowest of these states requires more than 10 volts energy (see Table I).

The picture changes entirely when the electron energy reaches a value equal to the first excitation potential.[2] Collision then results in a transfer of energy from the electron to the atom, which now becomes abnormal or excited. The excited atom usually radiates its energy, as light, within a period 10^{-8} sec. This light, however, is highly absorbable by other atoms of the same kind, exciting them in turn, and so is passed on from atom to atom until it reaches the confines of the gas envelope and is radiated into space or absorbed. A state of excitation thus persists in the gas for an appreciable time; and this time is increased further by a mechanism known as a "metastable" condition, which results when an excited atom loses a small amount of its energy by a collision of some kind and becomes thereby incapable of radiating light. Such atoms remain in the excited state until they lose their energy by collisions with other atoms or the walls of the container, or until they receive additional energy from an electron, by another collision, sufficient to ionize them. This latter process is important for arcs. The probability of a second electron collision is proportional to the number of excited atoms and the number of exciting electrons, hence to the square of the current. Most of the ionization in low pressure arcs is of this multistage or cumulative type.

If the energy of the impinging electron is still higher, it reaches in turn the other excitation potentials of the atom, of which there are several, and finally the ionizing potential. At this potential the energy is sufficient to cause the ejection of an electron from the atom, yielding a positively charged ion and 2 slow electrons, *viz.*, the original electron, which has lost its energy in the collision, and the one taken from the ion.

The probability that a collision will result in excitation is known only approximately. From the value zero, for electron energies less than the excitation potential, it jumps to a maximum when the energy is just equal to the excitation potential, decreasing rapidly as it exceeds this value. The best measurements available[3] give a maximum probability between 0.001 and 0.003 per collision at a voltage only slightly higher than the excitation potential, falling to $^1/_4$ the maximum at 0.50 volt above the critical value.

The probability that a collision will result in ionization is known quite accurately.[4] It is zero for

Electrical properties of mercury vapor and monatomic gases are discussed from a theoretical standpoint in this article. In the first part of the article, the author discusses briefly the elementary processes of excitation and ionization of atoms upon which the electrical properties of gases depend. With this insight into the fundamental processes as a background, the author discusses in Part II the electrical conductivity of gases under various conditions. This is the eleventh in a series of special articles prepared under sponsorship of the A.I.E.E. committee on education.

1. For all numbered references see list at end of article.

* There is, of course, the slight loss to be expected on the basis of classical mechanics, *viz.*, a fraction $2m/M$ per collision on the average. This amounts to approximately 3 parts in 10,000 and 5 parts in 1,000,000 per collision with helium and mercury atoms, respectively.

energies less than the ionizing potential, but, unlike excitation, it is very small *at* the ionizing potential and increases gradually and uniformly with further increase of energy. It is very nearly proportional to the excess of energy above the ionizing potential for energies up to twice the ionizing potential, reaches a maximum at about 10 times the ionizing potential, and is inversely proportional to voltage at high voltages. These probabilities are given in Table I, together with the ionization potentials and the excitation potentials. They are shown graphically in Fig. 2 for voltages up to 1,000.

Besides excitation and ionization, 4 other elementary processes are important to the electrical

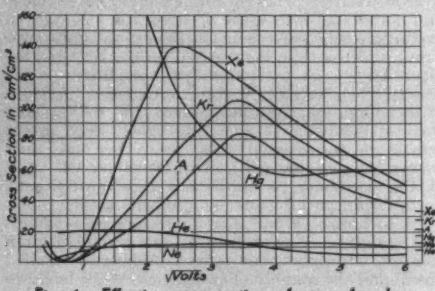


Fig. 1. Effective cross section of gases for slow electrons

Ordinates represent the total cross section of the atoms in 1 cu cm of gas at 1 mm (of mercury) pressure and 0 deg C. This is equal to the number of collisions an electron will make in traveling 1 cm through the gas. (From data by Ramsauer and Kollath)

behavior of atoms. The first is the exchange of charge (Umladung) which occurs when an ion collides with an atom.[5] The ion takes an electron from the atom and goes on its way as a fast moving atom, leaving a slow ion behind. It is to be noted that no free electrons are produced in this process. This exchange appears to be a very important process, occurring, for argon ions in argon, more than 4 times as frequently as the total number of calculated collisions; this means that the ion is able to grab an electron from an atom when it passes within a distance twice as great as would constitute a collision between atoms according to classical theory.

The next (fourth) process is electron emission caused by the impact of ions or excited atoms on

Table II—Ionization Potentials of Gases for Positive Ion Impact (From Beeck and Mouzon)

Gas	Ionization Potential in Volts				
	Li^+	Na^+	K^+	Rb^+	Cs^+
Ne	307	175	320	420	437
A	100	105	95	180	365
Kr	420	400	80	100	143
Xe	250	360	120	145	105

metals.[6] This process is responsible for the maintenance of electron emission at the cathode in the glow discharge. The probability of impact emission is greater the higher the energy, both kinetic and potential, of the impinging article, thus increasing with velocity of the ions and with the ionization and excitation potentials. The values of this probability, as far as they are known,[6] are given in Fig. 3.

Ionization of atoms by positive ion impact[7] is a much less probable process than those that have been discussed, yet it is believed to be important, especially at high voltages. This process also is found to set in at definite "ionization potentials" (Table II), though the theoretical interpretation of these potentials is not yet clear. The probability that an impact will result in ionization is the greater, and the ionization potential the lower, the nearer alike the ion and atom. These probabilities, as far as they are known, are shown in Fig. 4. It should be noted that they are only a few per cent of the corresponding probabilities for electron impacts. They increase with voltage, without reaching a maximum. That a maximum probably exists, at much higher voltages, is indicated by the fact that ionization by doubly charged helium atoms or "alpha particles" is inversely proportional to speed.

A fifth process, the ionization of atoms by fast moving atoms, has been discovered[8] recently and

Table I—Values of Ionizing Potential, $\overline{V}_i$, First Critical Potential $\overline{V}_c$, Mean Free Path of Electron λ, and Probability of Ionization $P(\overline{V})$.† (Data From P. T. Smith)

Gas	$\overline{V}_i$	$\overline{V}_c$	λ (cm) (at p = 1 mm & 0°C)	$P_{(10)}$	$P_{(20)}$	$P_{(50)}$	$P_{(100)}$	$P_{(500)}$	$P_{(1,000)}$	$P_{(5,000)}$	$P_{(10,000)}$
He	24.48	19.73	0.1203	0.00	0.25	0.86	1.25	0.97	0.49	0.183	0.056
Ne	21.47	16.60	0.0753	0.00	0.48	1.47	2.66	2.71	1.29	0.57	
A	15.69	11.57	0.0431	3.07	8.4	11.7	12.9	8.6	3.66	1.53	
Hg	10.39	4.66	0.0142*	8.1*	13.7*	17.9*	19.3*	14.6*	7.30*	3.35*	1.03*
Kr	13.3	9.9									
Xe	11.5	8.3									

† $P(\overline{V})$ = probability that an electron with $\overline{V}$ volts energy will ionize an atom in moving 1 cm through the gas at 1 mm pressure and 0 deg C.

*Since the pressure of mercury vapor at 0 deg C is only 0.000185 mm (of mercury), these values are to be interpreted as the values per millimeter pressure, and used only at low pressures. For higher pressures correction must be made for the actual temperature T of the vapor, by multiplying by $\sqrt{T/273}$ the values of λ given in the table, and dividing the values of P by the same factor

appears to be of great importance. It is believed to be much more probable, per collision, than ionization by ions, with which it intimately is connected through the exchange process discussed previously. Numerical values of this probability have not yet been obtained, since it is a matter of some difficulty to measure the number of neutral atoms in the beam; but it is known to be a maximum when the 2 atoms are of the same kind. This process is probably effective in thermal ionization, such as exists in high pressure arcs. In view of the high probability of the exchange process, high speed atoms must be as numerous as ions in all gaseous discharges; their ionizing power is therefore of great importance.

A sixth process, ionization of an atom by contact with an excited atom, is a probable and important

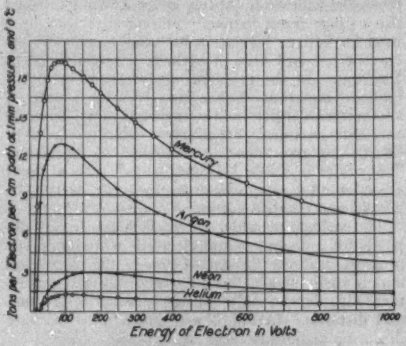


Fig. 2. Probability of ionization by electrons

Ordinates are the probabilities that an electron moving with energy V will produce 1 ion in moving 1 cm through a gas of the given kind at 1 mm (of mercury) pressure and 0 deg C. (See note, Table I, for mercury.) The probabilities for other pressures and temperatures are proportional to the number of collisions (for low pressures), and hence are directly proportional to pressure and inversely as the square root of temperature. (From data by P. T. Smith)

event in mixed gases. The excitation energy obviously must be sufficient for the purpose, which means that the excitation potential of the excited atom must exceed the ionization potential of the atom to be ionized. The probability of the process appears to be maximum when the excess of energy is small. This process is important in preventing loss of cathode material in certain low pressure arcs (see following discussion).

Part II—Electrical Conductivity of Gases

"Natural" Conductivity

An un-ionized gas between non-electron-emitting electrodes is a perfect nonconductor. This condition never can be quite realized, because cosmic rays and radioactivity of the earth cause a slight ionization of the air and a slight electron emission from the electrodes, which cannot be avoided. The "natural" ionization in air from these causes averages about 2 ions per cubic centimeter per second at atmospheric pressure at sea level, and nearly 100 times as many at the highest altitude at which cosmic ray measurements have been made. The saturation current between electrodes one centimeter square and one centimeter apart in air, due to this cause, is 3×10^{-19} amp and 3×10^{-17} amp, respectively. For argon at the same pressure these currents are approximately 40 times greater. Hence argon is adapted for use in measuring the intensity of X rays and cosmic rays. The "ionization chamber" carried by Commander Settle and Major Fordney on their November 1933, stratosphere flight contained argon at a pressure of 2.4 atmospheres.

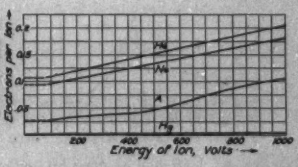
Conductivity With Electron Emitting Cathode; "Transmissivity" of Electrons by Monatomic Gases

Conductivity is of a higher order, even without ionization, when the cathode emits electrons. The atoms of the inert gases present such a small "effective cross section" to slow electrons (see Fig. 1) that they offer little resistance; and the deflecting collisions, which become more numerous with increasing velocity, merely change the direction but not the speed of the electrons. Thus a photoelectric cell containing argon will readily conduct currents ranging from a microampere to a milliampere, when suitably illuminated, at voltages too low to ionize the gas. The current in this case is limited either by electron space charge or photoelectric emission, whichever gives the smaller value.

Townsend Discharge; Amplification of Current by Gas Ionization

A third kind of conductivity, of a higher magnitude still, is obtained when the voltage is high enough so that ionization can take place.[10] This has 2 effects. In the first place, the number of electrons

Fig. 3. Electron emission resulting from impact of postive ions on nickel. (From data by Penning)



is doubled at each ionizing impact. If n_o is the number of electrons leaving the cathode, *e. g.*, photoelectrons in a photo-electric cell, and if the electric field and pressure are such that the probability of ionization per centimeter path is α (see Table I), then the number of new electrons produced in a distance dx will be $dn = n\alpha dx$, and the number reaching an anode d centimeters distant will be $n_o e^{\alpha d}$. The current thus will be amplified $e^{\alpha d}$ times. At low

gas pressures, of the order of 0.001 mm of mercury, the values of α can be found from Table I and Fig. 2, taking for $\overline{V}$ the voltage per mean free path (voltage gradient times mean free path) and multiplying by the pressure in millimeters of mercury. At high pressures, *e. g.*, 10 mm or more, and moderate voltages, the number of collisions is so large that an electron has ample opportunity to ionize before its energy rises more than a few per cent above the ionizing potential. Hence α is the number of ionizing potentials per centimeter (voltage gradient divided by ionizing potential). A value slightly higher than the ionizing potential obviously must be used in this calculation, in order to allow for a few impacts after reaching the ionizing potential, and for some loss of energy in excitation.

The second effect of ionization is that the positive ions neutralize part of the space charge of the electrons and allow the amplified currents to flow with lower voltage. This leads to distortion of the electric field, and, when carried beyond a certain point, to instability and a self-sustaining discharge.

This type of "amplification by ionization" is in general use in photo-electric tubes where maximum sensitivity is desired. Stable amplifications of 100-fold easily are obtained with small current densities. For large current densities, it is generally difficult to obtain more than 10-fold stable amplification.

Glow Discharge; Sparks

A fourth stage is reached when the gas amplification exceeds the probability that an ion striking the cathode will produce an electron by its impact. The discharge then is self-maintained. A single electron produced near the cathode by cosmic radiation or other means will be amplified $e^{\alpha d}$ times before reaching the anode, and these $e^{\alpha d}$ ions, when

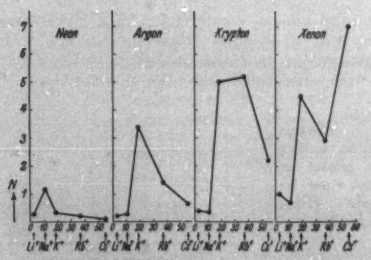


Fig. 4. Ionization of atoms by positive ion impact (Beeck and Mouzon)

they reach the cathode, will produce more than one electron; hence, the current gradually will build up to a value limited only by space charge or circuit resistance. This discharge is known as a "glow discharge." The normal glow discharge has the unique characteristic that its current density at the cathode is fixed for a given gas pressure. As the current

"Science Series" May Be Reprinted

If there is sufficient demand, all articles in the "science series for engineers," of which this article is one, will be reprinted in a substantially bound booklet of some 80 pages. For further details, see items on p. 1545 and in the advertising section, respectively, of this issue.

increases, the discharge utilizes more and more of the cathode surface, the voltage remaining constant; only when the cathode is entirely covered with glow does the voltage begin to rise. This property has been used for voltage regulation for small currents. The current per unit area of cathode is proportional to the square of the pressure, and depends upon the cathode material. Table III gives the values of the current density for the inert gases and mercury at 1-mm pressure. From these values the current density at any other pressure can be calculated. The values in Table III may be used without great error for most other electrode materials, except the alkalis and alkaline earths.

The voltage at which glow discharge begins depends for a given gas and electrode material on the pressure and the distance between the electrodes, and is easily shown, both theoretically and experimentally, depend only on the product of pressure and distance. In Fig. 5 are shown these sparking

Table III—Normal Current Density in Glow Discharge at Pressure of 1 Mm at 18 Deg C (Guntherschulze)

Gas	Cathode Material	Current Density, Ma per Sq Cm
Hg	Iron	0.010
A	Platinum	0.140
Ne	Platinum	0.018
He	Platinum	0.011

potentials for the gases under consideration, as a function of this product.[11]

The potentials at which glow discharge starts have been referred to as "sparking potentials." The glow discharge and the spark differ only in the final stage, namely, in whether the discharge remains limited by the combination of positive-ion space charge and the number of electrons produced by impact of these ions on the cathode, or becomes arc-like. Arcs will be discussed later. Both glow discharges and arcs are observed at all pressures from 1 mm of mercury to atmospheric. As far as the starting phenomena are concerned, they may be considered identical.

The most important characteristic of the starting of a spark or glow discharge, next to the sparking potential, is the time lag—the time that elapses

after the voltage is applied before the current reaches its full value. There are 2 kinds of time lag in all sparks. The first is the delay in waiting for the first electron. In pure gases, free from dust, this may be a considerable fraction of a second, or even many seconds if the distance be small or the pressure low. Since it is a question of waiting for the first cosmic ray or radioactive product to enter the space between

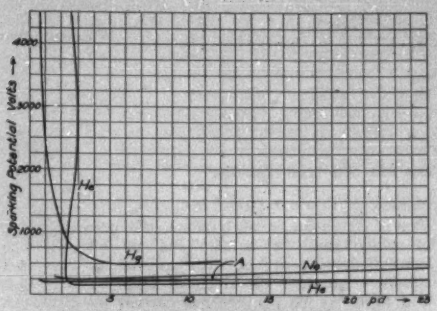


Fig. 5. Sparking potentials in gases, with iron or nickel electrodes, as function of the product, pd, of pressure and distance

Pressure, p, is in millimeters of mercury; distance, d, in centimeters. (From data by Penning for helium and neon, Ayres for argon, Smede for mercury)

the electrodes, the delay should be a matter of pure probability, and this has been demonstrated amply by experiment. It can be eliminated by illuminating the cathode with ultra-violet light. A photoelectric emission of only 0.001 μamp (10^{-9} amp) means 6 billion (6×10^9) electrons per second, and thus the average time lag between electrons is only $^1/_{6,000}$ μsec. In the case of a hot thermionic cathode, this kind of time lag is absent.

The second kind of time lag is the time required for the multiplication process. At low gas pressures this "building-up" time is from 1 to 100 μsec. It requires some motion on the part of ions, and hence is longer the heavier the atoms and the greater the distance from anode to cathode. The values for cold cathodes are longer than for hot cathodes, but generally are obscured by the much longer lag of the first kind, which has a mean value of the order of 10^{-3} sec at 1-mm pressure.

At high pressures the multiplication is effected by distortion of the electric field by the ions that are formed by electron impact without any motion on the part of the ions. It therefore can be very rapid, since the time required for electrons to cross the space is between 10^{-7} and 10^{-8} sec for practical spark lengths. The mechanism is as follows: Assume an electron to leave the cathode in a field slightly above the sparking potential. It will be multiplied along its path, producing more and more ions as the anode is approached. When all the electrons thus produced have reached the anode, there will be left in the space near the anode enough ions to increase appreciably the electric field in the rest of the space. The ions may be considered as stationary because of their sluggishness, and as building out the positive anode in the direction of the cathode. The second electron leaving the cathode therefore will travel in a stronger field, and will produce more ions than the first, thus making a still stronger field for the third, etc. Each stage in this process requires less than $^1/_{10}$ μsec. The multiplication per stage is greater the greater the spark length; hence, at high pressures, this type of time lag decreases with increasing distance between electrodes, which is opposite to the behavior at low pressures. Theory and experiment show that, for sparks of the order of 1 cm or more, at atmospheric pressure, the time required for this building up process is $^1/_{10}$ μsec or less. A typical oscillogram of a spark in air at atmospheric pressure is shown in Fig. 6.[12] It goes without saying that the "probability" lag, of the first type, was avoided when taking this oscillogram by irradiating the gap with ultra-violet light. Data for high pressure arcs in the inert gases are not available.

High Pressure Arcs

The fifth and last conducting stage, the arc stage, is reached when the cathode becomes capable of abundant electron emission, either thermionic or field emission. This makes possible the essential manifestation of the arc condition which is a low voltage drop, decreasing or remaining essentially constant with increasing current.

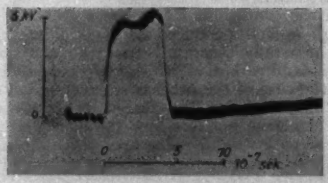


Fig. 6. Oscillogram of breakdown of sphere gap in air

The time lag is 1/10 μsec (Rogowski)

Arcs at atmospheric or higher pressure are distinguished from low pressure arcs by one important characteristic, namely, *the ionization in the arc path is maintained by the high temperature of the gas.* Several different methods of measurement agree in indicating that this temperature is about 5,000 deg K for arcs in air. Calculation, based upon the Saha equation for thermal ionization, shows that this temperature is sufficient to maintain the required degree of ionization. The calculated temperature for pure nitrogen is slightly higher, namely 5,400 deg, while the temperature for pure copper vapor at atmospheric pressure would be much lower, namely, 3,500 deg K. Approximately $^1/_2$ per cent of copper vapor mixed with the gas would account for all the

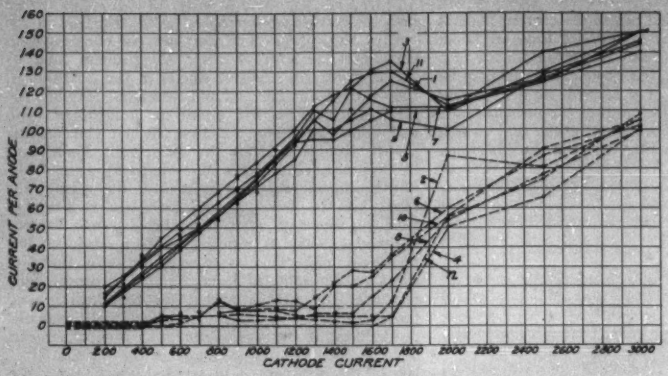


Fig. 7. Division of current between parallel connected anodes in a mercury arc rectifier, showing stability resulting from "positive resistance"

The rectifier was operated 6-phase, with one odd numbered anode and one even connected in parallel, forming 6 pairs

observed temperatures of arcs in air. It appears probable that a small amount of metal vapor always is present in the arc stream. Small variations in this amount would account for the variations in arc drop that have been observed.

Temperatures of arcs in monatomic gases have not been measured. Theoretical temperatures required to maintain thermal ionization of the arc stream are approximately 3,700, 5,500, 7,000, and 8,000 deg K, for mercury, argon, neon, and helium, respectively. A small amount of metal vapor, if present, would reduce the temperatures of neon and helium arcs to nearly the same values as those of argon and air.

Electron emission from the cathode in high pressure arcs is produced by 1 of 2 mechanisms: (1) It generally is agreed that the emission from tungsten and carbon electrodes is purely thermionic; (2) in the case of the other metals, emission appears to be "field emission," produced by the strong electric field of the positive ions close to the cathode, the same as in the mercury arc. (See discussion of mercury cathode under heading "Low Pressure Arcs.")

The negative resistance of high pressure arcs is accounted for at once by the fact that the ionization in the arc path is maintained by temperature, for this thermal ionization is an equilibrium condition, in which as many ions are formed per second as disappear by recombination, and no energy loss is involved in recombination. The only loss of energy therefore is the radiation and conduction of heat from the arc stream. This is proportional, per unit length, to the circumference of the arc stream, and hence increases as the first power of the diameter, whereas the conductivity increases as the cross section, that is, the square of the diameter.

Low Pressure Arcs

In discussing low pressure arcs, it will be convenient to discuss separately the phenomena at the cathode, in the arc stream, and at the anode.

The cathode of the mercury arc has been the subject of extensive investigations, the present status of which may be summarized as follows: The current density at the cathode is 4,000 amp per square centimeter of which at least 80 per cent, and probably 95 per cent, is carried by electrons. The remaining 5 to 20 per cent carried by positive ions forms a positive-ion space charge in front of the cathode, sufficient to give an electric field of approximately 500,000 volts per centimeter at the cathode. This is precisely the field strength required to produce a spark between clean cold electrodes of ordinary roughness in high vacuum. It is believed therefore that this field is responsible for extracting the electrons from the surface of the mercury. It is true that the quantum-mechanical theory requires voltage gradients of more than 20 times this value in order to produce field currents from smooth electrodes; but there is no reason for expecting the surface of the mercury to be smooth under these intense fields. The temperature at the cathode is

Table IV—Life Tests of Barium Coated Nickel Cathodes in Neon (From Measurements by Dr. L. R. Koller)

Neon Pressure, Mm	Hours Life at 1 amp	2 amp	3 amp	5 amp
0.100	2¾		1¼	
0.400	296	48	119	29
0.600	387	243	162	
1.500				1,069
2.000				1,626
3.500				2,370+

between 120 and 200 deg C—hence too low for any thermionic emission; and the impact of mercury ions of this velocity has been shown to produce no appreciable electron emission. However, the impact of the ions does produce rapid evaporation of mercury, blowing the ions away so that the "cathode spot" is compelled to move continuously and rapidly. Measurements on power rectifiers indicate that the

current is furnished by many small cathode spots, each contributing approximately 35 amp.

In thermionic cathodes, the most important phenomenon is positive ion bombardment of the cathode. This may produce 2 effects: disintegration and heat. If the ions strike the cathode with an energy of more than 25 volts, they disintegrate it, that is, knock off atoms of the cathode material; if their energy is less than about 25 volts, they have no effect other than to raise the temperature of the cathode. With ample thermionic electron emission and sufficient vapor pressure to furnish the needed ions (see subsequent discussion), the voltage drop adjusts itself automatically so that it is safely below the disintegration value. The heating effect is also negligible at low pressures, namely, between 1 and 100 microns. At higher pressures, from 1 mm to 5 cm (of mercury), concentration of the arc is sufficient so that its heating effect on the cathode must be allowed for.

The range of pressures from 1 mm to 5 cm exhibits another interesting characteristic, namely, an inhibition of evaporation of cathode material and of thermionic coating material, such as barium and thorium. A part of this inhibition is mechanical interference with evaporation by the atoms of the gas, the same mechanism that limits evaporation from filaments in gas filled lamps. It is believed, however, that the most important factor in the prevention of evaporation is ionization of the escaping atoms by contact with ions and excited

Fig. 8. Oscillogram showing current I and voltage E through a $^1/_4$-in. hole in mercury vapor at 17 deg C

The current remains constant while the voltage increases from 20 volts to 160. The 20-amp trace is for calibration

atoms of the gas. The excited atoms are in general more numerous than the ions, so that when their energy is sufficient, namely, more than the ionizing potential of the escaping material, ionization by excited atoms is the more likely process. Thus barium atoms escaping from a barium coated nickel cathode have a high probability of being ionized and being driven back to the cathode before they can escape, while nickel atoms, the ionizing potential of which is higher than the energy (4.66 volts) of metastable mercury, will not be ionized and will escape. Hence a cathode that is operated at so high a temperature that its life in vacuum or in a gas at very low pressure would be only a few hours, may live many thousands of hours at pressures of from 1 to 50 mm. Table IV shows a few values of the life of barium coated cathodes operated at different vapor pressures in neon.

The arc stream of a low pressure arc differs from that of high pressure arcs in that the temperature of the atoms is low, so that ionization must be maintained by electron impacts. However, recombination of ions and electrons occurs so seldom at low pressures that its effect is negligible, and the principal loss of energy from the arc stream is diffusion of electrons and ions to the walls of the container. This diffusion, like that of heat, is proportional to the circumference. Hence the energy required to maintain the ionization, and therefore the voltage gradient along the discharge, is inversely proportional to the diameter of the tube.

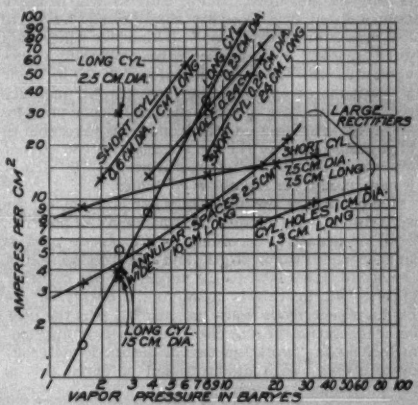


Fig. 9. Observed maximum current density in mercury vapor arcs as function of pressure

The limit is set by the approach to 100 per cent ionization of the vapor

Since low pressure arcs in general must be confined, they cannot expand with increase in current; hence the arc resistance is positive except for an initial stage. This initial stage represents the transition from single impact ionization to cumulative ionization, the latter process being the more efficient (hence the negative resistance) because it utilizes some of the energy of the excited atoms for ionization instead of allowing all of this energy to be radiated. It takes place in the range of current from $^1/_{10}$ to 1 amp per square centimeter. At higher currents, the resistance is positive. Such arcs are therefore stable and may be operated in parallel. In Fig. 7 is shown the current in 6 pairs of anodes of a mercury arc rectifier, connected 2 by 2 in parallel. It may be noted that 1 anode of each pair carried all the current during the initial stage, until the negative resistance period was passed, but thereafter the 2 shared the current nearly equally.

A question of special interest is the maximum current carrying capacity of low voltage arcs. Theory indicates that when all the atoms in the arc stream are ionized no further increase in conductivity

can be obtained except by increasing the velocity of the electrons, that is, by raising the voltage. Experimentally it is found that when the ionization reaches approximately 50 per cent of the total number of atoms, the voltage rises almost abruptly. In Fig. 8 is shown an oscillogram of the current through a $^1/_4$-in. hole in a carbon disk in mercury vapor at a pressure of 1 micron. It may be noted that the voltage rises abruptly to the limit of the 60-cycle a-c wave (160 volts crest) after the current reaches 10 amp, and that the current increases only slightly with this increased voltage. Table V gives the maximum observed currents in this test at a series of different pressures. In Fig. 9 are shown the maximum current densities that have been observed in low pressure mercury arcs of all kinds for which data are available. It may be observed that these values agree well with the experimental ones given in Table V, with the exception of the large current mercury rectifiers; in these the high mercury vapor pressure and large cross section offer conditions favorable to high temperature of the arc stream with consequent low vapor density. A temperature of 2,000 deg K would account for the observed values.

Phenomena at the anode of a low pressure arc are very simple. An anode drop, which may be positive, zero, or negative, according as the anode area is smaller, equal to, or larger than the cross section of the arc, delivers heat to the anode but has no other effect. The heating is equal to the energy of the impinging electrons times the current, plus the heat of condensation of the electrons which is approximately 5 volts (work function of the anode material) per ampere. With unidirectional potential this is the only anode phenomenon.

Table V—Maximum Current Capacity of Mercury Vapor, Current Through Hole 0.6 Cm in Diameter and 1 Cm Long

Mercury Vapor Pressure, Mm	Max. Current Density, Amp per Sq Cm
0.0091	30
0.0065	93
0.013	138
0.021	181
0.026	200
0.048	475

With alternating potential, as in a rectifier, there is an additional phenomenon of great importance, namely, the bombardment of the anode, when negative, by positive ions. With multianode rectifiers these ions may be drawn from the arc stream. In single-anode tubes they are the left-over ions that remain in the space at the end of the conducting cycle and their effect is by no means negligible when the anode voltage reverses rapidly. For example, in a typical test with 2,000-cycle sine wave alternating potential and pure resistance load, the disintegrating effect of mercury ions destroyed 0.02 g of anode material per ampere per hour at 3,000 volts (rms), and was roughly proportional to voltage. At 60 cycles with ordinary reactive loads, the corresponding loss to be expected on the basis of these tests is roughly 0.0007 g per ampere per hour, while with 60 cycles and pure resistance load, is only 0.00004 g per ampere per hour at 3,000 volts. In this latter case most of the ions have disappeared before the anode voltage becomes high enough to produce serious disintegration.

The effect of positive ion bombardment of the anode on its ability to withstand reversed voltage, which is a figure of merit of a rectifier, is a subject that is receiving much attention at present. No clear picture of the mechanism of this effect is as yet available.

Most of the phenomena dealt with in this paper are discussed in greater detail in the following treatises:

1. Gasentladungen, R. Seeliger, J. A. Barth, Leipzig, 1927.

2. Conduction of Electricity Through Gases, J. J. and G. P. Thomson, 3rd Ed., v. 1, 1928; v. 2, 1933; Cambridge Univ. Press.

3. Electrical Discharges in Gases, K. T. Compton and I. Langmuir, pt 1, *Rev. of Modern Physics*, v. 2, 1930, No. 2, p. 123–242.

4. Electrical Phenomena in Gases, K. K. Darrow, Williams & Wilkins, 1932.

References

1. Effective Cross Section of Atoms.

Ramsauer & Kollath, *Handbuch der Phys.* (Geiger-Scheel), v. 22, pt. 2, p. 243 (Springer, 1933).

2. Critical Potentials.

(*a*) Compton & Mohler, Nat. Res. Council, *Bull. No. 48*, 1924. (*b*) Franck & Jordan, "Anregung von Quantensprungen durch Stosse," *Handbuch der Phys.* (Geiger-Scheel), v. 22, pt. 2, 1933.

3. Probability of Excitation.

(*a*) Dymond, *Proc. Roy. Soc.*, v. 107, 1925, p. 291. (*b*) Glockler, *Phys. Rev.*, v. 33, 1929, p. 175.

4. Probability of Ionization.

(*a*) Compton & VanVoorhis, *Phys. Rev.*, v. 27, 1926, p. 724. (*b*) Jones, *Phys. Rev.*, v. 29, 1927, p. 882. (*c*) Bleakney, W., *Phys. Rev.*, v. 35, 1930, p. 139. (*d*) Smith, P. T., *Phys. Rev.*, v. 36, 1930, p. 1293. (*e*) Smith, P. T., *Phys. Rev.*, v. 37, 1931, p. 808. (*f*) Liske, J. W., *Phys. Rev.*, v. 46, 1934, p. 169.

5. Exchange of Charge Between Ion and Atom.

(*a*) Kallman, H., & Rosen, B., *Zeits. f. Phys.*, v. 61, 1930, p. 61; (*b*) v. 64, 1930, p. 806.

6. Electron Emission Due to Impact of Positive Ions on Metals.

(*a*) Penning, F. M., *Proc. Roy. Akad. Amsterdam*, v. 33, 1930, p. 841. (*b*) Oliphant, *Proc. Roy. Soc.*, A 124, 1929, p. 228.

7. Ionization of Atoms by Ions.

(*a*) Beeck, D., *Ann. d. Phys.*, v. 6, 1930, p. 1018. (*b*) Beeck, D., & Mouson, J., *Ann. d. Phys.*, v. 11, 1931, p. 739.

8. Ionization by Fast-Moving Atoms.

Beeck, D., *Proc. Nat. Acad. Sci.*, v. 18, 1932, p. 311.

9. Ionization by Contact With Excited Atoms.

(*a*) Penning, F., *Proc. Roy. Akad. Amsterdam*, v. 34, 1931; (*b*) *Zeits. f. Phys.*, v. 46, 1928, p. 335.

10. Amplification of Current by Ionization.

Townsend, J. S., "Electricity in Gases," Clarendon Press, Oxford, 1915.

11. Sparking Potentials.

(*a*) Gill & Pidduck, *Phil. Mag.*, v. 16, 1908, p. 280. (*b*) Ayres, T. L. R., *Phil. Mag.*, v. 45, 1923, p. 363. (*c*) Penning, F., *Proc. Roy. Akad. Amsterdam*, v. 34, 1931, No. 9. (*d*) Smede, L., *Elec. Jl.*, v. 25, 1928, p. 403.

12. Time Lag of Sparks.

(*a*) Rogowski, W., *Archiv. f. Elektrot.*, v. 20, 1928, p. 99. (*b*) Franck & Von Hippel, *Zeits. f. Phys.*, v. 57, 1929, p. 696. (*c*) Loeb, *Jl. Frank. Inst.*, v. 210, 1930, p. 15.

13. Temperature of Arcs.

(*a*) Ramsauer, *Elektrot. u. Maschinenbau*, v. 51, 1933, p. 189. (*b*) Von Engel & Steenbeck, *Naturwissensch.*, v. 19, 1931, p. 212.

14. Theory of the Mercury Arc.

Compton, K. T., *Phys. Rev.*, v. 37, 1931, p. 1077.

15. Thermionic Cathodes in Low Pressure Arcs.

Hull, A. W., A.I.E.E. Trans., v. 47, 1928, p. 753.

16. Positive Resistance of Mercury Arc.

Hull, A. W. & Brown, H. D., A.I.E.E. Trans., v. 50, 1931, p. 744.

Lightning Performance of 220-Kv Lines

Because of the scarcity of published records of lightning performance of 220-kv power transmission lines, the A.I.E.E. lightning and insulator subcommittee* has attempted to collect such data by means of a questionnaire sent to the various companies operating 220-kv lines in the United States and Canada. The data thus obtained is summarized in this paper.

LIGHTNING PERFORMANCE of transmission lines has been intensively studied, investigated by field research and operating records, and predicted by theory during the last decade. The results of much of this work have appeared in technical publications in the past; but in the 220-kv transmission field actual published operating records have been very few except for one system.[1]

In view of the large amount of organized lightning investigation and research work done and published on lines operating in the 132-kv range and below, it was felt that a more complete picture of 220-kv line operation under lightning conditions would be of interest and value at this time. This picture the present paper attempts to give, up to and including 1933, for the 220-kv lines in the United States.

Collection of Data and Lines Considered

The collection of data on which this paper is based was effected by a questionnaire sent to the several operating companies whose prompt response herewith is acknowledged. The questionnaire was framed to obtain information on many of the constructional and operational features of the lines that were considered as having any bearing on the lightning performance of the lines. Detailed characteristics of many of the lines, too voluminous to give here, have been reported before (see bibliography at end of paper). Analysis of the lightning data on these lines has been made in the light of existing and more recent theories of lightning performance of lines.

The 220-kv lines discussed here are situated in territory where the lightning conditions vary from light to severe. More than 60 per cent of the lines (right of way) is situated in California where isoceraunic data indicate 5 lightning storms per year; some 25 per cent is near the middle Atlantic coast, in New Jersey and Pennsylvania, where the storms average about 35 per year; 7 per cent is in New England where some 24 storms per year are recorded; and 7.5 per cent in Canada on a 187-kv line where lightning storms average some 15 per year. This 187-kv line in Canada has been included because it represents a line in the higher voltage class (above 132 kv); operating records for 6 years are available, and also the line embodies some of the extensively discussed features of lightning protection. The 287-kv Boulder Dam line has been included, although not yet in operation, because the general design of this line from the point of view of lightning disturbances is interesting.

The classification of all lines as regards the type of circuit is given in Table I. The types of towers employed on these lines are illustrated in Figs. 1 and 2. These types of towers are referred to the various lines in column 9 of Table II.

Tower Design

Tower design in recent years has been mostly of the type employing flat-top configuration with the 3 line conductors in a horizontal plane. The conductor spacing used with this type of tower varies from 20 ft in mild lightning districts to 28.5 ft in the more severe lightning territory.

For the flat-top single-circuit towers the conductor height at suspension towers ranges from 35 and 44 to 66.5 ft, although a height of 77 ft is used on the 287-kv lines; for the 2-circuit towers the corresponding height of conductor ranges from 85.5 to 112 ft.

Ground Wires

All lines except 3 are built with one or more ground wires. Two of the lines (Nos. 8 and 9 in Table II) which have no ground wire are in mild lightning territory, and the third line (No. 5), which when first built had no ground wire, has since had 2 ground wires added over about 35 per cent of the line. This line is in severe lightning country.

The more recently built lines, except in mild lightning terrain, have been built with 2 ground wires per tower line. On 5 of the lines where twin tower construction is used on the same right of way, 2 ground wires are used per tower, making a total of 4 for the 2 circuits.

Table I—Mileage of 220-Kv Line (Right of Way) in the United States

Type of Circuit	Miles
Single circuit, single right of way	866
Double circuit, single right of way	1,064
*Double circuit 187-kv, single right of way	136
Total single tower line	1,766
Twin tower line	770

*This line in Canada.

Full text of a paper prepared by the lightning and insulator subcommittee of the A.I.E.E. committee on power transmission and distribution, recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Sept. 14, 1934; released for publication Sept. 14, 1934. *Not published in pamphlet form.*

*Personnel of A.I.E.E. lightning and insulator subcommittee: Philip Sporn, *chairman;* I. W. Gross, *secretary;* C. L. Fortescue, K. A. Hawley, J. Allen Johnson, W. W. Lewis, J. T. Lusignan, and F. W. Packer.

1. For numbered references see bibliography at end of paper.

Table II—Design Features and Lightning Performance of 220-Kv Lines

1	2	3	4	5	6	7	8	9	10	11	12		13	14	15	
Line No.	Name of Company	Line Designation	Date First in Service	Length of Line (Miles)	Avg Tower Span (Ft)	No. of Circuits	Circuits per Tower	Tower Design (Fig. No.)	Ground Wires per Tower	Height of Ground Wires Above Cond. at Tower (Ft)	Ground Wire Location (See Figs.) (Feet) A	B	Cond. Height Above Ground at Tower (Ft)	Conductor Spacing (Ft)	Conductor Clearance at Tower In.	At Deg Swing
1	New England Pwr. Assn.	Comerford-Tewksbury	10/ 1/30	126.4	590	2	1	1	2	15	11	...	44	23.5	86	45
2	Pa. Water & Pwr. Co.	Safe Harbor-Westport	12/ 7/31	92.0	1,020	1	1	1	2	24.5	7.1	...	60	28.2	61	51
3	Pub. Serv. Elec. & Gas Co.	Roseland-Bushkill	4/ 8/32	45.7	1,150	1	1	1	2	13.8	14.3	...	59	28.5	72	49
4	Pub. Serv. Elec. & Gas Co. and Philadelphia Elec. Co.	Roseland-Plymouth Mtg.	8/31/30	46.2	1,050	1	1	1	2	13.8	14.3	...	59	28.5	72	49
				29.6		1	1	1	2	16.0	4.0	...	62	25.5	60	53
5	Pa. Pwr. & Lt. Co.	Wallenpaupack-Siegfried	4/11/26	65.0	1,110	1	1	1	0-2	10.5	11.3	...	66.5	22.6	54	45
6	Pa. Pwr. & Lt. Co. and Philadelphia Elec. Co.	Plymouth-Siegfried	2/18/28	48.7	1,270	1	1	1	2	13.3	13.1	...	66.3	26.3	73	45
				9.9						16	12.7	...	63.8	25.5	60	53
7	Philadelphia Elec. Co.	Conowingo-Plymouth Mtg.	3/ 5/28	57.6	1,170	2	1	1	2	16	12.7	...	63.8	25.5	60	53
8	Pacific Gas & Elec. Co.	Pitt Lines Nos. 1 & 2	9/—/22	202	720	2	1-2	1-2	0	..	..	...	45	19	54	?
													85.5	15		
9	Pacific Gas & Elec. Co.	Tiger Creek Nos. 1 & 2	6/—/31	109	790	2	1-2	1-2	0	..	..	...	45	19	60	?
													8.95	17		
10	So. Calif. Edison Co.	Vincent (Big Creek-Magunden)	1/24/28	128	1,470	1	1	1	2	12.8	10.3	...	55	22.3	72	30
11	So. Calif. Edison Co.	Vincent (Magunden-Gould)	11/14/26	95	1,150	1	1	1	2	12.8	10.3	...	55	22.3	72	30
12	So. Calif. Edison Co.	Big Creek 2A-Big Creek 3	7/15/28	6	1,090	1	1	1	2	13.8	10.3	...	55	22.3	72	30
13	So. Calif. Edison Co.	[3]East Big Creek	4/14/14	250	775	2	1	1	1	11	8.3	...	35.2	17.3	72	30
		[3]West Big Creek	11/18/13	260	810											
14	So. Calif. Edison Co.	East & West Lighthipe Laguna Bell	10/30/27	6.7	1,110	2	1	1	2	13.3	10.3	...	55	22.3	72	30
15	So. Calif. Edison Co.	East & West Gould Laguna Bell	8/ 1/23	22.9	1,230	2	1	1	1	12.5	10.3	...	55	22.3	72	30
			11/ 3/23													
16	So. Calif. Edison Co.	Lighthipe-La Press	3/27/30	9.5	880	2	2	2	1	16.3	15.5	...	111	20	72	30
17	So. Calif. Edison Co.	Lighthipe-Long Beach Steam	6/16/28	9.4	900	2	2	2	1	16.3	16.5	...	111	20	72	30
18	City of Los Angeles, Calif., Dept. of Water & Pwr.	[1]Boulder Dam	Not in service	265.5	950	2	1-2	1	2	31.5	7.5	...	77	33.5	84	43
								2	2	31.5	0.1	...	112	24.5		
19	Shawinigan (Can.) Water and Pwr. Co.	[2]Nos. 25 & No. 26	8/—/27	136	910	2	2	2	2	10	..	5.0	74	12.0	41	45

1. Designed for 287.5 kv. 2. Designed and operated at 187 kv. 3. Operated at 150 kv before 1924; lightning performance given from 1929 on.

Since the location of the ground wires with respect to the line conductors has been given much theoretical attention, it is interesting to analyze the construction of 220-kv lines in this regard. The vertical height of the ground wires above the conductors, at the towers, varies from 10.5 to 24.5 ft, and reaches 31.5 ft for the 287-kv line; the average height is from 14 to 16 ft. As regards locating the ground wire in such a position above the line conductor as to provide a shield against the line conductor being struck, it is interesting to note that on every 220-kv line, and even on the 287-kv line, the ground wires on flat-configurated towers are set closer to the tower center line by some 4 to 15 ft than is the line conductor immediately below it. The notable exception to this practice of "insetting" the ground wire is on the one 187-kv line where the 2 ground wires "overhang" the line conductor by 5 ft.

Line Insulation and Tower Clearance

The impulse voltage insulation[2] at the tower is indicated for each line in columns 15 to 18, Table II; the values for suspension insulators alone (omitting the effect of arcing shields, if any) vary from 1,300 kv to more than 2,000 kv with a 1x5-μsec minimum positive impulse wave. The average value for lines in severe lightning areas is about 1,700 kv.

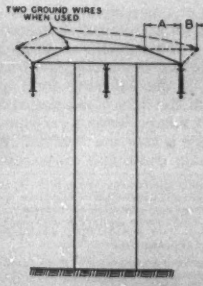


Fig. 1. Single-circuit tower

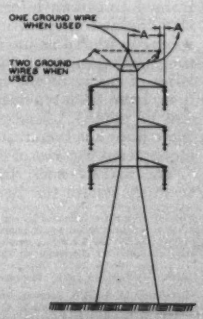


Fig. 2. Double-circuit tower

Table II Continued—Design Features and Lightning Performance of 220-Kv Lines

16	17		18	19	20	21		22	23	24	25	26	27	28	
Clearance Impulse (1x5-μsec pos.) Flashover at Tower, kv	Suspension Insulators		Insulator Impulse (1x5-μsec pos.) Flashover, kv	Type of Country	Nature of Soil	Tower Footing Resistance, Ohms		Additional Grounds at Tower	Lightning Severity	Avg Line Outages per 100 Miles of Line per Year	Grading Shields Used	Tower Flashovers per Year Avg[10]	Inoceramic Factor	Outages per 100 Miles of Line per Year at Inoceramic Factor of 50	Line No.
	No.	In. Spacing				Avg	Max.								
1,740	15	5¾	1,670	Rolling, hilly, flat	Various	300	1500+	None	Severe	3.7	Ring & ring	1.0	24	7.7	1
1,250	20	5	1,930	Rolling	Clay, shale, sand (poor)	[9]25 70	[9]85 400	Counterpoises & rods—salted	Severe	0.55	None	0.5	36	0.76	2
1,460	16	5¾	1,775	Hilly, flat	Rock, clay, marsh	26 [4]18	300+	Counterpoises (Some)	Severe	1.10	Ring & ring	0.5	35	1.6	3
1,460 1,230	16 16	6 5¾	1,840 1,775	Hilly, flat rolling	Rock, clay sand	6.1 [6]3.4	105 [6]12.5	None	Severe Mild	3.5	Ring & ring Ring & ring	1.33	33	5.3	4
1,110	14 to 16	5¾	1,565 1,775	Mountainous to rolling	Rock, sand, clay	40.2 [6]25.5	330	Counterpoise (Some)	Severe	[6]31.0	Ring & horn	51	35	44	5
1,480 1,230	16 14	5¾ 5¾	1,775 1,565	Rolling, flat	Rock, clay	[11]16.1 [12]4.7	[11]61 [11]10.4	None	Mild Severe	1.7	Ring & ring None	1.5	35	2.4	6
1,230	16	5¾	1,775	Hilly, rolling	Rock, clay	[8]10	[8]40	Counterpoise & ground rods	Mild	5.5	Ring & ring	2.0	35	7.8	7
1,110	13	5 5½	1,300 1,410	Mountain, hilly Flat	Rock, clay Sand	...	...	Ground plate at One tower leg	Mild to Light	1.0	Corona shield	2.0	5	10	8
1,230	13 to 20	5¾	1,460 2,200	Mountain, hilly Flat	Rock, clay	...	...	Ground rod at One tower leg	Light	0.6	Corona shields	0.7	5	6	9
1,460	13	6¼	1,590	Mountain, hilly	Rocky	...	...	None	Light	0.9	Ring & horn	1.2	5	9	10
1,460	13	6¼	1,590	Mountainous to flat	Rock, sand clay	...	...	None	Light	2.75	Ring & horn	2.6	5	27.5	11
1,460	13	6¼	1,590	Mountain	Rocky	...	...	None	Light	0	Rings	0	5	0	12
1,460	12	5¾	1,355	Mountainous to flat	Rock, clay sand	...	...	None	Light	0.31	Rings	0.6	5	3.1	13
1,460	13	6¼	1,590	Flat	Sandy	...	...	None	Light	0	Ring & horn	0	5	0	14
1,460	13	5¾	1,460	Hilly, flat	Rock, sand	...	...	None	Light	1.7	Ring & horn	0.4	5	17	15
1,460	15	6½	1,860	Flat	Sandy	...	...	None	Light	2.6	Rings	0.2	5	26.3	16
1,460	15	6¼	1,800	Flat	Sandy	...	...	None	Light	0	Rings	0	5	0	17
1,700	24	5	2,300	Mountainous to flat	Rock, sand gravel, clay	...	...	2 Counterpoises per tower line	Mild Light	..	Ring & ring	...	..	..	18
850	10	4¾ 5	980 1,025	Hilly	Rock, sand Gravel	[9]200+	[9]300+	Counterpoise (being installed)	Mild	5.6	None	13.6	15	18.7	19

3. After installing auxiliary grounds. 4. After installing counterpoises. 5. Past 6 years only. 6. Measured with ground wires in place. 7. Based upon "Flashover Voltages of Insulators and Gaps," Elec. Engg., v. 53, June 1934, p. 882–6. 9. Measurements on representative towers. 10. Found by inspection. 11. On 9.9-mile section. 12. On 48.9-mile section.

Evaluation of the impulse strength of clearances between line wires and structure, at the tower, have been based upon gap breakdown characteristics[3] of the clearance distance with the conductor swing (angle of swing) for which the line was designed. This angle of swing has been reported as varying from 30 to 53 deg for the different lines. Corresponding impulse strengths for the clearances reported vary from 1,110 to 1,740 kv, that is, of the same order of magnitude as the insulator flashover voltages, although it may be expected that the extreme angle of swing will not occur coincident with severe lightning conditions.

Tower Footing Resistance and Counterpoises

Most of these lines extend through considerable hilly, rough country where ground conditions are poor (see Table II, columns 19, 20, and 21) and normal tower footing resistances are high. Average tower footing resistances in the order of 16 ohms or more are common, and one line reports an average of 300 ohms.

On 6 of the 19 lines counterpoises are used in varying extent to lower the normal resistance. That this means is effective in lowering the measured resistance is clearly indicated (column 21, Table II).

Since the counterpoise has come into recent and somewhat extensive use as a means of reducing tower footing resistance in order to secure the expected protection from lightning, a brief description of the counterpoises used at locations of high resistance on these lines may be of interest.

Line 2. From 4 to 8 wires per tower, each 50 ft long and terminating in 8-ft ground rods. Rods and wires salted. Also one continuous counterpoise $4^1/_2$ miles long of $^3/_8$-in. "copperweld" cable.

Line 5. Continuous buried 2/0 stranded copper cable, 2.8 miles long connecting 14 consecutive towers. Also "crowfoot" counterpoises for $19^1/_2$ miles of line (101 towers) each counterpoise consisting of 4 50-ft lengths of 2/0 stranded copper conductor buried 1 ft in the ground, extending 45 deg to the line and connected to the tower legs.

Line 7. Two 1,000-ft copper cables buried parallel to line and bonded to towers.

Line 18. Two $^1/_4$-in. black copper rods per tower line, buried 3 ft or less in ground. Wires run radially from the tower until 130-ft separation is reached, then parallel to line conductors.

Line 19. Single No. 6 B.W.G. galvanized iron wire now being installed, buried in the earth, over about 20 miles of right of way.

Mid-Span Lightning Strokes

In answer to the question "Have you any definite evidence of line or ground wires being hit by lightning (or evidence of arcing between conductors) in mid-span?" all companies reported "No" except 2. One of these 2 remarked: "Yes, 20 to 30 ft from the tower"; the other stated: "One instance of direct hit to conductors at mid-span (no tripout)." A third company reported "No," but believes from their records that the conductors frequently are struck.

Line Damage and Outages

Damage to insulators and conductors was indicated for all lines, as being of minor operating importance. The duration of line outages varied from 1 to $4^1/_2$ min, except for the lines of one company which reported a duration from 10 to 20 min. This delay, however, appears to be attributable to operating practice rather than inability to put the line back in service.

For comparative purposes the line outages on each line have been converted to the number occurring per 100 miles of line (right of way) per year and, further, corrected by isoceraunic curves[3] to a yearly storm frequency of 50. Records of all lines, on the foregoing basis, are given in Table II, column 28, and a summary of average results in Table III.

Definite conclusions are rather difficult to draw from these records, although several features are outstanding when the outages are studied with line construction and lightning territory in mind. In severe lightning territory the line (No. 5) built and operated for some time without any ground wire, but now partially equipped with ground wire, has 10 times as many outages as other lines having ground wires and situated in similar territory. Although the larger number of outages may be attributed partly to the slightly lower insulation and clearances at the towers than used in more recently built lines, and the local lightning may be more severe, the greatest controlling factor is probably the absence of a ground wire.

Table III—Average Line Outages Caused by Lightning on 220-Kv Lines* in the United States

	Outages per 100 Miles of Line per Year	
	Actual	On Basis of 50 Storms per Year
Average all lines	3.3	9.8
All lines having ground wires (excluding No. 5)	1.6	7.0
Lines with ground wires in severe lightning territories	2.6	4.2
Lines with ground wires in light lightning territories	1.0	10.3
Lines without ground wires in light lightning territories	0.8	8.0
†187-kv line—2 ground wires, in mild lightning territory	5.6	18.7

*Excluding lines 18 and 19, Table II. †This line in Canada.

Lines in light lightning territory that have an outage record actually averaging in the order of 1 per 100 miles of line per year, give an indicated performance of 10 outages in an area experiencing 50 storms per year area against a corresponding outage record of 4.2 for lines specially constructed against lightning flashover. The special construction referred to comprises 2 ground wires placed high over the line to provide better shielding, higher line insulation, and, particularly, reduction in tower footing resistances.

The importance of low tower footing resistance is indicated in the outage records of lines Nos. 1 and 19. Line No. 1 is of twin tower construction, with 2 ground wires per tower line, but with tower footing resistances averaging 300 ohms. The outage record is correspondingly high, namely, 7.7 on the basis of 50 storms per year. Likewise line No. 19 (187 kv) with 2 ground wires placed well out over the line conductors to provide better shielding has an outage record of 18.7, and here again the average tower footing resistance indicated is more than 200 ohms.

The line (No. 2) having the best record has 2 ground wires placed well out over the line conductors and high (24.5 ft) above the conductors. This line has the highest insulation (insulators only) of any of the 220-kv lines although the conductor clearance (at 51-deg swing) is only nominal. One important thing to note about this line, however, is that normal tower footing resistances averaging about 70 ohms have been reduced by salted counterpoises and ground rods to about 25 ohms. This line has had an operating record over 2 years of 0.76 outages per 100 miles per year on a 50 isoceraunic basis, which is practically the same as the actual average performance record of all 220-kv lines in light lightning territory.

Summary and Conclusions

While, as before mentioned, the records of line performance are not sufficiently complete or clear cut to prove or disprove definitely the theories of lightning performance of high voltage lines that have been advanced during the past few years, it is believed the following conclusions applying to 220-kv lines may be drawn fairly from the records presented here:

1. The use of one or more ground wires on transmission lines results in a relatively large reduction in outages caused by lightning.

2. Low tower footing resistances, in addition to ground wires, further reduce line outages. From practical considerations, low footing resistances alone, without ground wires, are of little value in reducing outages.

3. The line, of appreciable length, having the best lightning performance record (line No. 2, Table II), actual as well as on a 50 isoceraunic basis, has high insulation, 2 ground wires high above the conductors and slightly "inset" from the vertical, and several towers equipped with counterpoise wires and ground rods both salted to bring the tower footing resistances down to about 25 ohms. Just how much each of these features contributes to the good performance of this line is not evident from the record.

4. Better shielding by locating ground wires almost directly over (or "overhanging") the line conductor does not materially improve the line performance, if tower footing resistances are high.

5. Lines built without special lightning protective features in light

lightning territory probably would be bad performers in severe lightning locations.

6. Damage to line and insulators initiated by lightning flashovers, is of negligible importance from a line service and maintenance point of view.

7. In the more severe lightning territory the use of counterpoise wires to reduce lightning troubles is being tried with considerable apparent success. More data, however, are required to prove the degree of benefits to be derived from the use of counterpoises.

8. Although lines in very light lightning territory sometimes indicate a relatively large number of outages due to lightning when referred to an isoceraunic factor of 50 (column 28, Table II), it must be remembered that these lines actually operate with a lightning outage record of the same order or better than lines in lightning infested country where special protective methods have been employed to reduce lightning troubles. In short, remedial measures are required in design of lines in proportion to the severity of the lightning territory traversed by the lines, if uniformly good performance is to be obtained.

Bibliography

1. Lightning Investigation on a 220-Kv System (Pa. Pwr. & Lt. Co., 1931–33), Edgar Bell. Elec. Engg., v. 53, 1934, p. 1188–94.

2. Flashover Voltages of Insulators and Gaps, A.I.E.E. Lightning and Insulator Subcommittee. Elec. Engg., v. 53, 1934, p. 882–6.

3. *Monthly Weather Rev.*, v. 52, July 1924, U. S. Dept. of Agriculture, Weather Bureau.

4. Transmission at 220-Kv on the Southern California Edison System, H. Michener and others. A.I.E.E. Trans., v. 43, 1924, p. 1229–34.

5. Pit River Power and 220,000-Volt Transmission Problem, F. G. Baum. *Elec. World*, v. 82, 1923, p. 205–12.

6. Wallenpaupack Hydro-Electric and 220-Kv Transmission Development, A. E. Silver, A. C. Clougher. *Elec. World*, v. 88, 1926, p. 559–68.

7. Vincent 220-Kv Transmission Line, C. B. Carlson and H. Michener. A.I.E.E. Trans., v. 45, 1926, p. 1053–63.

8. Latest 220,000-Volt Transmission on the Pacific Coast, G. R. F. Nuttall. *World Power*, v. 7, 1927, p. 23–30, p. 304–7.

9. 220-Kv Transmission Line for the Conowingo Development, P. H. Chase. A.I.E.E. Trans., v. 47, 1928, p. 900–6.

10. Lightning Laboratory at Stillwater, New Jersey, R. N. Conwell and C. L. Fortescue. A.I.E.E. Trans., v. 49, 1930, p. 872–8.

11. Service Controls Fifteen Mile Falls Transmission, C. A. Booker. *Elec. World*, v. 96, 1930, p. 443–7.

12. Safe Harbor-Westport 230-Kv Transmission Line, E. Harrison. Elec. Engg., v. 51, 1932, p. 834–8.

13. Mechanical Features Differ on Mokelumne 220-Kv Line, E. M. Wright. *Elec. World*, v. 98, 1931, p. 872–4.

Vapor Conducting Light Sources

Developments in vapor conducting light sources made both in European and American practice are outlined in this paper. The various types of sodium and other vapor arc lamps are considered, together with the principal factors affecting their operation.

By
R. D. MAILEY
FELLOW A.I.E.E.

Gen. Elec. Vapor Lamp Company, Hoboken, N. J.

RECENT development work on vapor conduction lamps has been devoted to 2 principal types of work. One of these is the perfection of the so-called "hot cathode," of various vapor resistant glasses, and of a-c operating circuits. The other type of work to which development has been devoted is a study of tubular versus bulbular lamp forms, of the factors affecting depreciation, and of an economic rating, i. e., the relative importance of life and efficiency.

While similarity of work and thought in the lamp development laboratories in the United States and abroad does at present result from the continuous and reciprocal interchange of information, a difference in product results from individual interests and emphasis.

Various Types of Hot Cathodes

Of the many forms of hot cathodes, a simple one consists of a few inches of 20-mil tungsten wire wrapped closely with 5-mil nickel wire, and coiled into a helix about 0.2 in. in diameter. This concentrated nickel-covered tungsten filament with a fused-on and activated coating of alkali-earth oxide is heated by a 10-amp 2.5-volt current to such a temperature that it will emit a 6 to 7 amp current for over 1,000 hr. Two such cathode electrodes assembled in a bulb of such dimensions as to give a sodium arc drop of 30 volts constituted the 10,000-lumen sodium lamp exhibited at the New York meeting of the A.I.E.E. on November 21, 1933. This was but a typical design and by changing the dimensions of the cathode and of the enclosing bulb, larger as well as smaller units have been made.

A similar arc rated at 60 watts has been marketed as the essential part of a small unit designed primarily for use in the physical and chemistry laboratory.

A similar cathode for 2-volt a-c operation in the center of an elongated bulb with cylindrical anodes at the ends of the bulb but connected in multiple, forms the a-c cathode, d-c arc sodium lamp developed by Philips in Holland and made by the General Electric Vapor Lamp Company in the United States. This was the sodium lamp used in the Balltown Road demonstration at Schenectady, N. Y., during 1933.

In contrast with the above type of electrode with a voltage gradient on the activated surface of the

Full text of a paper recommended for publication by the A.I.E.E. committee on production and application of light, and based upon a talk presented by the author before the illumination group of the Institute's New York Section, Nov. 21, 1933. Manuscript submitted March 9, 1934; released for publication July 10, 1934. *Not published in pamphlet form.*

cathode, there is the uni-potential cathode of the type already used for several years in hot cathode neon and mercury arcs. This cathode is a cylinder of nickel coated with a fused-on and activated layer of alkali-metal oxide heated by an axially placed filament of tungsten. Such cathodes have been used in a sodium arc rated at 200 watts and intended for general use. Mercury lamps using practically this same cathode have been on the market for several years for use as low intensity sources of ultraviolet radiation for hygienic use in the home.

Hot cathodes of the type just described are heated independently of the arc, much as are a-c radio tube cathodes, and like the larger radio cathodes, require in some cases, a period of preliminary heating before high voltage or high current operation. An alternative type of cathode is one of such small heat capacity that a short initial period of glow discharge operation provides an adequate temperature for normal operation. Such a cathode has recently been used in a tubular type sodium arc made in Holland and referred to later. This type of cathode had previously been used in neon and mercury arcs of both foreign and domestic design.

Mention should also be made of circuit arrangements by which the heating current is automatically reduced or shut off in the former type of cathode so designed that the normal arc heating will maintain it at the proper emitting temperature. Thus the high current capacity and long life of the independently heated cathode is combined with the efficiency of the arc heated cathode by a slight complication of the operating circuit.

Vapor Resistant Glasses

The relation between the glass composition and the depreciation of vapor conduction lamps has always been known to be very important; this relationship became critical in the case of the sodium arc, for which it has been necessary in the last 2 years to develop a new type of glass specifically for its resistance to hot sodium vapor. While tubes and bulbs have been made of such a glass, the associated glass working difficulties have been such as to result in the use, especially in domestic sodium lamps, of a sodium resistant glaze applied to the inner surface of tubes and bulbs of ordinary glasses. Considerable experimental work is now being done on both glass and glaze compositions and will doubtless result in an improvement of the already fairly satisfactory materials.

The depreciation of sodium arcs can be almost entirely attributed to the cathode and to the glass bulb or tube. For efficiency, both must operate at a temperature which jeopardizes their effectiveness and so depreciation becomes a phase of a very complicated problem of lamp design and rating.

Tubular Versus Bulbular Lamp Forms

In addition to the obvious complexities of cathode design which had, however, already been extensively investigated for use in neon lamps, sodium arcs are being made in both bulbular and tubular forms with the greater emphasis on the latter abroad. For example, the Antwerp Tunnel and approaches are illuminated by a 100-watt unit in which a tube about 0.75 in. in diameter and 16 in. long is folded up in such a manner as to permit enclosure in a cylindrical vacuum jacket of 2.5 in. by 5 in. internal dimensions. A similar U-shaped unit 0.5 in. in diameter and 18 in. long, is enclosed in a jacket of 1.5 in. by 9 in. internal dimensions.

The serious limitation to a development of the tubular lamp is the necessity of inclosure in a vacuum jacket in order to insure that a satisfactory arc temperature is maintained by the arc energy and without any accessory heating.

Operating Circuits

The method of operation and type of circuit to be used with the sodium arc is still a matter of very divergent practice. The foreign tubular lamps have generally been for 220-volt a-c operation while one of the best known of the bulbular lamps has an a-c cathode but requires about 15 volts direct current for the arc. A physically very similar domestic bulbular lamp is, however, operated on the full wave rectifier principle thus securing the unflickering light of d-c operation and the circuit advantages of an a-c supply.

The 200-watt unit first described represents the domestic interest in a full a-c sodium arc. While the flicker of the light results in stroboscopic effects under certain conditions, this is thought to be of no importance in the applications now in mind.

Other Types of Arc Lamps

Closely parallel to this development of sodium arcs is that of an a-c mercury arc using arc-heated oxide-coated cathodes, a limited quantity of mercury, and a design of lamp tube such as to insure a normal mercury vapor pressure of about one atmosphere. On 220-volts alternating current, automatic starting, when cold, is secured and an efficiency of about 35 lumens per watt is obtained with inductive ballasting. In England, a street lighting demonstration is being made with 420-watt units of this type.

There are yearly reports of vapor and gaseous conduction lamps giving light of daylight quality. These are generally nitrogen or carbon dioxide Geissler tubes or mercury-amalgam lamps. The latter have long been a promising subject for investigation and still are laboratory curiosities. They require a temperature control for their satisfactory operation much more difficult to obtain than that needed for a sodium or an ordinary mercury arc.

Arc Efficiency Ratings

The possibility of operating sodium arcs on direct current and on alternating current with either resistive or reactive ballasting, has raised an old confusion as to the efficiency rating of arc lamps. Series a-c operation with inductive ballast reduces the energy loss per unit external to the arc proper to so

low a value that there is a temptation to use only the arc watts in calculating the lumens per watt. This method of rating is obviously the most nearly an absolute rating for laboratory purposes. Most of the published sodium arc efficiency ratings have been based upon constant current or upon inductive ballasted series operation, and 50 lumens per watt seems to be an average practical initial rating, consistent with a life of 1,000 hr or more and a depreciation about such as is characteristic of high efficiency incandescent lamps. Laboratory ratings very much higher than this have been obtained but only further experience will indicate their practicality.

Limits to Amplification

The amplification obtainable in a vacuum tube amplifier is limited by the noise in the circuit. Of the various sources of noise the most fundamental and inevitable is thermal agitation of electricity. Other sources are the influence of ions and of shot effect and flicker effect on the current in vacuum tubes, poor contacts, mechanical vibration, and hum from a-c cathode heating. These noises and their effects in limiting amplification are discussed in this paper. Although the natural noise level of an amplifier is exceedingly low, modern amplifiers have reached such a stage of perfection that their noise levels often are practically at the natural limit.

By
J. B. JOHNSON
MEMBER AM. PHYS. SOC.

F. B. LLEWELLYN
MEMBER AM. PHYS. SOC.

Both of Bell Telephone Laboratories, New York, N. Y.

NOISE in amplifiers is now a familiar term. Any one who has had his favorite radio hour ruined by static knows the effect of an incoherent background of noise. Although static was one of the first noises observed in radio amplifiers, its origin is really outside the circuits. At one time it seemed that other sources of noise of purely local origin, such as poor batteries, loose contacts, gassy tubes and induction from power lines, might be eliminated entirely so that the circuits would be capable of amplifying any signal, no matter how small. It was found, however, that the noise level cannot be lowered indefinitely; that there are limits below which, in the nature of things, noise cannot be reduced.

Of the sources of noise, the most fundamental and inevitable is thermal agitation of electricity. In a perfect amplifier all other noises would be reduced to a level below that of thermal agitation. Next in order comes the influence of ions and of shot effect and flicker effect on the current in the vacuum tubes. Under control to a greater extent, but nevertheless of a malignant nature, are the effects of poor contacts, mechanical vibration, and hum from a-c cathode heating. In dealing with these disturbances, the circuit and vacuum tube of the first stage of the amplifier are the most important, for here the signal being amplified is at its lowest level. When the signal is so faint that it is masked by the noise remaining as the natural limit of the circuit, then the only possible remedy is to raise the signal level.

The natural noise level is exceedingly low, yet modern amplifiers have reached such a stage of perfection that their noise levels often are practically at the natural limit. This is true not only of special amplifiers built for experimental purposes, but of many amplifiers used in commercial circuits. The natural limits to amplification which will be discussed in this review are therefore of very practical interest.

Thermal Agitation[1,2,3,4,5,6]

The free charge of any conductor is in random motion in equilibrium with the thermal motion of the molecules of the conductor and this flow of charge creates a random voltage across the terminals of the conductor. This voltage usually is observed in a system composed of an amplifier with an input circuit and an output device. Its mean-square value across the output device is given by the expression

$$V_n^2 = 4kT \int_0^\infty RG^2 df \qquad (1)$$

where the symbols have the following meanings:

k is the Boltzmann gas constant and is equal to 1.37×10^{-23} watt-second per degree

T represents absolute temperature, degrees Kelvin

R represents the resistive component in ohms of the input impedance as measured across the input terminals of the amplifier

G represents the voltage gain of the amplifier, and is equal to the ratio of voltage across the output device to voltage across the input terminals of the amplifier

f represents frequency in cycles per second

R and G are in general functions of frequency

In the simple case where the amplifier has a constant gain over a frequency range F and no gain out-

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 29–25, 1935. Manuscript submitted Sept. 11, 1934; released for publication Sept. 28, 1934. *Not published in pamphlet form.*

1. For all numbered references see bibliography at end of paper.

side of this range, and where R is also constant over the same frequency range and is at the normal temperature of 300 deg, the mean-square noise voltage across the input terminals of the amplifier is

$$V_t^2 = 1.64 \times 10^{-20} RF \tag{2}$$

This is the voltage that would be produced by a generator supplying to the resistance R the power

$$W = \frac{V_t^2}{R} = 1.64 \times 10^{-20} F \tag{3}$$

The power W, sometimes expressed as 1.64×10^{-20} watts per cycle, is independent of R and may be regarded as the apparent input power of the thermal agitation. It depends only on the frequency range of the amplifier, since the temperature cannot be varied conveniently or very effectively and it sets a lower limit to the possibility of amplifying electrical impulses of any kind. Any signal much smaller than the thermal noise would be masked hopelessly. The only factor under control in the noise equation is the frequency range F, which should be no greater than is needed for the transmission of the signal.

An example will illustrate the magnitude involved in this limit to amplification. When the signal is speech requiring a frequency band of 6,000 cycles, then the apparent power generated at the input of the amplifier by thermal agitation is 0.985×10^{-16} watts, which is about 138 db below the common reference level of 0.006 watts. (The level of 10^{-16} instead of 0.006 watts is being considered as a reference point for the decibel scale in communication circuits. This is approximately the level of thermal noise in a 6,000-cycle channel.) If the input resistance were one megohm the corresponding rms noise voltage would be 9.94 μv.

A signal represents a certain amount of available power, and when this is so small that it is near the thermal noise level it must be used efficiently to produce voltage at the grid of the amplifier tube.[7,8] Let the signal be supplied by a generator of voltage E and internal resistance R_1 which delivers power to a load resistance R_2, the combination forming the input circuit of the amplifier as shown in Fig. 1. The mean-square signal voltage on the grid of the amplifier tube is

$$V_m^2 = \frac{E^2}{R_1^2}\left(\frac{R_1R_2}{R_1 + R_2}\right)^2 \tag{4}$$

However, the resistance required by eq 2 for the noise is the combination of R_1 and R_2 in parallel, so that the mean-square noise voltage on the grid of the amplifier tube is, from eqs 2 and 3

$$V_n^2 = WR = W\left(\frac{R_1R_2}{R_1 + R_2}\right) \tag{5}$$

Hence the signal-to-noise ratio is

$$\frac{V_m^2}{V_n^2} = \frac{E^2}{WR_1}\left(\frac{R_2}{R_1 + R_2}\right) \tag{6}$$

In general, the internal resistance R_1 of the signal generator is fixed, so that R_2 is the only available variable. In the usual case of matched impedances where R_1 and R_2 are equal, the signal-to-noise ratio is 3 db poorer than in the ideal case where R_2 is made very large compared with R_1. This is one of the few examples where a mismatch of impedances is advantageous. The use of an ideal step-up transformer between R_1 and R_2 in Fig. 1 will be of no avail, so far as the thermal noise is concerned, because its effect in eq 6 will be only to replace R_2 by R_2/N^2 where N is the turns ratio of the transformer.

In some systems the impedance at the input of the amplifier is unavoidably small. It may be so small that the voltage of the thermal agitation of

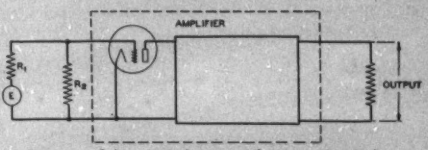


Fig. 1. Schematic diagram of a vacuum tube amplifier showing equivalent input circuit

the input circuit, even when amplified by the first tube, is lower than the noise voltage originating in the output circuit of that tube. Ideally, the noise in the plate circuit also should be caused by thermal agitation only, and the equations for it have been derived.[9,10] In practice, however, the noise in the plate circuit is found to be considerably greater, for reasons that will be discussed presently.

Shot Effect and Flicker Effect Without Space Charge

Early in the study of noise arising in vacuum tubes it was shown[1,11] that under certain conditions a noise is produced that depends on the fact that the electric current is a flow of discrete particles, the electrons, which are emitted from the cathode in a random manner. The random electron emission produces a statistical fluctuation in the current that flows through the tube and coupling impedance. This fluctuation, called the shot effect (German Schroteffekt, in analogy with the random scattering of shot from a shot gun), appears as noise in the output of the amplifier. When the current in the tube is limited by the rate of emission of electrons rather than by the space charge, so that the resistance of the tube is nearly infinite, then the shot effect produces a mean-square voltage across the output impedance of the amplifier given by[12,9]

$$V_m^2 = 2ei\int_0^\infty Z^2G^2df \tag{7}$$

in which

e represents the charge on the electron and is equal to 1.59×10^{-19} coulomb

i represents space current in amperes

Z represents the magnitude in ohms of the coupling impedance

G represents the voltage gain of the amplifier from Z to the output

f represents frequency in cycles per second

For an amplifier having a flat frequency response curve over frequency range F the expression be-

comes, for the effective shot noise across the impedance Z

$$V_s^2 = 31.8 \times 10^{-24}\, iZ^2F \tag{8}$$

The expression holds quite accurately for tubes in which the cathode is made of either clean or thoriated tungsten and for high-vacuum photo-electric tubes, and it has been used in determining the charge on the electron.[13]

When an oxide coated cathode is used, fluctuations of a larger magnitude[14] are superimposed on the true shot effect. These fluctuations are inappreciable above about 10 kc, but increase rapidly in magnitude toward the lower frequencies. They also increase with the current at a faster rate than the shot effect fluctuations. This disturbance has been ascribed to a state of flux and change in the activating material on the surface of the cathode,[14,15] and the phenomenon has been called the "flicker effect" (from the analogy of a flickering candle).

There are 2 practical circuits in which the pure shot effect may set the ultimate noise level. One of these is the circuit in which the grid of an amplifying tube is left "floating" at its equilibrium potential as usually is done in the first stage of amplifiers used for ion counters and other instruments for measuring very small charges.[18,19] The grid then emits a few electrons and receives positive ions and electrons from the surrounding space. These currents are very small, but are not subject to space charge limitation so far as the grid is concerned. Because the grid impedance is very high, the shot voltage developed by the small grid current may exceed the thermal voltage of the grid impedance. The second circuit is that in which a photo-electric cell works into the amplifier.[19,20,21] Vacuum cells generate shot noise of very nearly the theoretical value given by eq 7, while gas filled cells give even greater noise.

The total noise generated in the output of the vacuum photo-electric cell is the sum of the shot noise and thermal noise across the coupling resistance R, as given by eqs 8 and 2. The mean square of the signal voltage, however, is $(\Delta i R)^2/2$ where Δi is the amplitude of the current variation. The ratio of signal to noise is then

$$V_m^2/(V_t^2 + V_s^2) = 1.50 \times 10^{12}\, \frac{(\Delta i)^2}{F}\, \frac{R}{iR + 0.0516} \tag{9}$$

This equation shows the expected fact that for a given value of Δi it is better to keep the direct photo-electric current small (high modulation). It also brings out the curious result that when the direct voltage drop in the coupling resistance is much more than $^1/_{20}$ volt the noise is largely shot noise and the signal-to-noise ratio is independent of the coupling resistance, while if this voltage is much less than $^1/_{20}$ volt the thermal noise predominates and the signal-to-noise ratio is proportional to the coupling resistance.

Shot Effect and Flicker Effect With Space Charge

When, as in an amplifier tube, the current in the tube is limited partly or wholly by space charge rather than by the cathode temperature, then the conditions are changed[15,16,16] in 2 respects. First, while the electrons still are emitted from the cathode at random times, they must arrive at the plate in a more orderly manner. Simple statistical laws no longer apply, the flow of current is smoother and the fluctuations are greatly reduced. Second, the impedance of the tube is no longer infinite, but has a finite value. The equation for the shot effect (eq 7) now must be modified,[9,14,17] by substituting for the current i the quantity $j(\partial i/\partial j)^2$, where j is the total current emitted by the filament and $\partial i/\partial j$ is the rate of change of space current with emission current for the particular conditions used in the observation of the fluctuating voltage. Furthermore, in place of the coupling impedance Z the effective impedance Z_e of this in parallel with the tube resistance r_p must be used. The equation now reads

$$V^2 = 2ej\left(\frac{\partial i}{\partial j}\right)^2 \int_0^\infty Z_e^2 G^2 df \tag{10}$$

In the absence of space charge j and i are identical, $\partial i/\partial j$ is unity, and Z_e becomes Z, so that the equation then represents the pure shot effect. With increasing space charge the value of $\partial i/\partial j$ approaches zero and Z_e becomes smaller so that the shot effect becomes very small. Similarly the flicker effect, being connected with the process of emission and not with the subsequent history of the electrons, also is made ineffective by the space charge. In fact, in well designed tubes the fluctuation noise of both shot effect and flicker effect in the space current appear to be reduced to such an extent as to be negligible.

Ions in the Space Charge

The effect of ions in the grid current already has been discussed. Ions also may cause fluctuations in the plate current of the tube. The space charge which limits the current between cathode and anode consists of electrons in rapid progress toward the anode. A massive ion placed in this region travels much more slowly and contributes to the space charge for a much longer time than does an electron. While its own charge contributes little to the current, one ion may cause the current to change by the amount of hundreds of electrons during its flight through the space charge region, and the action of many ions would be additive.

Probably most of the ions existing in a tube are positive. Some of them are molecules of residual gas that have lost an electron by collision with an electron of the space current. Residual gas has been found to increase the noise of tubes, especially at the higher pressures. Observations at very low pressures are not conclusive, and it is not certain whether in any modern tubes the noise level is determined by the presence of residual gas.[9,14,19,20,21,22,23,24]

Positive ions may be emitted also by the cathode. These never can attain a high velocity because they remain in a region of low field intensity. They may be trapped for a time in the region of the potential minimum near the cathode before they finally pass to the grid or possibly become neutralized by an electron. In modern tubes with low temperature

filaments the effect of these ions is reduced greatly, yet still may account for a large part of the difference between the observed tube noise and the theoretical thermal noise of tubes.[14,25,26,27,28]

Noise in Commercial Tubes

Noise generated in an amplifier should consist largely of the thermal noise of the input circuit, to which is added the noise produced in the plate circuit of the first tube. It is convenient to consider that the tube noise comes, not from the plate circuit of the tube, but from a fictitious resistance R_e in series with the resistance R_s of the input circuit.[3] The effective thermal noise of the input circuit then is given by the expression

$$V^2 = 4kTF(R_s + R_e) = 1.64 \times 10^{-20}F(R_s + R_e) \qquad (11)$$

The tubes therefore may be rated conveniently in terms of R_e. The transformation to volts or to watts can be accomplished readily by eq 2 or 3. If, with a given tube and circuit, R_e approaches or exceeds R_s in value, the tube is responsible for an appreciable part of the total noise. The choice of another tube in which the ratio of R_s to R_e is more favorable then may be considered.

For the calculation of tube noise several formulas have been proposed, either entirely empirical[3] or with some basis on theory.[9,24,29] These formulas generally fail in the prediction of noise in tubes for the reason that the greater part of the noise in practical tubes is caused by things that have not been included in theory and that are still in a state of flux so far as manufacturing is concerned. It is best therefore to rely only on actual measurements of the noise in specific types of tubes. With modern tubes, the noise level of a given type of tube can be represented reasonably well by measurements made on a small number of samples.

Published data on noise of tubes are rather meager. The best series of measurements is that of Pearson,[16] which covers 4 Western Electric tubes at different frequency bands. These tubes are known commercially as types 102*G*, 262*A*, 264*B*, and 259*B*. The General Electric tube type *PJ*-11, designed specially for work at low frequencies, was studied by Metcalf and Dickinson.[24] They also give data, for the low frequency region, on the tubes known commercially as types 222, 240, 201, and 112. Johnson and Neitzert[30] have given data for the *PJ*-11 and the type '38 tube. Certain British tubes were studied by Moullin and Ellis,[29] and of these the type *AC/2HL* tube was found to have the lowest noise level. Brintzinger and Viehmann[31] studied a few German tubes. Of these the type *RE*-084 appears to have the lowest noise rating, but the data cannot be reduced to absolute measure.

In many of these studies the tubes were operated at voltages different from those usually employed. For these, the original papers should be consulted. In general for the best triodes R_e has a value of a few thousand ohms, while for screen tubes it has a value of a few tens of thousands. At the lowest voice frequencies the values may be somewhat greater.

Other Sources of Noise

While the more fundamental sources of noise have been discussed, it may be well to add some remarks on a few types of disturbance that often can be eliminated.

Noise From A-C Cathode Heating.[32–39] The indirectly heated cathode may be operated on alternating current when the tube is employed in radio frequency circuits. In audio amplifiers with gains in excess of 50 db, additional precautions must be taken to reduce the effects of the electric and magnetic fields of the heater and of coupling impedance between the heater and the other electrodes. Even under the best conditions, however, the hum level is of the order of 20 db above the tube noise measured with d-c heating.

Noise From Vibration.[32,33,39,40] Mechanical vibration changes the relative positions of the tube elements and hence causes disturbing noise. This is especially objectionable at audio frequency, although a radio frequency carrier may become modulated sufficiently to produce noise.

The remedy, used in the so-called "low microphonic" tube designs, is to stiffen the construction of the tube elements and to apply damping to their vibration, as well as to cushion the tube by a suitable mounting and to shield it from sound waves. The indirectly heated cathode is superior to the filamentary cathode in regard to noise from vibration.

Noise From Poor Insulation.[32,33,39] Noise arises from resistance changes at contacts and across thin films of conducting material deposited on insulating supports in the vacuum tube. Leaky capacitors may produce a similar noise.

Noise From Faulty Resistances. Many resistors in which the resistance element is a thin film are sources of noise. If no current flows in them only thermal noise is generated, but when direct current passes through them more noise is produced. The noise voltage is roughly proportional to the direct current. These resistors must be chosen carefully for circuit branches where current flows.

Signal-to-Noise Ratio[7,29,41,42]

In so far as noise is concerned, the merit of a transmission system is dependent not only on the amount of noise present, but also on the strength of the signal, so that a determination of the ratio of the signal level to the noise level is necessary. Fortunately, this ratio has a reference value for any given transmission system determined uniquely by the ratio of the signal to thermal noise in the input circuit. The ratio of the signal level to noise level is here the greatest the ratio ever can attain, because noise that originates at subsequent points in the amplifier contributes to the noise level without increasing the signal.

This fact provides a basis for the rating of amplifiers, the thermal noise of the input circuit being used as a comparison signal. For example, the noise output of an amplifying system may be 0.3 mw which falls to 0.2 mw when the input circuit is short-circuited. The thermal noise from the input cir-

cuit is then the difference between these 2 readings, namely, 0.1 mw, and the signal-to-noise ratio of the actual system is 3 times, or 4.8 db worse than its best possible value with a given signal. These data may be expressed in terms of an equivalent input resistance which has the advantage that the amplifying properties of the tube have been taken into account. This leaves for the engineer only the problem of selecting a tube having an input capacity of such a value that the construction of a relatively high impedance input circuit is possible.

So far, the discussion has been based upon the properties of amplifiers only, no mention being made of the effects of modulators, detectors, frequency converters, and other nonlinear devices on the signal-to-noise ratio. A detailed discussion of the noise in such devices is beyond the scope of this paper, but the relations in the most commonly used ones may be indicated and their general properties outlined.

First, consider a system composed of a radio frequency amplifier followed by a detector and a pair of headphones. A certain amount of noise will be heard in the phones if the gain of the amplifier is great enough. This noise is caused by the various components of the radio frequency noise beating together in the detector to form audio frequency components. Next, suppose that an unmodulated carrier is introduced into the amplifier. It will be observed that the audio noise in the phones increases. The increase in audio noise is produced by the radio frequency carrier beating with the radio frequency noise components and this increase is proportional to the strength of the carrier.

If a small percentage of modulation is added to the carrier, the audio signal-to-noise ratio in the phones will be determined by the properties of the amplifier in the same way as though the system were a straight amplifier without any detector. Comparison of the actual system with the ideal may be made by introducing the carrier into one of the amplifier stages subsequent to the input, and then measuring the audio noise with the input circuit in its normal condition and again with the input circuit short-circuited. The ratio of these 2 energy values gives the ratio of the equivalent input resistance of the actual system to the equivalent input resistance of the noisy amplifier alone. The ratio of the ideal signal-to-noise ratio to the actual one may be found by dividing the difference between the 2 audio energy readings by the reading taken with the input circuit in its normal condition.

If the percentage of modulation of the carrier is large, the system will be noisier because there will be appreciable audio noise components caused by beats between the side bands and the radio frequency noise components. Again, if the carrier level is not large compared with the noise level in the amplifier, the system will be noisier because the beats between the noise components are appreciable compared with the beats between carrier and the noise.

The same considerations apply to the first detector in a double-detection receiving system. If, as is usual, the beating oscillator voltage is large compared with the noise components, then the frequency band of the noise will be shifted in position in the same manner as the signal, and the signal-to-noise ratio of the system will be unchanged by the frequency conversion.

The signal-to-noise properties of any system are considered satisfactory when the total output noise differs only slightly from that produced by thermal agitation in the input circuit alone, and this difference may be measured by eliminating the input thermal noise (as by the short-circuit method) and noting the change produced in the output noise.

Bibliography

1. Ueber spontane Stromswankungen in verschiedenen Elektrizitätsleitern (On Spontaneous Current Fluctuations in Various Electric Conductors), W. Schottky. *Ann. d. Phys.*, v. 57, 1918, p. 541–67.

2. Thermal Agitation of Electricity in Conductors, J. B. Johnson. *Phys. Rev.*, v. 32, 1928, p. 97–109.

3. Thermal Agitation of Electric Charge in Conductors, H. Nyquist. *Phys. Rev.*, v. 32, 1928, p. 110–13.

4. The E.M.F. of Thermal Agitation, E. K. Sandemann and L. H. Bedford. *Philosophical Mag.*, v. 7, 1929, p. 774–82.

5. Thermal Agitation of Electrons in a Metallic Conductor, N. H. Williams and D. A. Wilbur. *Science*, v. 76, 1932, p. 519–20.

6. A Measurement of Boltzmann's Constant by Means of the Fluctuations of Electron Pressure in a Conductor, E. B. Moullin and H. D. N. Ellis. Cambridge Philosophical Soc. *Proc.*, v. 28, 1932, p. 386–402.

7. A Rapid Method of Estimating the Signal-to-Noise Ratio of a High Gain Receiver, F. B. Llewellyn. I.R.E. *Proc.*, v. 19, 1931, p. 416–20.

8. Stabilized Feed-Back Amplifiers, H. S. Black. Elec. Engg., v. 53, 1934, p. 114–20.

9. A Study of Noise in Vacuum Tubes and Attached Circuits, F. B. Llewellyn. I.R.E. *Proc.*, v. 18, 1930, p. 243–65.

10. Fluctuation Noise in Vacuum Tubes, G. L. Pearson. *Physics*, v. 5, 1934, p. 233–42 and *Bell. Syst. Tech. Jl.*, v. 13, 1934, p. 634–53.

11. Zur Berechnung und Beurteilung des Schrotteffektes (On the Calculation and Critical Examination of the Shot Effect), W. Schottky. *Ann. d. Phys.*, v. 68, 1922, p. 157–76.

12. The Theory of the Schroteffekt, T. C. Fry. Franklin Inst. *Jl.*, v. 199, 1925, p. 203–20.

13. Determination of Elementary Charge E From Measurements of Shot Effect, A. W. Hull and N. H. Williams. *Phys. Rev.*, v. 25, 1925, p. 147–53.

14. The Schottky Effect in Low Frequency Circuits, J. B. Johnson. *Phys. Rev.*, v. 26, 1925, p. 71–85.

15. Small Shot Effect and Flicker Effect, W. Shottky. *Phys. Rev.*, v. 28, 1926, p. 75–103.

16. Shot Effect in Space Charge Limited Currents, E. W. Thatcher and N. H. Williams. *Phys. Rev.*, v. 40, 1932, p. 474–96.

17. On the Reduction of Shot Effect Fluctuations, E. W. Thatcher. *Phys. Rev.*, v. 40, 1932, p. 114–15.

18. The Application of the FP-54 Pliotron to Atomic Disintegration Studies, R. L. Hafstad. *Phys. Rev.*, v. 44, 1933, p. 201–13.

19. The Shot Effect in Photoelectric Currents, B. A. Kingsbury. *Phys. Rev.*, v. 38, 1931, p. 1458–78.

20. Schroteffekt und Wärmerauschen im Photozellenverstärker (Shot Effect and Thermal Noise in Photoelectric Cell Amplifiers), F. V. Orbán. *Zeits. f. Techn. Phys.*, v. 13, 1932, p. 420–4 and v. 14, 1933, p. 137–43.

21. Natürliche Schwankung schwächster Photoströme (Natural Fluctuations of Very Small Photoelectric Currents), E. Steinke. *Zeits. f. Phys.*, v. 38, 1926, p. 378–403.

22. Fluctuation Noise Due to Collision Ionization in Electronic Amplifier Tubes, S. Ballantine. *Phys.*, v. 4, 1933, p. 294–306.

23. Receiver Design for Minimum Fluctuation Noise, N. P. Case. I.R.E. *Proc.*, v. 19, 1931, p. 963–70.

24. A New Low Noise Vacuum Tube, G. F. Metcalf and T. M. Dickinson. *Phys.*, v. 3, 1932, p. 11–17.

25. Abnormal Shot Effect of Ions of Tungsten and Tungstic Oxide, J. S. Donal. *Phys. Rev.*, v. 36, 1930, p. 1172–89.

26. Shot Effect of the Emission From Oxide Cathodes, H. N. Kozanowski and N. H. Williams. *Phys. Rev.*, v. 36, 1930, p. 1314–29.

27. Effect of Positive Ion Shot Effect on Space Charge Limited Currents, L. P. Smith. *Phys. Rev.*, v. 35, 1930, p. 1430.

28. Shot Effect in Space Charge Limited Currents, E. W. Thatcher and N. H. Williams. *Phys. Rev.*, v. 39, 1932, p. 474–96.

29. The Spontaneous Background Noise in Amplifiers Due to Thermal

Agitation and Shot Effects, E. B. Moullin and H. D. M. Ellis. *Jl.* I.E.E., v. 74, 1934, p. 329–356.

30. The Measurement of Small Alternating Voltages at Audiofrequencies, E. A. Johnson and C. Neitzert. *Rev. Sci. Inst.*, v. 5, 1934, p. 196–200.

31. Das Rauschen von Empfängern (Noise in Radio Receivers), W. Brentzinger and H. Viehmann. *Hochfr. und Elektrosnk.*, v. 39, 1932, p. 199–207.

32. Vacuum Tube and Photoelectric Tube Developments for Sound Picture Systems, M. J. Kelly. *Jl.*, Soc. Motion Picture Engrs., v. 18, 1932, p. 761–81.

33. Analysis and Reduction of Output Disturbances Resulting From the Alternating-Current Operation of the Heaters of Indirectly Heated Cathode Triodes, J. O. McNally. I.R.E. *Proc.*, v. 20, Aug. 1932, p. 1263–83.

34. A Practical Alternating-Current Radio Receiving Tube, H. M. Freeman. Elec. *Jl.*, v. 19, Dec. 1922, p. 501–5.

35. Thermionic Tubes, F. G. McCullough. I.R.E. *Proc.*, v. 10, Dec. 1922, p. 468–85.

36. A Combined Kenotron Rectifier and Pliotron Receiver Capable of Operation by Alternating Current Power, A. W. Hull. I.R.E. *Proc.*, v. 11, April 1923, p. 89–96.

37. AC as a Filament Supply Source, B. F. Meissner. *Radio Broadcast*, v. 10, Feb. 1927, p. 393–6, March 1927, p. 495–7.

38. The Cause and Prevention of Hum in Receiving Tubes Employing AC Direct on the Filament, W. J. Kimmell. I.R.E. *Proc.*, v. 16, Aug. 1928, p. 1089–1106.

39. The Measurement and Reduction of Microphonic Noise in Vacuum Tubes, D. B. Penick. *Bell. Syst. Tech. Jl.*, v. 13, Oct. 1934, p. 614–33.

40. Microphonic Improvement in Vacuum Tubes, A. C. Rockwood and W. R. Ferris. I.R.E. *Proc.*, v. 17, Sept. 1929, p. 1621–32.

41. Fluctuation Noise in Radio Receivers, S. Ballantine. I.R.E. *Proc.*, v. 18, Aug. 1930, p. 1377–87.

42. A Common Source of Error in Measurements of Receiver Selectivity, E. N. Dingley. I.R.E. *Proc.*, v. 22, May 1934, p. 546.

High Velocity Streams in the Vacuum Arc

The high velocity streams of particles in the vacuum arc have been subjected to a detailed study, and the results are presented in this paper, together with a discussion of many of the phenomena involved. Experimental determinations of the relations between arc current, mass of condensed metal, pressure in the arc tank, force between electrodes, and velocity of the vapor stream are included. Results with several different electrode materials are presented.

By
E. C. EASTON
ASSOCIATE A.I.E.E.
Harvard University
Cambridge, Mass.

F. B. LUCAS
NONMEMBER
Lehigh University
Bethlehem, Pa.

F. CREEDY*
MEMBER A.I.E.E.
University of British
Columbia, Vancouver

THE PRESENT paper is in part a continuation of work recorded in a former paper entitled "Forces of Electric Origin in the Iron Arc" (A.I.E.E. Trans., v. 51, 1932, p. 556–63), and in part suggested by the work of R. Tanberg reported in a paper "On the Cathode of an Arc Drawn in Vacuum" (*Phys. Rev.*, v. 35, 1930, p. 1080–9). The former paper contains curves of arc current against force between electrodes for an iron arc in air at atmospheric pressure. Under the caption "Tests on the Iron Arc Between Fixed and Moving Electrodes" the present paper discusses this relation for the iron arc in a vacuum. The remainder of the paper is devoted to a check on Tanberg's measurement of the velocity of the vapor stream emitted from a copper cathode, and to an extension of this work to vapor streams from both anode and cathode of 11 different materials.

Full text of a paper recommended for publication by the A.I.E.E. committee on electric welding, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–25, 1935. Manuscript submitted Oct. 16, 1933; released for publication July 12, 1934. *Not published in pamphlet form.*

* Formerly of Lehigh University, Bethlehem, Pa.

Instrument for Measurement of Impulses

To permit the study of high current arcs, the impulse caused by the application of current for a short known period is measured. Because of the destructive action of a heavy current arc it is impracticable to measure a steady continuous force. The instru-

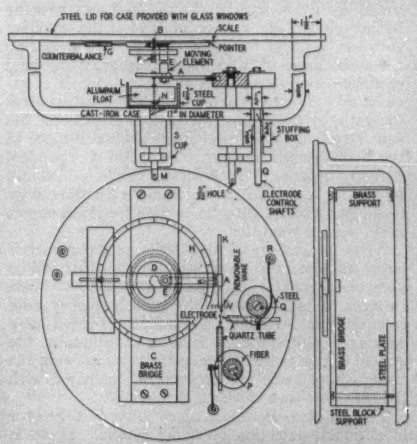


Fig. 1. Instrument used for measurement of impulses caused by high current arcs

ment used for the measurement of these impulses is a development of the idea of the Grassot fluxmeter, and gives a definite permanent reading for each observation. It is shown in Fig. 1. Here the diameter of the tank is 17 in. with the other parts drawn to scale. The tank is of cast iron, capable of being evacuated of gas, and containing an arm A mounted on a moving element pivoted at B and N. To A may be affixed an arcing electrode K or a quartz rod holding a glass vane V. B is a knife edge bearing mounted on the brass bridge C which also contains a hole D through which the shaft E of the moving element passes. Rod E connects the arm A and the aluminum float with an arm G which is equipped at one end with a counterweight and at the other with a pointer whose tip indicates the position of A on a scale H attached to the lid. In order to relieve pivot N of the weight of the moving element (about 1.25 lb) cup L is filled with mercury. The aluminum float is so proportioned that when the mercury completely covers its surface, the moving element rises slightly off the pivot N. A very small adjustable weight may then be added so that the moving element rests very gently on N, and it will be found that the whole instrument is almost completely free from static friction, no friction being left except the fluid friction between the float and the mercury. Since the mercury tank container is grounded onto the cast iron tank, an excellent electric circuit is provided for current passing through the electrode K. The fixed electrodes consist of 2 steel or fiber disks attached with appropriate insulation to the tops of the shafts P and Q. Terminals such as R are provided with flexible leads so that current may be led to electrodes clamped in the disks mounted on P and Q.

As shown in Fig. 1 the instrument is equipped with a vane V. The arc is struck by contacting electrodes P and Q. With this arrangement, forces due to particles projected from P onto the vane may be measured. If electrode Q and the vane V are removed, an arc may be struck between electrode P and K and the corresponding forces between these electrodes measured. In this case, however, difficulties arise in manipulating the arc. The instrument is far too sensitive to permit contact between K and P in order to start the arc. It is necessary therefore to arrange a high voltage discharge of 2,000 volts between P and K for this purpose. The arc having been struck with a current of say 5 amp (an operation not without difficulty since the high voltage arc in vacuum tends to go in any direction except the one desired) a further switch is closed so that a direct current of the desired value, which may be several hundred amperes, is caused to flow through the arc path for a fraction of a second, thus producing the impulse desired. A similar switching circuit is shown in the paper previously referred to (A.I.E.E. Trans., v. 51, 1932, p. 556–63).

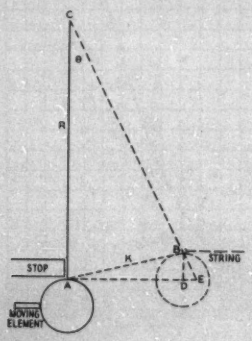


Fig. 2. Calibration pendulum

With either method of operation, that is, with vane V or electrode K, the energy imparted by the impulse to the moving system causes it to rotate (the arm A being repelled) until this energy has been absorbed by the fluid friction of the mercury on the float. Thus the number of degrees through which the pointer turns may be used as a measure of the impulse. It will be noted that the instrument has no spring or other control and therefore comes to rest when its energy is dissipated, and a reading may be taken at leisure. The moving element may be returned to zero position by turning the shaft M; mercury friction causes the pointer to follow.

The instrument is calibrated by means of a pendulum (see Fig. 2), 2 readings being taken. In one the swing of the pendulum is so adjusted as to give a deflection slightly greater than that due to the arc which it is desired to measure, and in the other so as to give a deflection slightly less than that due to the arc. Knowing the dimensions of the apparatus, the value of the impulse corresponding to any angle θ can be readily calculated. A coefficient of restitution due to the bob not being perfectly elastic is, of course, taken into account. The instrument was mounted on a solid concrete base but nevertheless it was found necessary to calibrate after every reading in order to get accurate results. If this precaution is taken, however, it is found that the measurements are quite accurate, as shown by their reproducibility after several months.

Owing to the construction of the instrument, it was not possible to obtain an extremely high vacuum, values of pressure varying from 20 to 50 microns of mercury being the best obtainable, the usual values being between 40 and 50 microns. Careful studies will be presented in the following paragraphs of the effect of varying the vacuum, which seemed to show that a further increase of vacuum would produce no effect other than slight increase of the forces measured. No fundamental changes in the phenomena due to higher vacuum, therefore, seem to us likely.

Tests on the Iron Arc Between Fixed and Moving Electrodes

The method of adjusting the instrument to give accurate results was only gradually discovered as the result of experiments in its use. The curves of Figs. 3, 4, and 5 were among the first obtained. Nevertheless they have been included because they are suitable for the qualitative indication of certain interest-

Table I—Summary

Electrode Material		Average Current Amperes	Average Pressure Microns	R.M.S. Velocity in Cm/Sec: Cosine Dist.	R.M.S. Velocity in Cm/Sec: Maxwellian Dist.	Observer
Cathode Stream Summary						
Copper	(Cu)	11–32	0.2	6.73×10^4	1.04×10^4	*A*
		14–18	0.2	8.73×10^4	1.35×10^4	*A*
Copper	(Cu)	20	0.2	1.60×10^4	2.48×10^4	*B*
				1.32×10^4	2.04×10^4	*B*
Silver	(Ag)	166	.45	6.28×10^4	9.7×10^4	*C*
Aluminum	(Al)	110	.58	4.50×10^4	6.95×10^4	*C*
				1.19×10^4	1.84×10^4	*C*
Gold	(Au)	53	.90	2.65×10^4	4.06×10^4	*C*
Carbon	(C)	73	.42	2.32×10^4	3.58×10^4	*C*
				1.12×10^4	1.73×10^4	*C*
Cadmium	(Cd)	43	.66	1.06×10^4	1.64×10^4	*C*
Copper	(Cu)	115	.80	8.09×10^4	1.25×10^4	*C*
Iron	(Fe)	142	.80	5.70×10^4	3.80×10^4	*C*
Magnesium	(Mg)	55	.45	1.77×10^4	2.74×10^4	*C*
Molybdenum	(Mo)	135	.35	1.76×10^4	2.72×10^4	*C*
Tin	(Sn)	60	.61	0.77×10^4	1.19×10^4	*C*
Zinc	(Zn)	57	.56	3.44×10^4	5.31×10^4	*C*
Anode Stream Summary						
Copper	(Cu)	120	.50	8.22×10^4	1.27×10^4	*C*
Iron	(Fe)	106	.60	6.54×10^4	1.01×10^4	*C*
Tungsten	(W)	145	.40	7.68×10^4	1.19×10^4	*C*

Observer: *A*—Tanberg; *B*—Berkey and Mason; *C*—Easton, Lucas, and Creedy

ing phenomena. Unfortunately, time did not permit a repetition of these tests after the instrument and the operating technique had been perfected.

It is shown in Fig. 3 that deflection of the instrument is independent of the arc length. Because of this, it was found possible to take observations at zero arc length, and thus, by touching the electrode tips together and throwing the high current on directly, to obviate the need of high potential for starting. In Figs. 4 and 5 the deflections produced by different currents are shown. In the tests leading to Figs. 3, 4, and 5, the pressure in the instrument corresponded to about 5 mm of mercury.

It must be emphasized that Figs. 4 and 5 show early observations of *deflection* against current. Separate calibration checks for each point were not made at this stage of the work. Therefore, a curve of *force* against current in which the scattering would be much less, has not been included. The curves drawn in these 2 figures pass through the upper limits of the observations since later tests showed that most of the low readings were caused by improper laboratory manipulation. These curves show the trend of the forces under consideration but are not to be considered as quantitatively correct. With this understanding we are entitled to make the following conclusions of a definite character.

1. Force is produced whether the anode or the cathode is stationary.

2. With the anode moving, the force is much smaller for low currents than with the cathode moving. Hence it is easily understood that the anode force might be overlooked if experiments were made with small currents only.

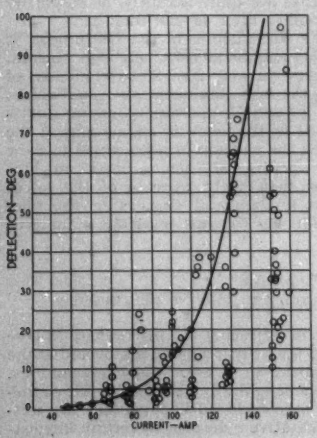


Fig. 4. Deflection versus current with moving electrode positive

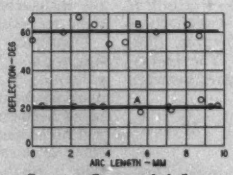


Fig. 3. Curves of deflection versus arc length with constant current

A. Moving electrode positive. 110 amp
B. Moving electrode negative. 150 amp

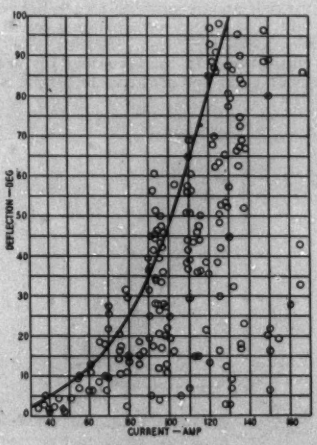


Fig. 5. Current versus deflection with moving electrode negative

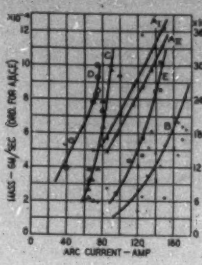
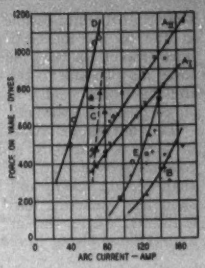


Fig. 6. Curves of current versus mass of metal condensed on vane. Constant pressure

A. Copper cathode. Pressure = 50 microns
B. Tungsten anode. Pressure = 40 microns
C. Carbon cathode. Pressure = 42 microns
D. Zinc cathode. Pressure = 56 microns
E. Copper anode. Pressure = 50 microns

Fig. 7. Curves of current versus force on vane. Constant pressure

A. Copper cathode. Pressure = 50 microns
B. Tungsten anode. Pressure = 40 microns
C. Carbon cathode. Pressure = 42 microns
D. Zinc cathode. Pressure = 56 microns
E. Copper anode. Pressure = 50 microns



3. With large currents the forces in the 2 cases are of quite the same order though not equal.

These conclusions are similar to those which might be reached after a consideration of the curves shown in the previous paper (A.I.E.E. Trans., v. 51, 1932, p. 556–63). In vacuum, however, the forces were much greater than those in air.

Tests on Velocity of Vapor Stream

After the apparatus had been improved, a number of tests were run to determine the velocity of the vapor stream emitted by electrodes of various metals. The tests on copper, iron, tungsten, carbon, and zinc were completed early in 1933. In the following pages they are described in detail. Several months later, other metals were investigated. Brief reports on these follow after the first series. The final curve (Fig. 11) shows all the cathode stream velocities, computed on the assumption of a Maxwellian velocity distribution, plotted against melting point of the electrode material. Table I shows at a glance the results of our work together with those of Tanberg and of Berkey and Mason. Our velocities are given in 2 values, one calculated on the assumption of a cosine distribution of normal velocity, and the other on the assumption of a Maxwellian velocity distribution. All velocities mentioned in the text are computed as with a Maxwellian distribution to facilitate comparison with the results of the others.

Under the assumption of a cosine distribution of normal velocity, the velocity is calculated from the formula

$$V = \frac{2\sqrt{2}}{\pi}\frac{K}{m} = 0.9\frac{K}{m}$$

where

K is the force against the vane in dynes
m is the mass of metal condensed in grams per second
V is the root mean square velocity (normal to the vane) of the particles in the arc stream in centimeters per second

The coefficient 0.9 is based upon the assumption that all arc particles proceed from the electrode, each with the same velocity; that they travel away from the electrode in all directions (but not with uniform distribution) so that particles leaving the electrode at any instant will lie on a hemisphere at a later instant; that they all travel in a straight path. The so-called Maxwellian distribution of velocity is obtained by substituting 1.39 for 0.9 in the above formula (R. Tanberg, *Phys. Rev.*, v. 35, 1930, p. 1080–9). This assumes that all directions of velocity are equally probable and that every particle has the same mass.

There will naturally be criticisms of any choice of distribution. Probably neither the cosine distribution nor the Maxwellian distribution is correct. Both results include the questionable assumption that all impinging particles adhere to the vane. Neither satisfactorily accounts for the effect of electric or magnetic fields on the particles. Neither makes any distinction between forces due to metal particles and forces due to gas given off by the electrode. In the absence of real knowledge as to the nature of the arc stream, the most important thing is to determine, if possible, a definite relation between the velocities of the streams between different metals, all calculated in only one way. Our results indicate a relation. They do not and cannot at the present state of our knowledge give an exact quantitative picture of the phenomena.

Tests on the Copper Arc

(Most of the conclusions of this section were derived by E. C. Easton.)

As in all tests concerning vapor stream velocity, a glass vane, substituted for the moving electrode K as described previously, was set up about 2 cm in front of the electrode P from which the vapor stream was to be emitted. The arc was struck by contact between P and Q (Fig. 1). The pressure in the tank during each test was measured on a McLeod gauge, while the mass of metal condensed on the vane was measured to 0.01 mg on a bullion balance.

A vapor stream was found to come from both the anode and the cathode, although the anode stream was not noticeable until currents of over 40 or 50 amp were used.

The following sections present curves of current against mass of condensed metal, current against force on vane, current against velocity of stream, and velocity of stream against pressure in the tank. It was not always possible to direct the vapor stream at the center of the vane, although, of course, an attempt was made to do so. Thus some variation both of the mass of the metal and of the observed force should be expected. It is obvious in all these

tests that it is impossible to be sure that all the force is due to the material deposited. Some material may drop off the vane before being weighed, and some force may be due to the emission of gas occluded in the electrodes. The results must always be read subject to this reserve.

The curves for copper are curves *A*I and *A*II in Figs. 6, 7, and 8, and curve *A* in Fig. 9. The copper arc was found to be considerably more stable than certain others and thus the curves for copper show less scattering than do similar curves for other materials where the arc could not be so readily manipulated owing to reduced stability.

Curves for Cathode Stream

Both the data for current against mass and current against force (curves *A*I and *A*II in Figs. 6 and 7), permit the drawing of 2 curves. Thus for current against mass 2 smooth curves can be drawn, each of which includes about half the observed points. Likewise there are 2 smooth curves for current against force. If the curves marked by the same Roman numeral, that is, I and I or II and II, be taken together, the resulting velocity curves (*A*I and *A*II, Fig. 8) pass directly through the observed velocity points. There are apparently 2 conditions under which the copper arc may exist, each condition being marked by a different velocity of the cathode stream. That the double curves are not due to variation in the position of the vane with respect to the arc is indicated by the fact that 2 distinct velocity curves appear. Were the possibility of 2 curves of current against mass merely a coincidence occasioned by variation in the position of the vane, there should have been, assuming only one arc condition, a corresponding disposition of the curves of current against force. In this case the lower mass curve would be taken with the lower force curve, and the 2 sets of curves would lead to the same velocity. In the actual tests, however, the observed velocities show that 2 conditions exist and that the lower mass curve must be considered with the higher force curve, and *vice versa*.

The curve of velocity against pressure (*A*, Fig. 9) taken at an average current of approximately 150 amp, shows that the velocity of the cathode stream

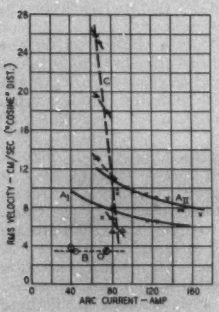
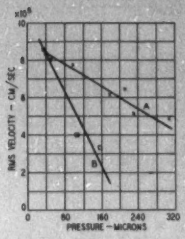


Fig. 8. Curves of current versus velocity. Constant pressure

A. Copper cathode. Pressure = 50 microns
B. Zinc cathode. Pressure = 56 microns
C. Carbon cathode. Pressure = 42 microns

Fig. 9. Curves of pressure versus velocity. "Cosine" distribution assumed

A. Copper cathode. 150 amp
B. Copper anode. 135 amp



decreases with increase in pressure. The data show that the mass of condensed metal varied very little with the pressure while the force on the vane fell off as the pressure increased.

By extrapolation to a current of 20 amp and a pressure of 0.2 micron, the values obtained for the velocity of the cathode stream are 2.41×10^6 and 3.48×10^6 cm per second. Working at a pressure of 0.2 micron and with currents ranging from 14 to 18 amp, Tanberg found a velocity of 1.35×10^6 while Berkey and Mason ("High-Velocity Vapor Stream in the Vacuum Arc" by R. C. Mason, A.I.E.E. Trans., v. 52, 1933, p. 245–8) working under the same conditions found a velocity of 2.48×10^6 cm per second. In these tests each investigator measured the velocity by the method of force on the vane, essentially the same method as used in our work. By different methods these same investigators found velocities of 1.04×10^6 and 2.04×10^6 cm per second, respectively. Using the force on vane method, Berkey and Mason report that their observed velocities ranged from 1.62 to 3.7×10^6 cm per second "with not very great accuracy." It would be interesting to know whether their scattered points could not have been better combined into 2 distinct velocities. It would also be worth while to know the range of variation in Tanberg's work. All these results seem to indicate 2 conditions of stability in the copper arc. However, because of the great difficulty of making accurate measurements, and because of failure to find a definite indication of a similar state of affairs in a few tests on arcs of other metals, we do not feel justified in announcing definitely the discovery of 2 possible conditions of stability.

If the velocities observed over a current range of 80 to 160 amp be averaged, a velocity of 1.25×10^6 cm per second at 50 microns is obtained. If this velocity be translated to a pressure of 0.2 micron it becomes 1.29×10^6, close to Tanberg's value of 1.35×10^6.

Curves for Anode Stream

A discovery of considerable interest brought out by this investigation is that a high speed vapor stream is emitted from the anode. All previous arc theory has denied the possibility of such a condition.

With the anode, the condition of dual stability was not observed, although the small number of points taken does not constitute the basis for any

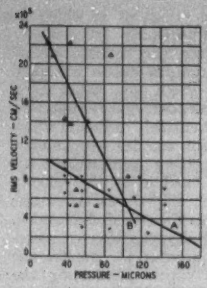


Fig. 10. Curves of pressure versus velocity. "Cosine" distribution assumed

A. Tungsten anode
B. Carbon cathode. 73 amp

definite conclusions. The velocities observed were apparently independent of the current, and had a mean value of 1.27×10^6 cm per second at a pressure of 50 microns. Curves of current against force and mass as well as of pressure against velocity are given in curves E of Figs. 6 and 7, and B of Fig. 9.

Inspection of the electrodes showed that while some change in the shape of the ends had taken place, there was very little boiling of either electrode. In all experiments the quartz tube surrounding electrode Q (Fig. 1) was so proportioned as to screen the vane from any particles which that electrode might emit.

The curve of force against current shows that for low current values the force is almost unobservable. Future investigators of this phenomenon will have to resort either to much more sensitive measuring devices or to large currents and short time intervals if this vapor stream is to be studied accurately.

Tests on the Tungsten Arc

The electrodes used in the tungsten tests consisted of a bundle of 5 $^1/_{16}$ in. pure tungsten rods held in place in a piece of Vitreosil tubing. When both electrodes were of tungsten it was found impossible to strike the arc in a vacuum. Because of difficulties in striking the arc satisfactorily even with anodes of other materials, tests on the tungsten arc were limited to a study of the anode stream using a tungsten anode and copper cathode.

In order to make sure that none of the cathode material was striking the vane, a chemical analysis was made of the metal condensed on the vane. The analysis showed that copper was not present.

Curves of current against force and mass as well as of velocity and pressure are shown in B of Figs. 6 and 7 and A of Fig. 10. The curves of current against force and mass show the velocity to be independent of the current. The mean velocity of the anode stream is 1.19×10^6 cm per second at a pressure of 40 microns and average current of 145 amp. The velocity diminishes with increase in pressure.

Tests on the Carbon Arc

Because of lack of time, tests on the carbon arc were limited to a study of the cathode stream. The electrodes used were 0.25-in. solid carbon arc-lamp electrodes. The various curves are shown as C in Figs. 6, 7, and 8, and B in Fig. 10.

The observed velocities varied from 8.5×10^5 to 4.0×10^6 cm per second at a pressure of 42 microns within a current range of 60 to 80 amp. At an average current of 73 amp the observed velocities appeared to be divided into 2 groups. Taking the average of each of these groups the 2 values 1.73×10^6 and 3.58×10^6 cm per second are obtained. These are the 2 values for carbon shown on Fig. 11. Apparently there may be at least 2 conditions of stability with carbon. The velocity apparently decreased as the pressure rose but the observed points are so scattered that no definite slope can be assigned to the curve.

Tests on the Iron Arc

Tests on the iron arc were conducted with electrodes made up of a bundle of 4 $^1/_8$-in. iron rods held in Vitreosil tubing. The rods were of pure iron (kindly supplied by Prof. G. E. Doan) with a gas content of approximately 0.07 per cent oxygen, 0.001 per cent hydrogen and no nitrogen.

Cathode Stream Tests

The observations with iron are very much scattered and therefore curves have not been included. The variation in velocity from 5.41×10^5 to 1.05×10^6 cm per second in a current range of 120 to 160 amp suggests the possibility of several conditions of stability. A few readings at high pressures indicate that the velocity decreases with rise in pressure. At an average current of 142 amp and pressure of 50 microns, the weighted mean of the velocity of the cathode stream is 8.8×10^5 cm per second.

Anode Stream Tests

A few points taken with the anode stream showed a velocity variation between 1.47×10^5 and 1.19×10^6 cm per second at an average pressure of 60 microns and current of 106 amp. Most of the points lay between 7.91×10^5 and 1.19×10^6. Discounting the other observations, the average velocity under the stated conditions is 1.01×10^6. Because of the few points taken, no curves are given for the anode stream.

It is interesting to note that the first 3 readings taken on the anode stream were smaller than those which followed. The same phenomenon was ob-

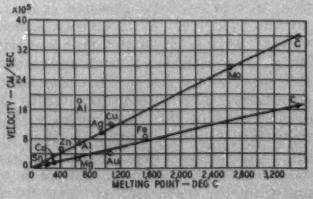


Fig. 11. Curves of cathode stream velocity versus melting point. Maxwellian velocity distribution assumed

served in connection with the first few readings on the cathode stream. It appears as though the electrodes must form in some way which alters the velocity of the emitted stream. The electrode formed as the cathode apparently had to be reformed when used as anode.

The pure iron arc was difficult to strike in vacuum, a starting current of 35 amp being necessary. This high starting current probably introduced some error due to the condensation of metal from the starting arc which was not included in the timing of the actual high current shot.

Cathode Stream Tests on Zinc Electrodes

The electrodes used were 0.25-in. chemically pure zinc rods. Tests on the cathode stream indicated the necessity of "formation of the electrode." Although the electrode from which the stream was emitted had been in use as anode and was not touched when the polarity was shifted, the first 2 velocities observed from the cathode were lower than any which followed. The mass of condensed metal was relatively larger for the first 2 shots. The results are shown in *D* of Figs. 6 and 7 and *B* of Fig. 8.

The velocity for a fixed pressure appears to be constant, no double condition of stability being apparent. The average velocity at a pressure of 56 microns and current of 57 amp is 5.31×10^5 cm per second.

Later Tests on Other Metals

Tests were later conducted to determine the velocity of the vapor stream emitted from the cathode of an arc between electrodes of the following metals: molybdenum, aluminum, silver, tin, cadmium, gold, and magnesium. The electrodes varied in form as follows: molybdenum, bundle of 3 $^1/_8$-in. rods; silver, 0.25-in. rod; tin and cadmium, $^3/_{16}$-in. rods; gold, roll of $^1/_{32}$-in. sheet about $^3/_{16}$-in. diameter; magnesium, bundle of several thin strips about $^3/_{16}$-in. thick.

These experiments brought into relief some possibilities of error in earlier experiments which had not previously been considered. Tests on the cathode stream using low melting point metals showed that a large amount of vapor surrounds the vane, as ample deposits were observed on the back of the vane holder and on portions of the tank shielded from the direct stream from either electrode. The discovery of this large amount of vapor in the region of the vane led to the conclusion that a Maxwellian velocity distribution would be more fitting than our previously assumed cosine distribution of normal velocity. With copper, which gave off little vapor, the deposit on the vane was seen to be strongest at the center while none appeared on the back of the vane. This led to the adoption of a cosine distribution. The subsequent tests showing metal on the rear of the vane indicate that a cosine distribution which permits velocities in one direction only cannot be entirely correct, and suggest the Maxwellian distribution. There is good reason to question the existence of this distribution but it seems more correct for the pressures at which we worked than the cosine distribution.

In an attempt to measure the cathode stream velocity of tungsten, a cadmium anode was used with a tungsten cathode. With this arrangement the arc struck easily. The deposit on the vane was, however, found to be almost entirely cadmium which had come from the shielded anode. Apparently, then, especially with low melting point metals, the weight of condensed metal used in all the velocity calculations must have been slightly excessive due to condensation of metal from the shielded electrode. This means that all our velocity readings are somewhat low, the error being greater the greater the relative amount of metal vapor permeating the region of the vane.

On the accompanying curves of cathode stream velocity against melting point of the cathode material (Fig. 11) the metals seem to be divided, those which gave off relatively large deposits lying on the lower curve. Zinc, however, lies on the upper curve although it gave off large amounts of vapor. So far all attempts to show that all points should fall on one curve have failed. It will be noticed that 2 points are given for aluminum. The 2 values represent observations on 2 different samples. A bundle of 3 $^1/_8$-in. rods of pure aluminum gave a velocity of 1.84×10^6 cm per second while a 0.25-in. rod of aluminum wire of unknown composition gave 6.95×10^5.

The phenomenon of decreasing velocity with increasing pressure is probably due to a change in the velocity distribution, the directions of the velocities at the vane becoming more haphazard as the pressure increases (assuming the arc particles to be of the size of molecules). Only a few readings were taken on each of the metals tested. The velocities herewith presented may be somewhat in error for that reason.

The conclusion reached from these observations is that the velocity of the cathode stream may be proportional to the melting point of the cathode material, this conclusion being, of course, drawn with reserve due to the known possibilities of error and difficulty of obtaining accurate results.

A check test on the copper electrodes used in the earlier tests gave a cathode stream velocity in the range of those observed several months previously and thus showed that our apparatus gave fairly consistent results.

Thermal Origin Indicated

Reviewing the evidence it seems that a thermal origin for these streams of particles is irresistibly indicated rather than an electric mechanism of the type suggested by K. T. Compton and others. The belief in a thermal origin is chiefly supported by the fact that these streams of particles come both from the cathode and the anode. It has been suggested that at a sufficiently high vacuum the anode spot would become so large that the anode would no longer be heated and the stream of particles would therefore cease. If this should prove to be the fact, it would of course only strengthen the belief that these phenomena are of thermal origin.

Diesel Electric Rail Cars and Locomotives

Gasoline and Diesel electric equipment used for motive power on rail cars and locomotives is considered in this paper. The more important problems such as the securing of a suitable method of drive for Diesel electric locomotives are considered, especially for heavy railway work. A comparison of Diesel electric with steam and with electric locomotives is given, and possible future developments are indicated.

By
N. W. STORER
FELLOW A.I.E.E.

Westinghouse Elec. and Mfg. Co., East Pittsburgh, Pa.

THE internal combustion engine has become a tremendous factor in the everyday life of the American people. With more than 26,000,000 automobiles in this country alone, to say nothing of the streams of trucks and buses which are found on the highways, the sum total of the potential power of these small gasoline engines is at least 10 times that of all the steam locomotives in the country. Little wonder then that the railroads feel the competition, for all of these engines are used in transportation work of one kind or another.

With the gasoline engine constantly before them, the Diesel engine making progress with the cheap fuel oils, and the success the railroads have had with both the gas and Diesel rail cars and locomotives, it is natural that the executives should look to these same agencies to help them out of their difficulties still further. We are apparently on the verge of a large development in this field.

The use of gasoline engines on the railroads for light cars dates back to the early part of this century. Quite a number of cars with mechanical drive were built for local service on Western railways. A number of others were built with electric drive, but the cost of gasoline and other factors were such as practically to stop the development before the war broke out. After the war, however, it began again with renewed vigor, first with modified gasoline buses adapted for running on rails. These, of course, had the standard automobile or truck type of drive. They gradually grew into the standard railway type of passenger car, first with mechanical drive, then as the size of engines increased, with electric drive, which is now practically universal.

Full text of a paper presented before the Institute's Cleveland, Ohio, Section, March 13, 1934, and recommended for publication by the A.I.E.E. committee on transportation. Manuscript submitted Apr. 25, 1934; released for publication May 31, 1934. *Not published in pamphlet form.*

Widespread Use on Rail Cars and Locomotives

The use of gasoline and Diesel electric rail cars has grown to quite large proportions, considering the times. There is scarcely a railroad of any size that has not one or more in service. The engine has grown from the early beginnings with 75 or 100 hp until there are now cars in operation with 800 or even 900-hp engine capacity, either with single or double power plants. The latest development, of course, is the high speed streamlined train that is expected to revolutionize rail passenger service. This is at present in more or less of an experimental stage and there is no telling how far its influence will extend, but the interest displayed in it and the number of trains built and on order insure that it will have a thorough tryout. It seems to be the refutation of the old idea that the Diesel engine is good for slow or possibly moderate speeds but too heavy for high speeds.

The Diesel engine is making rapid progress in locomotives as well as in rail cars. It has won a very strong position in switching service with engines of 300-hp to 800-hp capacity. Few locomotives of larger than 1,000 hp have thus far been built. The Canadian National locomotive with articulated cabs, each with one 1,330-hp high speed Diesel engine, is still the largest built, but it will not be long now until larger locomotives driven by Diesel engines will have been constructed.

Problems in Application for Heavy Railroad Work

There are many problems connected with the use of internal combustion engines for heavy railroad work:

1. *The Engine.* The engines must be developed in large enough units, of small enough dimensions, light enough, reliable and satisfactory in every way so that the locomotives driven by them will have advantages that will outweigh the increased cost over steam locomotives. The question of engine design, however, will not be taken up in this paper as it is a very large subject in itself, which is being ably handled by engine builders.

2. *The Drive.* The perfect engine may be designed and built, but it is of little use in a locomotive without a satisfactory means of transmitting the engine torque to the driving wheels. The electric drive with a generator driven by the engine furnishing current with variable voltage to electric motors geared to the drivers, is generally accepted as the best system that can be devised, but some engineers see in it a round-about and inefficient way of getting the power to the wheels. They yearn for what seems to be a more simple means such as some unknown mechanical drive. This has been fairly well discussed many times before, but at the risk of being tiresome will be considered briefly in this paper.

3. *Control.* The engine may be perfect, and the generator and motors 100 per cent good, but the locomotive will not be up to its possibilities until it is equipped with a control system that will not only be perfectly smooth in its application of power to the locomotive, but will whenever it is needed utilize every bit of power the engine can develop without overloading it.

4. *Auxiliaries.* There are many auxiliaries on a locomotive that are of vital importance in the performance of the locomotive, many of which require power for various purposes: engine starting, air compressors, blowers or fans for cooling radiators for engine oil and

water, blowers for cooling motors on large locomotives, and pumps for oil and water. Power for all these purposes should be furnished by the engine, which is the sole source of power. Passenger locomotives will probably also have a boiler for train heating which may, as in the case of the one on the Canadian National Railroad, be equipped with an economizer to save the heat in the waste gases from the engine.

The Drive

A typical speed-tractive effort curve for 2 1,500-hp Diesel driven locomotives is shown in Fig. 1. The first is a curve or series of straight lines connected together, marked 1, showing the speed and tractive effort for a 1,500-hp engine with a 4-speed mechanical drive; and second, a curve marked 2, showing the speed-tractive effort that would be developed with the best electric drive. There is also a curve showing the full output of the engine translated into speed and tractive effort with 100 per cent efficiency. Comparison between this curve and the ones below it, shows the loss in power due to the drive either by inefficiency or by inability to run the engine at full speed.

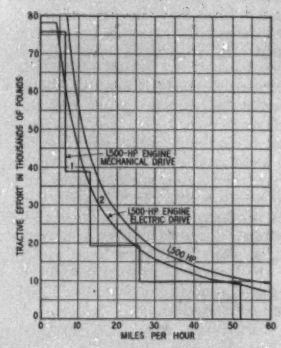


Fig. 1. Comparative performance of Diesel engine locomotives with different drives

1. 4-speed mechanical drive
2. Electric drive

The efficiency of the mechanical drive is assumed to be 85 per cent at the low gear, 88 per cent on the second, and 90 per cent on the 2 higher speeds. Considering the fact that a clutch, one or more gear reductions, jack shaft and side rods will be necessary with this type of drive, it is felt that these efficiencies are liberal. The efficiency of the electric drive is calculated to be 60 per cent with maximum tractive effort, reaches a maximum of 85 per cent at about 20 mph, and holds that value over the remainder of the speed range. This efficiency is not up to the maximum assumed for the mechanical drive, but the average power available at the wheels is much greater, as will be seen in Fig. 2, which puts the same facts developed by Fig. 1 in a different form. This shows the horsepower available at the wheels over the entire range of speed, first with the 4-speed mechanical drive, and second with the electric drive.

From this it will be noted that the average horsepower available over the range of speed from 10 mph up with the mechanical drive is about 1,000 hp, while with the electric drive it is about 1,250 hp, the electric being at least 25 per cent higher than the mechanical drive. This shows plainly that to have the same average horsepower available at the wheels with a mechanical drive would require an engine 25 per cent larger than with the electric drive. Even then the control would not be smooth with a single engine, as power would have to be cut off while changing from one gear ratio to another; this has inevitably in the past been productive of broken couplings, etc. It is essential, therefore that there be at least 2 engine units so as to maintain a drawbar pull at all times by changing one at a time. This is a time waster.

The question of clutches is also very important. The best clutch is, of course, an electric clutch, but even with the advantage of that clutch it is hard to see how the Diesel powered locomotive can be particularly successful with mechanical drive with the huge engines that are required. With a solid connection between motor shaft and driving axles the whole system would be subject to severe shocks. The engine could seldom be worked up to its full torque without danger of stalling it, since its torque would have to equal or excel the requirements of the train at all times. The foregoing shows clearly the necessity for a larger engine if a geared mechanical drive is used. A hydraulic or some efficient drive with a large number of speed ratios might change the picture somewhat.

Comparison of Diesel Electric With Steam Locomotive

It is interesting to study the Diesel electric locomotive in comparison with one driven by steam. An excellent analysis of this is given by A. H. Candee in "Performance of Diesel Locomotives," an article in the *Railway Age*, Dec. 2, 1933, p. 789–90. In this article is compared the performance in switching service of a steam locomotive with an output of 1,220 hp and a weight on drivers of 111 tons, with a Diesel electric locomotive with an engine capacity of 800 hp and a weight on drivers of 115 tons. The Diesel electric locomotive has a higher tractive effort at low speeds due in part to the heavier weight on drivers but much more to its uniform torque as compared to the pulsating torque of the steam locomotive. The curves shown indicate that the Diesel electric has a decided advantage in acceleration due to this fact, which enables it to gain distance up to a speed of 8 or 10 mph. It is therefore well ahead when those speeds are reached. The speed curves show that the 2 locomotives will give equal performance for runs varying from 740 ft with a load of 500 tons to 1,620 ft with a load of 2,000 tons. Above those distances the advantage is with the steam locomotive. On shorter runs the advantage is with the Diesel electric locomotive. To equal the performance on longer runs the Diesel electric locomotive should have the same horsepower available at the wheels as the steam locomotive.

Comparison of Diesel Electric With Electric Locomotives

In connection with this subject, it may be well to mention the idea, which has gained some ground, that the development of the Diesel electric locomotive will put a damper on the progress of the electrification of railways. The contrary is likely to be the case. The introduction of Diesel electric locomotives on steam railroads will educate the operators in the advantages of electric propulsion. There will be no quarrel between the straight electric and the Diesel electric locomotive. Each will be applied in the place where it is most economical. Regarding the advantage of the electric over the Diesel electric locomotive in heavy service, Fig. 3 shows comparative curves of the 1,500-hp Diesel electric locomotive indicated in Figs. 1 and 2, and a trolley fed electric locomotive equipped with identically the same motors as the Diesel electric locomotive. The electric locomotive will have the same maximum tractive effort and the same maximum speed as the Diesel electric, the only difference being that the maximum voltage is available on the trolley at all tractive efforts. The comparison is quite startling as it shows that at the maximum tractive effort where the Diesel electric locomotive has a speed of 4.3 mph, the straight electric locomotive may reach a speed of 21.25 mph—practically 5 times as great. With lower tractive efforts the speed of both locomotives increases, but while the Diesel electric locomotive speed increases at a more rapid rate, it does not reach the same speed as the electric locomotive until the tractive power has fallen from 78,000 lb down to 10,500 lb at 45 mph.

In Fig. 4 these curves are put in a different form, plotted in terms of horsepower and speed; this figure shows the maximum horsepower available on the electric locomotive to be about 4,400 at maximum tractive effort as compared with a maximum of 1,275 on the Diesel electric locomotive available from about 24 to 52 mph. The average horsepower of the electric locomotive is much larger and is good evidence of the advantage of having a central station with unlimited power back of the motors on the locomotive. It gives a much higher rate of acceleration and higher speed on grades than is possible with a constant or limited output locomotive.

Motor Capacity

The question naturally arises in one's mind on noticing such figures as just given, as to why it is necessary to equip the Diesel electric locomotive having only 1,500-hp capacity in the engine, with motors which are able to carry, even for a short time, a load of 4,400 hp. The answer is simple. The current capacity of the locomotive driving motors is fixed by the tractive effort required. The voltage is determined by the maximum speed required with full engine output. These 2 conditions, together with the range of speed over which the continuous load is required, are the ones which determine the size of the motor. Of course, the high voltage and the high currents are never applied to the motor simultaneously on the Diesel electric locomotive as they are with the trolley fed motors, but the weight of material is nearly as much as if they were to be so applied.

It is further desirable to have larger motors than are necessary to handle simply the engine output at one speed. The motors, in order to utilize the full output of the engine over a range of locomotive speed from the minimum to the maximum, should be large enough to carry this load continuously over a considerable portion of the speed range. For that reason it is customary with the Diesel electric locomotive to rate the motors at a voltage considerably below the maximum which they receive from the generator. In the case, for instance, of the locomotive for the Canadian National Railway equipped with 1,330-hp motors, the motors can carry the full tractive effort obtainable at 10 mph at their one-hour rating. They will operate continuously from 17.5 mph up to 50 mph with all the power the engine can give them. The increase in speed from 17.5 up to 26 mph is obtained by increasing the voltage of the generator. From 26 mph up to 50, the motors are operated at constant voltage but with weakened fields, there being several steps in shunting the fields.

With the Diesel electric where the power is limited to practically the rating of the engine, it is quite essential that the motors as well as the generator be of maximum efficiency so as to transmit the maximum percentage of power to the wheels. The size of copper in the windings of these motors and generators is of special importance when it comes to heavy loads. Since the copper loss increases as the square of the current, while the power input to the generator remains constant, the copper loss in percentage also increases as the square of the current.

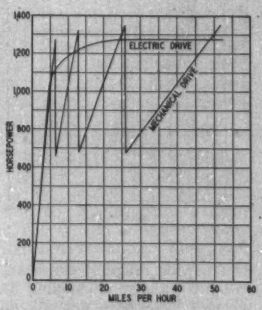


Fig. 2. Comparison of horsepower available at wheels with 1,500-hp Diesel engine locomotives, with different types of drive

1. 4-speed mechanical drive
2. Electric drive

Generator

The generator for a Diesel electric equipment is materially larger than one which would be used for the same engine located in a power house delivering current to a constant voltage network. The power house generator, for instance, would have as its

maximum current the amount necessary to give the output with the engine delivering its rated load and with a normal line voltage. The continuous rating would scarcely be more than 85 per cent of this maximum so that the rating of a generator in horsepower would be not more than 80 per cent of the engine rating. The generator for the locomotive, on the contrary, would be materially larger as it must be able to load the engine to its full rating over a considerable range of voltage besides carrying very heavy loads at starting. The generator in fact must be able to carry the current required for the motors which as has just been shown, are necessarily large for the engine capacity. Series-parallel control will make a material reduction in the generator capacity in a class of service such as switching or on cars where very frequent stops are made. Otherwise the generator must be able to carry the same currents that are supplied to the motor circuits.

Control

There have been a great many schemes of control suggested and tried on gas and Diesel electric cars and locomotives. The one fundamental aim of practically every engineer who has worked on the problem has been to obtain a simple equipment that will automatically load the engine to its full capacity

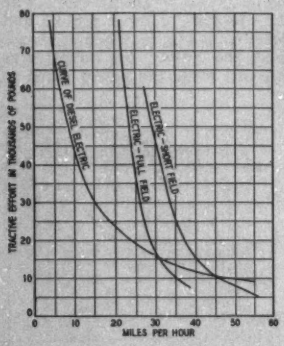


Fig. 3. Comparative performance of 1,500 - hp Diesel electric locomotives and electric locomotives, both having identical motors

over a wide range of car speed and tractive effort without danger of stalling it. Many ingenious schemes have been devised, all of which may be divided into 2 general types:

1. Those which rely on the inherent characteristics of the generator or generator and exciter; and,

2. Those which rely on minute variations of engine speed to make the generator torque conform to that of the engine.

Control Schemes Depending Upon Engine Characteristics

There are many schemes of the first kind. One of the best was described by N. L. Freeman in a paper "Control Systems for Oil and Gasoline Electric Locomotives and Cars," A.I.E.E. Trans., v. 49, 1930, p. 1262–8. This scheme uses a specially designed exciter with 2 of its 6 poles having a differential series winding so proportioned as to give the generator curve a very close approximation to that of the engine and thus load the engine to its full capacity while covering a considerable range of current and voltage. This is a simple scheme and so far as performance is concerned is quite satisfactory in most respects. However, it does not and cannot load the engine under all conditions of temperature, altitude, and engine variations. There are many variables which affect the output of a gasoline or Diesel engine. If any of these limits the torque, the engine will slow down and its output will be correspondingly reduced. When the windings of the generator are cold the generator will be loaded to a much higher torque at any given speed and current, which, in turn, will pull down the speed even if the engine is in perfect condition. These are well known characteristics of any scheme depending upon inherent regulation of the generator and exciter for loading the engine. Some schemes such as the one described, have characteristics which reduce the load very rapidly as the speed falls, so as to acquire a balance with a relatively small reduction in speed, but they can never develop the maximum horsepower-hours from the engine in a given time.

Torque Control Scheme

In the same paper, Mr. Freeman described the best known scheme of the second type, the "engine torque control" system. This depends upon variations in engine speed from its fixed rate to furnish the regulating impulses that make the torque required by the generator conform to that developed by the engine.

In the torque control scheme, the slightest decrease in speed, no matter what the torque of the engine may be, results in an instantaneous reduction of load by the introduction of resistance in the field circuit. On the contrary, an increase in speed cuts the resistance out of the circuit. The scheme adopted works very quickly, and the resistance is cut into the circuit and out again very rapidly so that the speed is maintained at whatever point is desired. It can readily be seen that this scheme will operate independently of the condition of the engine or the throttle opening. There are, of course, limits to its performance, but it has been known to work and maintain the speed of the engine even with 3 cylinders out of 6 cut out of service. This control will enable the generator to accept all that the engine can give it and transform it into current and voltage for the motors with its maximum efficiency.

Torque control is adapted to either throttle control of the engine or an engine with variable speed governor. The proper way to handle the throttle control is to select a certain number of speeds at which it is desirable to operate the engine. These will correspond to certain notches on the master controller. It is obvious that it is un-

necessary to operate at full speed when only a small amount of power is required, and the control can be adjusted so as to operate with the best throttle opening for each speed until the maximum throttle is reached. Then the loading above that speed will always be with maximum throttle, but with variations in speed, if desired.

The way to control an engine with a variable speed governor is to load the generator so as to keep the speed slightly below that for which the engine governor is set. The governor will then keep the throttle open as long as the generator is able to load the engine. Only when the maximum voltage has been reached and the load falls off will the governor act to cut down the throttle opening. Whenever the controller is moved to a higher speed notch, the load on the generator is momentarily decreased, which allows part of the engine torque to be used to accelerate the engine to the higher speed. The instant that is reached, the load is applied in full, and the generator again takes all that the engine can give it.

The apparatus required for this control is very simple, rugged and reliable and has been proved by several years of service. The auxiliary generator exciter is regulated for a constant voltage after it reaches a certain speed, say $^3/_4$ of the rated speed of the engine. A sensitive but very rugged relay is connected across the exciter terminals in series with a variable resistor. The slightest variation in speed affects this relay, which, if the speed has fallen, opens a contactor which inserts a resistor in the field circuit of the main generator. This, of course, lowers the voltage of the generator and consequently lowers the load, which restores the speed and the generator would run above the speed if the switch did not close again immediately. By a special connection which anticipates the change in speed, the contactor is kept vibrating at such a rate as to maintain the load constant over the full range of current and voltage until the motors can no longer use the load because of operating at maximum voltage and weakest field.

Auxiliary Operations With Torque Control

Corollary to this scheme are many possibilities for auxiliary operations. There is battery charging from a constant voltage circuit through a small resistor; also constant voltage available for operating compressor motor, blower motors, or even motors for such uses as air conditioning. The torque control also utilizes the main generator to furnish current for charging the battery and driving the auxiliary motors at idling, also as a motor for starting the engine from the battery, a scheme which has also been adapted to the differential system. It is uneconomical to design the auxiliary generator to cover the full range of speed but this is entirely unnecessary since the main generator can just as well furnish the low voltage current required at idling speed. No additional switches are required since the battery starting switches are simply closed when the idling speed is reached, and the starting series field acts as a differential winding which prevents excessive loading. With this equipment the following results are thus gained:

1. Perfect control of the generator loading to balance the power available from the engine at all times and speeds.

2. Engine starting from battery current through the main generator.

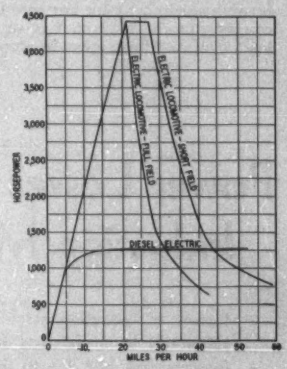
3. Constant voltage current from the auxiliary generator for battery charging and for auxiliary motors and field excitation during the operating speeds of the engine.

4. Current for battery charging and auxiliary motors from the main generator at idling speed.

The additional relay and contactor required over the control for a differential equipment are offset

Fig. 4. Comparison of horsepower available at wheels with Diesel electric locomotives and electric locomotives

1. 1,500-hp Diesel electric locomotives
2. Same traction motors supplied from trolley



by cheaper exciter and main generator. The apparatus is all rugged and reliable. The principle of the scheme is right since it depends rather upon the torque and speed of the engine than on any inherent characteristics of generator and exciter which are not constant under all conditions. One point is worthy of mention in connection with the use of this scheme for large engines. With some of these machines, the auxiliary load is quite a considerable item and is not constant. The control adapts itself incidentally to permitting the auxiliary load to come off first, and of using whatever power is left in the engine to handle the train. This intermittent load such as a compressor gives, or the motor of an air conditioning equipment, would affect any scheme of differential control seriously and make it advisable to use a separate engine for operating the auxiliaries. It is unnecessary to go to such an expense and complication where the torque control system is used.

The idea seems to prevail in some quarters that the term "torque control" necessarily includes not only control of engine loading, but all the auxiliaries. Such is not the case. Directly driven auxiliaries may be used with torque control just the same as with any other system, and the battery may be charged enough in some classes of service such as switching, if charged only in idling from the main

generator. This removes all load but the field current for the main generator from the auxiliary generator so that it becomes simply a small exciter. The control for auxiliaries is also eliminated from the electrical equipment. Therefore, before comparing this system with differential or self-excited generators, they should be put on the same basis so far as auxiliaries are concerned.

Future Possibilities

In conclusion, there is a great field ahead of the Diesel engine for railroad work unless some new development provides an engine that can do the work at a lower cost. The electrical manufacturers can furnish equipment for any size of Diesel engine that can be put on a locomotive or rail car. They can load it at all times so as to secure the most efficient use of the power available. Whether the railroads are to be electrified by Diesel electric or by central station power may be a question in the minds of some people. To anyone, however, who is familiar with the situation, the conclusion is inevitable that each one will have its own field. If, when, and as the manufacturers of Diesel engines can produce engines of 2,000 to 3,000 hp in single units, which will have a weight per horsepower of 10 to 20 lb, which will be efficient and reliable, and with dimensions suitable for mounting on a locomotive, there will be a great demand for Diesel electric locomotives, especially for lines with rather lean traffic where it would certainly be uneconomical to electrify. However, there seems to be scarcely any question or any room to doubt that it will be more economical to electrify railroads with heavy traffic than to operate them with Diesel electric locomotives.

Power Losses in Induction Machines

By
PAUL M. NARBUTOVSKIH
ASSOCIATE A.I.E.E.
Stanford Univ., Calif.

Losses in induction machines have been subjected to a detailed study by many investigators, but due to the complex nature of some of these losses, particularly several forms of load loss in induction motors, a clear understanding of their nature has not been available. Since the majority of such losses are connected with the magnetic flux in the machine, a study of the distribution of magnetic flux in the stator and rotor is necessary; such a study is presented herewith. The flux losses considered are divided into 2 groups, those occurring at the fundamental frequency, and those occurring at tooth frequency.

IN THE study of the efficiency of electrical machines the knowledge of sources of power loss within the machine is imperative. Many excellent papers have been written, giving methods of determining and predetermining some particular forms of loss in induction machines, and making a substantial contribution to our knowledge of the subject. Some of the losses, however, are quite complex and do not readily yield to a mathematical treatment or to an experimental determination. This is particularly true in regard to some forms of load loss in induction motors. Before a quantitative analysis of these losses is made it is necessary to have a clear understanding of their nature. The object of this paper is to show the mechanism of various losses in induction machines, as determined from the works of various investigators.

All losses in induction machines, except friction, windage, and copper resistance loss, are intimately connected with the magnetic flux within the machine. It is obvious, therefore, that a detailed study of flux distribution is a logical way of approach to the study of the problem of losses. Caused by the changing flux, all losses can be conveniently classified into 2 groups: losses occurring at the fundamental frequency, and losses occurring at high, or tooth, frequency. Both of these groups involve a certain amount of iron losses (hysteresis and eddy current), and copper eddy-current losses. The paper will proceed with the discussion of the above 2 groups of losses taken separately.

Fundamental Frequency Losses

In the fundamental frequency losses there are included losses caused by the uniformly rotating main flux, and leakage fluxes in both rotor and stator, varying at the fundamental frequency. These losses occur at line frequency in the stator, and at

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and tentatively scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Aug. 17, 1934; released for publication Sept. 14, 1934. *Not published in pamphlet form.*

slip frequency in the rotor. The diagram of Fig. 1 (a line reproduction of a photograph of a flow of liquid, taken by Dr. W. M. Thornton, see I.E.E. *Jl.*, v. 37, 1906, p. 125–37) gives an idea of the flux distribution in the air gap and the armature of an electric machine. As can be seen from the drawing, in any point of the magnetic circuit the flux may be considered as consisting of 2 components: a radial component, and a tangential component. The radial component in the teeth and slots constitutes the greatest percentage of the total flux in the region of the maximum flux density. This component is active in producing all useful currents and voltages in the induction motor windings. The tangential component constitutes the greatest percentage of the total flux in the region of a minimum air gap flux. Because of the presence of this tangential component, the flux in the teeth and slots never dies down to zero value while reversing in direction, but varies elliptically.

In order to see in what way the losses occur the truth of the following general statements will be noted: In any volume of a conducting or magnetic (or both) material, losses of energy will necessarily be caused by any change in the pattern of magnetic flux penetrating the volume, provided the hysteresis and resistance effects in the material are not zero. The reverse statement is also true, i. e., no loss can be caused in an insulated volume of any material by moving it in a magnetic field at a uniform speed, provided the flux pattern in the volume remains the same. The truth of these statements regarding a magnetic material can be readily seen if we remember that a hysteresis loss is caused only by a change in the magnetic state of the material, the change being either in intensity or the direction of the field. In a conducting material, the change in the flux pattern causes different electric potentials to be generated in different parts of the volume. These potentials produce eddy current losses within the volume. It will be seen that a moving flux of a constant space distribution is not capable of producing eddy currents within an insulated volume, because the rate of cutting the flux is the same in this case in all parts of the volume.

In the light of the foregoing statements it can be seen that both eddy current losses and hysteresis losses are produced in the machine iron, and eddy current losses in the copper conductors, because the flux pattern changes at the fundamental frequency as the flux rotates. In regard to eddy currents in the conductors, it may be convenient to consider separately 2 mutually perpendicular components of flux: radial, and tangential. The cyclic variation in the radial component produces opposite potentials at the sides of conductors in the slots. Thus, the eddy current loss that is due to this mode of flux variation may be reduced by laminating the conductors in the radial direction. In a similar manner, the variation in the tangential component produces opposite potentials at the top and bottom of each conductor. The remedy is to laminate the conductors in the tangential direction.

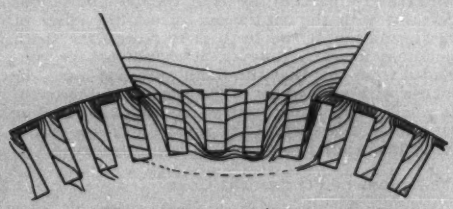


Fig. 1. Flux distribution in the air gap and in a part of armature of a salient pole machine

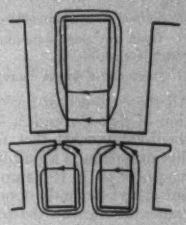


Fig. 2. Illustration of the leakage flux due to load currents

The losses described above occur at no load as well as at load. When the motor is loaded an additional fundamental frequency loss takes place. This loss is caused by leakage fluxes, as shown in Fig. 2. Surrounding each individual slot, this flux crosses the top of each slot in the tangential direction. While the current in the conductors reduces from maximum to zero value and the field disappears, the lower (internal) part of the slot is cut by a greater flux than the upper (outer) part, the difference between the 2 fluxes being equal to the flux crossing the slot when the field is a maximum. When no saturation in the iron is present, the losses caused by this leakage flux are proportional to the square of the load current, and, therefore, their effect is to increase the effective resistance of the circuit by a constant amount. With the stator or rotor slots closed by a thin iron bridge, the saturation in the latter increases the density of flux within the slot. This causes additional losses which appear with load, and which cannot be accounted for by adding a constant amount to the effective resistance of the circuit. With bar-wound stators these losses may reach a considerable value.

In low slip rotors, the fundamental frequency losses hardly amount to any appreciable value (disregarding the copper loss that is due to the main useful current), because of the low frequency of the loss producing fluxes. However, it must be pointed out that the leakage fluxes, being affected by the saturation in the iron, must have higher harmonics in them.

High Frequency Losses

Before proceeding with the discusson of the tooth frequency losses, a study of flux distribution disre-

garding the presence of copper conductors in the slots will be made. Eddy currents in these conductors set up their own fluxes, which change the flux distribution as determined by the shape of the magnetic circuit alone. This makes the problem of flux investigation more complicated.

Three modes of tooth frequency flux pulsation may be indicated which produce a certain amount of iron loss. They are:

1. Surface, or tooth tip pulsations.
2. Tooth flux pulsations (flux pulsations penetrating the whole length of a tooth).
3. Pulsations of flux in the core.

All these modes of flux pulsation constitute a variation of flux through a small cycle superimposed on the fundamental flux wave. As the cause of the flux pulsation is a pulsation of the permeance of the magnetic path, the amplitude of the high frequency pulsations depends upon the magnitude of the fundamental flux at the instant, i. e., it varies at the fundamental frequency. Considering the hysteresis pulsation loss alone, it must be pointed out that the hysteresis loop of the pulsating flux is, in general, unsymmetrical due to the presence of the fundamental flux. Furthermore, it has been shown[1] that, with an unsymmetrical hysteresis loop, the losses are relatively greater than with an ordinary symmetrical loop of the same flux amplitude. The eddy current loss caused by the high frequency flux variation shows also an effect unobserved under ordinary frequency conditions. Because of the skin effect in the iron, the eddy current loss increases less rapidly than the square of the frequency, for frequencies above 100 cycles. This influence of the skin effect relatively decreases the eddy current loss at the tooth frequency. It must be noted that, on the whole, the unsymmetrical hysteresis and the skin effect tend to equalize each other.

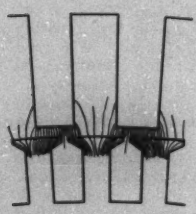


Fig. 3. Illustration of the tooth tip variation of flux density

Surface Flux Pulsations

Of the 3 manners of flux variation mentioned above, the first one is quite similar to the pole-face flux variation in salient pole machines that is due to passing teeth. It does not penetrate the whole length of the tooth, but disappears at a certain distance from the tooth tips. A rough illustration of this mode of flux variation is given in Fig. 3. It may be seen that the magnitude of the surface flux pulsations depends upon the fringing of flux in the air gap, i. e., upon the geometry of the magnetic path. Thus, the surface flux pulsations in the rotor increase with an increase in the width of the rotor tooth tip, but decrease with an increase in the air gap, because of the effect of flux fringing. At the same time a relatively narrower slot in the stator causes a smaller magnitude of surface flux pulsation in the rotor. With both stator and rotor slots closed, the flux pulsation is reduced to a minimum. With only the rotor slots closed (or semi-closed, as is commonly the practice), the surface flux pulsations in the stator are practically negligible, but may amount to a considerable value in the rotor.

Tooth Flux Pulsations

If an individual tooth is watched, whether in the stator or in the rotor, while the teeth of the opposite magnetic member are passing by, it will be noticed that the permeance of the magnetic path terminating in the tooth in question is oscillating through a definite cycle which repeats itself with every passing tooth. These oscillations of the permeance of a path terminating in a rotor tooth T are illustrated in Fig. 4; Fig. 4*a* shows a position of tooth T for the maximum permeance, whereas Fig. 4*b* shows its position for a minimum permeance. Since for a fixed average air-gap induction the magnetic potential between the rotor and the stator cores remains constant (it actually varies at a comparatively low fundamental frequency, disregarding the possible flux pulsations in the core), the variation in the permeance of the path of an individual tooth results in a similar variation of the tooth flux. This condition may be expressed algebraically as

$$\phi(R_t + R_a + R_s) = C$$

where the left hand member of the equation represents the total magnetomotive force in the cross-hatched path terminating in a single rotor tooth; ϕ is the magnetic flux in the tooth; and R_t, R_a, and R_s are the reluctances of the tooth, the air gap, and the stator teeth, respectively. Disregarding the effect of saturation, R_t is a constant, but, according to Fig. 4 $(R_a + R_s)$ oscillates at the tooth frequency. Obviously, ϕ must oscillate accordingly, in order to make the whole term constant. The magnitude of these flux pulsations depends upon the effect of slot fringing, i. e., depends upon the same factors as the surface losses. Since the fringing of flux increases with the saturation of the teeth, the tooth pulsations decrease with the saturation. Thus, the effect of the saturation of the teeth is to reduce the tooth pulsation losses. However, it should not be concluded from this that the tooth pulsation losses diminish with an increase of flux density in the teeth. It would be more accurate to say that the effect of saturation is to reduce the rate of increase of the tooth frequency losses, as the flux increases.

Pulsations of Flux in the Core

The arrangement of teeth in the stator and rotor may be such that the motion of the rotor causes

some tooth frequency variation in the total permeance of the magnetic circuit. With the ratio of rotor teeth to stator teeth markedly different from unity this variation, if any, is small, but when present it may cause the total mutual flux to pulsate. Actually, the pulsations in the total permeance of the magnetic circuit are more likely to manifest themselves as high frequency ripples in the magnetizing current than as an actual variation of the total flux. In either case, however, some loss is caused by the pulsation of the total permeance of the magnetic circuit. If this loss appears as the I^2R loss that is due to the high frequency component in the exciting current, the energy of the loss may be dissipated as heat, not necessarily within the motor, but in the line and the supply-generator conductors as well. But no matter where it be consumed, within the motor it will appear as a mechanical load on the rotor, and therefore it will always form a part of the input of the motor.

Copper Eddy Currents and Their Effect Upon the Flux Pulsations

So far an attempt has been made to describe the tooth frequency losses on the assumption that the copper conductors in the slots have no effect on the flux distribution. It is now intended to show the effect of the tooth flux pulsations upon the high frequency currents in the copper, and the mutual effect of these currents upon the magnetic flux. It has been shown experimentally[4] that the effect of the eddy currents is to reduce the amplitude of the flux pulsations, and, at the same time, to increase the power loss. Three kinds of high frequency flux pulsations which produce eddy currents in the copper conductors will now be considered in turn:

1. Pulsations of the slot leakage flux.
2. Pulsations of the tooth flux proper.
3. Pulsations of the fundamental leakage flux.

Effect of Slot Leakage Flux Pulsations

A sketch of the magnetic field of an induction motor showing the manner in which the slot leakage flux pulsates is given in Fig. 5. This drawing represents a rather typical open slot stator and a semi-closed slot rotor construction. Because of the small distance between the rotor tooth tips, the tooth pulsations in the stator are very small.

It may be convenient to consider the slot leakage flux as consisting of radial and tangential components. The amount of the radial component in the slot pattern obviously depends upon the position of the stator tooth relative to the rotor slot. When the stator tooth is directly opposite the rotor opening, the thin rotor tooth shoulders may become saturated easily, and a considerable part of the flux may penetrate the slot. Thus, at this relative position of the stator and rotor teeth the amount of the radial component of the tooth leakage flux is a maximum. When the stator and rotor teeth are in a position directly opposite each other, most of the flux passes through the teeth and only a small part penetrates the slot. Thus, at this position of the rotor and stator teeth, the radial component of the slot leakage flux is a minimum.

The tangential component of the slot leakage flux is generated in exactly the same manner as the tangential component of the fundamental frequency leakage flux. Whenever a flux density in any 2 adjacent teeth is different, the tips of the teeth are at different magnetic potentials, which causes some of the flux to cross the slot from one tooth to another. As the sign of the difference in flux density of any 2 neighboring rotor teeth varies twice during the time one rotor tooth moves one stator slot pitch, the direction of the tangential component in the slot between the teeth varies accordingly twice during that time. The pulsations of the tangential slot-leakage flux, together with the pulsations of the radial component, cause a part of the high frequency eddy currents.

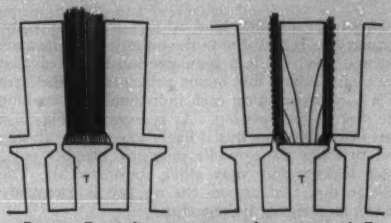


Fig. 4. Two relative positions of a rotor tooth T with respect to stator teeth, illustrating the variation of the permeance of the magnetic path which terminates in the rotor tooth

Effect of the Tooth Flux Pulsations

In a squirrel cage rotor the flux pulsation in the teeth is one of the causes of a circulating current in the short-circuited bars. Every 2 neighboring bars represent a closed low resistance electric circuit, which links with the magnetic flux in the tooth between the bars. High frequency pulsations of flux in the tooth induce high frequency pulsations in the bars, which in turn cause circulating currents. The effect of these currents is to set up fluxes of such a magnitude and direction as to oppose the flux variations producing the currents. The remaining flux pulsations in the teeth are just sufficient to induce voltage to overcome the resistance and the inductance of the bars. (An analogy is implied here between the electric curcuit in question, and a short-circuited low-voltage secondary of a transformer.) Since both the resistance and the leakage reactance of the bars are extremely low, the amplitude of the residual flux pulsations is very small.[4] Thus, at least as far as the squirrel cage rotor is concerned, the tooth frequency loss takes place not in the form of iron loss, but mostly in the form of copper resist-

4. For all numbered references see list at end of paper.

ance loss in the bar windings, due to eddy and circulating currents.

In a wound rotor, especially if the rotor conductors are comparatively small, the damping effect of the tooth frequency currents is not so pronounced as in a squirrel cage rotor, and the tooth frequency iron loss is probably an appreciable item.

Pulsation of the Main Leakage Flux

One more possible kind of high-frequency eddy-current loss is that due to the pulsations of the main leakage flux. It has been previously stated that the main leakage flux occurs principally in the form of a flux surrounding each individual slot, crossing the slot at the opening. As is shown in Fig. 6, a part of this leakage flux is likely to cross the air gap and to enter the opposite magnetic member (*e. g.*, rotor leakage flux may enter stator teeth). The leakage flux that crosses the air gap is commonly known as a zigzag leakage flux.

The reluctance of the path of the leakage flux which crosses the air gap depends upon the relative position of the stator and rotor teeth. When the teeth of one magnetic member are opposite slots of the other, the reluctance is a minimum. When the slots and teeth of the stator oppose the slots and teeth of the rotor, respectively, the reluctance is a maximum. This partial variation of the reluctance

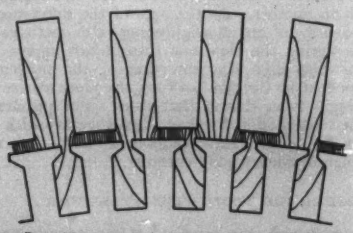


Fig. 5. Illustration of variation of slot leakage flux pattern caused by the relative position of rotor and stator teeth

may cause some pulsation in the magnitude of the leakage flux, and of the pattern of the flux in the slots. As the amount of leakage flux depends upon the load current in the conductors, the possible leakage-flux pulsation loss should vary approximately as the square of the load current.

Tooth Frequency Losses in the Stator

The above discussion of tooth pulsation phenomena was concerned mainly with the rotor of an induction motor. Flux pulsations in the stator present essentially the same features, although with the typical semiclosed (or closed) rotor slots, pulsations of flux in the stator are very small.

An interesting phenomenon must, however, be considered here: The damping of the rotor flux pulsations by the tooth frequency rotor currents increases markedly the pulsations of flux in the stator. H. Weichsel described this pehenomenon in a discussion appearing on p. 161–3 of the A.I.E.E. Transactions, v. 44, 1925. According to his description, the phenomenon was established by means of a search coil placed around a single stator tooth. The voltage induced in the coil was recorded, by means of an oscillograph, before and after the rotor windings were placed, with the rotor running at the same speed, and the same value of the excitation (impressed voltage) in both cases. The high frequency voltage was found to be increased greatly as a result of the damping currents in the squirrel cage winding. This observation is helpful in explaining the experimental fact that damping out the rotor flux pulsations by the eddy currents at the same time increases the total tooth frequency loss in the motor. If there is any decrease in the rotor

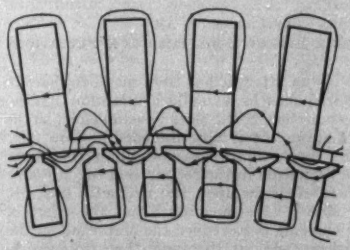


Fig. 6. Illustration of zigzag flux, and the effect of relative position of rotor and stator teeth upon the pattern of leakage flux in the slots

pulsation loss that is due to the damping currents this decrease is made up with excess by the increase in the stator tooth frequency loss.

Losses Due to Minor Fields

There are some minor losses in induction motors which have not been described above. Only 2 of them will be briefly mentioned here. One of these losses occurs in the end laminae of both rotor and stator, and is caused by the end-fringing of the main flux. An electromotive force induced by this fringing flux causes currents to flow in the plane of the end laminae, because, as the field changes its strength the lines of fringing flux cut the iron in a direction perpendicular to the planes of the laminae. This loss occurs at the fundamental frequency.

The other loss occurs in squirrel cage motors only, and is due to the nonsinusoidal flux distribution in the air gap. Ordinarily, the stator winding is placed in such a manner that the flux distribution only approaches a sine wave form (*e. g.*, it may have a trapezoidal shape). It may be shown that in this case the total air gap flux has irregular, high frequency components. When the air gap flux apparently moves at the synchronous speed of the

machine, only the true sine wave component participates in this motion, and is useful in producing the driving torque of the motor. The effect of the irregularities in flux distribution is to produce circulating currents in the squirrel cage bars, which increase the no-load loss, and make the flux wave more nearly sinusoidal.

Stray Load Losses

If the external causes of loss in induction motors are excluded, such as those caused by an unbalanced voltage, nonsinusoidal voltage wave, etc., the losses described above seem to cover all the possible modes of appreciable and nonproductive expenditure of energy within a machine. It seems to be logical, therefore, to look for the stray load losses, i. e., the additional losses appearing with load, among those previously described. In order to do this, it is necessary to see which of all the losses vary with the load, and in what manner.

First, it will be noted that some of the losses actually decrease with load. Consider, for instance, the manner in which the fundamental frequency flux changes with load. With a constant impressed voltage, the flux which links with the primary winding decreases slightly with load, because of the IR drop in the primary winding. This causes a slight decrease in the fundamental frequency iron loss.

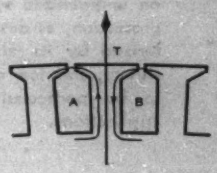
On the other hand, there are losses which definitely increase with the load. As the leakage flux is the only loss-affecting factor that changes with load, it must directly or indirectly account for the increase in the losses with load, i. e., it must account for the stray load loss. In the first place, the leakage flux produces a fundamental-frequency eddy-current loss in the rotor and stator conductors. With a bar-wound stator, this eddy current copper loss may reach an appreciable value. In rotor bars this loss hardly amounts to much, because of the low rotor frequency. In any case, the effect of this loss is to increase the effective copper resistance by a constant amount.

Furthermore, the leakage fluxes are likely to produce a high value of saturation in the tooth tips and, particularly, the thin tooth tip shoulders of semi-closed or closed slots. This saturation in the tooth shoulders causes a redistribution of flux in the air gap, and, what is more important, in the slots, every time the leakage flux exceeds a certain value. This occurs every half cycle. Accordingly, the load-leakage flux in the slots, when iron tooth tip shoulders get saturated, has pronounced higher harmonics in it. This increases the eddy current losses in the copper conductors that are due to the fundamental leakage flux, and may account for the fact, observed by some experimenters,[1] that machines which have closed slots in both rotor and stator show a high value of the stray load loss.

Other Contributing Factors

Another phenomenon that may contribute to the stray load loss is the tooth pulsation of the main leakage flux, illustrated in Fig. 6. Consider the extreme case of a closed slot rotor. At low load, when the rotor leakage flux is low, the iron bridges that close the slots are not likely to become saturated. Such being the case, the iron bridges represent a sufficient magnetic shielding against any effect of the stator teeth upon the distribution of the leakage flux in the rotor slots; i. e., no tooth pulsation of the rotor leakage flux is possible. When the motor is loaded, the rotor leakage flux assumes an appreciable value, the thin iron bridges become saturated easily, and the situation becomes as illustrated in Fig. 6, i. e., tooth pulsations appear in the leakage flux that crosses the slots. The eddy current power loss

Fig. 7. Illustrating the effect of leakage flux upon resultant flux in a rotor tooth



caused by these pulsations contributes to the stray load loss.

Within the stator and rotor teeth themselves, leakage flux may cause some distortion of the main flux. Figure 7 is intended to illustrate this point. Though the leakage flux that is due to the current in A is distributed through the cross section of tooth T, its density is not uniform throughout the cross section of the tooth, being greater near A and less near B. Similarly, the leakage flux density that is due to B is greater near B and less near A. If the direction of the main flux is as shown by the arrow, it is obvious that the resultant flux is of a greater density near A, and of a smaller density near B. Thus, the effect of the leakage fluxes within the teeth is to distort the resultant tooth flux, crowding it to one side of the teeth. This effect increases with load and may account for a part of the stray load losses.

As may be seen, the stray load loss in induction motors, whose satisfactory method of experimental determination is still a problem, is very likely a composite effect of several factors. The relative importance of these factors can hardly be discussed without further experimental investigations.

References

1. The Unsymmetrical Hysteresis Loop, J. D. Ball. A.I.E.E. Trans., v. 34, 1915, p. 2693–2715.

2. Squirrel-Cage Induction Motor Core Losses, T. Spooner. A.I.E.E. Trans., v. 44, 1925, p. 155–60.

3. Induction Motor Load Losses, H. G. Reist and A. E. Averrett. A.I.E.E. Trans., v. 32, 1913, p. 423–8.

4. Induction Motor Core Losses, F. L. Alger and R. Eksergian. A.I.E.E. Jl., v. 39, 1920, p. 906–20.

5. Tooth Pulsation in Rotating Machines, T. Spooner. A.I.E.E. Trans. v. 43, 1924, p. 252–61.

6. Surface Iron Losses With Reference to Laminated Materials, T. Spooner and I. F. Kinnard. A.I.E.E. Trans., v. 43, 1924, p. 262–80.

7. Tooth Frequency Iron Losses in Slip Ring Induction Motors, D. B. Hoseason. *The Electrician*, v. 91, 1923, p. 240–2.

A New Method of Ground Fault Protection

A new high-resistance "thyrite" and a new 3-element cold-cathode tube having unusual characteristics constitute the basic elements in a new high voltage relay combination for relaying or detecting ground faults on ungrounded systems. This scheme of protection, as described herein, is characterized by its reliability, simplicity, sensitivity, and low cost. It has been found to be particularly valuable in network applications.

By
F. M. STARR
ASSOCIATE A.I.E.E.

Gen. Elec. Co.
Schenectady, N. Y.

A GROUND fault which involves considerable current may be isolated by means of phase-current relays. If the ground fault does not draw appreciable current, its isolation becomes a problem.

A new relay combination has been developed for ground fault protection on ungrounded or delta-connected lines or on lines which may become ungrounded incident to the opening of one end. The relay scheme has been made possible by the development of a new "thyrite" resistor having extremely high resistivity and a new 3-electrode cold-cathode gas-filled electronic tube of unusual characteristics. ("Thyrite" indicates a resistor having an inverse nonlinear voltage-current characteristic.)

The development of the new method of ground fault protection and of the necessary devices was initiated as a result of the need for this type of equipment on ungrounded tie-lines and feeders. A particularly urgent need for such equipment has been evidenced on both primary and secondary network high voltage feeders. The application of the scheme to secondary networks is of considerable importance because it not only provides ground fault protection but it also performs an important function in the network operation as well.

To illustrate a general class of applications, consider the typical case of the ungrounded line section in Fig. 1. Here is shown a line section with a power source at each end feeding the line through delta-connected transformer windings. A large number of such line sections are in operation at various voltages among the various power systems of the country, and very few of them have any provision for ground fault protection. A ground fault on a line of this type displaces the voltage but does not draw any appreciable current.

Now consider another example: In Fig. 2 is shown a line section with a grounded source of power at A and an ungrounded source at B. Source A might be a grounded transformer bank as shown or it might be a grounded wye connected generator. In either case a ground fault at F will draw current from A sufficient to operate current relays to open circuit breaker B_a; but after breaker B_a opens, the current flow ceases and breaker B_b remains closed. The type of line section shown in Fig. 2 is universally used as a feeder for secondary networks, and in some cases, as a feeder for primary networks.

In this paper are presented an explanation and description of the new ground-fault protective scheme and associated devices, a discussion of their operating characteristics, and a discussion of the specific applications of which the above 2 cases are general classifications.

General Requirements

Before discussing the relay and its various applications, it seems pertinent to state the general specifications which a relay combination of the type under consideration must have. Since the application is a broad one, the requirements are necessarily severe. Specifically, they are:

1. The relay combination must depend only upon voltage displacement incident to a ground fault for its operation, since voltage displacement is the only appreciable change in the electrical system for this particular type of fault.
2. The general scheme must be applicable to all system voltages.
3. The equipment and its operation must be thoroughly reliable.
4. Correct operation over a wide temperature range must be insured.
5. Satisfactory operation of a given unit over a wide variation in system voltage must be assured.
6. In the case of the secondary network application, the device must not interfere with or be affected by high-voltage d-c cable testing.

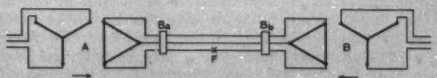


Fig. 1. A typical delta-connected line section

Line sections of this type usually are not protected for ground faults

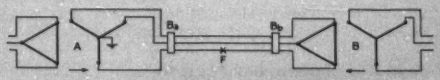


Fig. 2. A typical line section grounded at one end

This line section cannot be isolated by current relays. Circuit breaker B_a may be opened but a ground fault at F draws no appreciable current from B_b

Full text of a paper recommended for publication by the A.I.E.E. committee on protective devices. Manuscript submitted Feb. 23, 1934; released for publication Sept. 7, 1934. *Not published in pamphlet form.*

7. The equipment must be as reasonably inexpensive as possible without jeopardizing reliability.

Several schemes immediately suggest themselves as possible solutions to the above specifications. Wye connected potential transformers have been used occasionally for certain applications of this type. Potential transformers, however, are expensive, especially at higher voltages, and furthermore, they cannot be applied to cables which are tested with high voltage direct current.

A capacitor coupling device is also a possible solution to the problem. Here again, however, the installation is costly, and one which in many cases will be difficult to mount. Moreover, it was found in testing a capacitor coupling device that the range in system voltage which would give satisfactory relay operation was limited to a rather narrow band.

A third alternative, and the one which was finally adopted, consists of a resistance coupling device. Such a device must necessarily be of extremely high resistance in order to insure negligible losses. Moreover, it must have a nonlinear characteristic to permit selectivity over a wide range in system voltage.

A considerable amount of research led to the development of a new thyrite having extremely high resistivity and a highly nonlinear characteristic, both properties being essential and necessary to a highly sensitive resistance coupling unit. Coördinated with the thyrite development was the development of a new 3-electrode cold-cathode tube (shown in Fig. 11) having the necessary characteristics to control a relay circuit from the potentials impressed by the coupler unit. The coördinated design of the various elements of the device has resulted in a relay combination having a high degree of sensitivity, selectivity, and reliability.

The Coupler Unit

The simplicity and ruggedness of the coupler unit are evidenced in Fig. 3 which shows a design for 13,800-volt applications. The connections for the

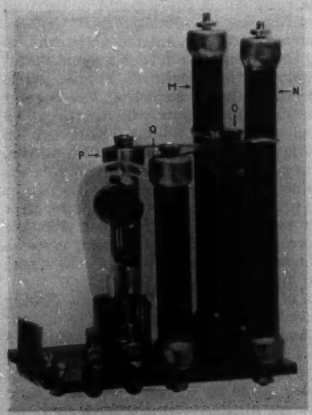


Fig. 3. The new high voltage coupler unit

This unit was designed for mounting inside a transformer tank under oil and for direct connection to the 13,800 - volt studs. Elements M and N are the porcelain bushings which house the thyrite resistors. Elements O, P, and Q are the porcelain bushings which house the linear resistors

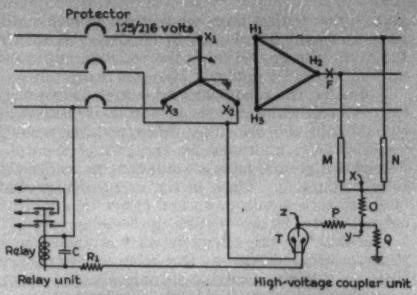


Fig. 4. Recommended connections for the high voltage coupler and relay units when applied to a secondary network transformer and protector

The elements of the coupler unit may be identified in Fig. 3 and the elements of the relay unit may be identified in Fig. 7

essential elements of the coupler together with its associated relay circuit as it would be applied to a typical secondary network transformer and protector are shown in Fig. 4. The several elements of the device may be identified as follows:

Elements M and N are the thyrite resistors which connect directly to 2 of the high voltage conductors. These are the nonlinear resistors which normally have an extremely high resistance. The resistance of each may be defined by the voltampere relation:

$$e = Ci^{0.16}$$

where e is the impressed volts, i is the resulting current in amperes, and C is a constant having a value of from 50,000 to 500,000 ohms depending upon the particular application.

Elements O, P, and Q are linear resistors likewise having high resistances but relatively small as compared with the resistances of elements M and N.

The tube T is a small 3-element cold-cathode glow tube. The relay is a sensitive a-c relay.

Essentially the coupler unit is a potentiometer connected between line and ground, the potential at point Y being impressed through current limiting resistor P on the grid of the glow tube.

Under normal conditions, the resistances of M and N will be large compared with the resistances of O, P, or Q; and points x, y, and z will be, for all practical purposes, at ground potential. This means that leg voltage (i. e., 7,980 volts in this case) is normally impressed on both M and N. The normal current in both M and N will be approximately 1.9 μa (rms); in O approximately 1.9 μa; and in both P and Q approximately 0.9 μa. Thus, the normal loss in the device will be roughly 0.030 watts, which is negligible.

In the event of a ground fault at point F, the potential of point x will be drawn toward H_2 allowing approximately full phase voltage to appear across resistor N. But, whereas the potential across N has increased 1.73 times, owing to its nonlinear characteristic its current will have increased 25 to 30 times. Since this current flows through resistors O

and Q, the voltage drop across these elements will have increased likewise 25 to 30 times. Thus, in the event of a ground fault, the potential impressed at points y and z suddenly increases many times.

Normally, the tube passes no current between its electrodes since the impressed 220 volts is insufficient to maintain the arc drop. However, the several hundred volts impressed on the grid of the tube following a ground fault are sufficient to render the tube conducting. Thus, in the event of a ground fault the tube breaks down and passes the requisite current—some 20 ma—to pick up the relay.

The tube for this circuit is what is known as a positive tube. That is, the relay or secondary circuit of the tube is conducting only when a positive potential (i. e., a potential in phase with the voltage impressed upon the secondary circuit) of sufficient magnitude is impressed upon the grid of the tube. In Fig. 5 is shown the breakdown voltage of the tube as a function of grid potential, point A being the normal operating point for a fault at F. It is assumed in this curve that the control voltage and grid voltage are in phase.

Actually, the control and grid voltage are never in phase for any ground fault condition. For example, with a ground fault at F as shown in Fig. 4, the grid voltage ($H_1 - H_2$) is 30 deg displaced from the secondary control voltage ($X_2 - X_3$). Tests have shown that the circuit connection shown in Fig. 4 will always provide a sufficient component of grid voltage in phase with the control voltage to insure correct relay operation regardless of which phase is grounded.

It should be noted that the phase connections shown in Fig. 4 are not the only suitable ones. With the high voltage coupler connected to ($H_1 - H_2$) the secondary circuit may be excited from either ($X_2 - X_3$) as shown, or ($X_1 - X_2$). Voltages separated by 30 deg should always be selected. Polarity and phase rotation appear to have slight effects, but, in general, these factors may be ignored in making connections.

Although the connections shown in Fig. 4 refer specifically to the secondary network application in which the control voltage of 220 volts alternating current is directly available, the same equipment may readily be applied to any other secondary voltage by using small step-down autotransformers; or, as an alternative, direct current may be used, if available, as an energy source in the relay circuit.

In the original tests on this device, 3 thyrite units, connected in wye to the 3-phase conductors, were used instead of 2 as shown. Later it was found that practically equivalent results might be obtained with only 2 units. The coupler using 2 thyrite units is preferable to one employing 3, since, (1) it is less expensive, (2) it is readily adaptable to transformer banks composed of 3 single-phase units, (i. e., the coupler may be mounted in a single-phase transformer tank without requiring cable connections to either of the other 2 units), and (3) it is subjected to a less severe duty during the d-c cable test.

Fig. 6. The high voltage coupler unit as it appears when mounted inside the grounding-switch compartment of a 3-phase network transformer

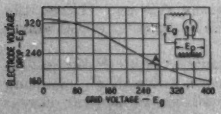


Fig. 5. Voltage breakdown characteristic of the new 3-electrode cold-cathode tube

This curve shows the in-phase 60-cycle grid voltage required to initiate current flow between the electrodes as a function of the applied electrode voltage. The grid voltage in this case was impressed through a 20-megohm resistor and the electrode current was limited by the impedance of the relay coil. Point A is the normal operating voltage for a fault on any one of the 3-phase conductors

The Relay Unit

The elements of the relay unit are seen in Fig. 4 to consist of a sensitive relay, a capacitor, and a current limiting resistor. A photograph of the unit is reproduced in Fig. 7.

As noted above, the relay is excited and picks up its contacts in the event of a feeder ground fault, owing to the valve action of the glow tube. The relay and tube constants are such that the current in the relay circuit is approximately 20 ma rms when excited as a result of a ground fault. The current in the relay circuit is peaked, and, although alternating, flows only for a portion of each half cycle (this is due to the nonlinear characteristic of the thyrite as reflected in the grid action of the tube). Capacitor C is placed across the relay coil in order that the intermittent current which flows shall not cause a chattering of the relay armature. Resistor R_1 serves to limit the current in the relay circuit.

The contacts of the relay may be circuit closing and may be used for direct tripping of a circuit breaker or the network protector in the event of a feeder ground fault. The contacts may also be circuit opening and used to open the restraint circuit of a master relay so as to render it sensitive and capable of operating in the event of a feeder ground

Fig. 7. A view showing the elements of the relay unit

fault. In this latter scheme the relay serves indirectly in providing ground fault protection.

Permissible Range in System Voltage

As has been pointed out, a particularly attractive feature of the coupler unit is the wide variation in system voltage over which it will perform successfully. The circuit of Fig. 4 will give successful relay operation for system voltages varying approximately from 80 per cent of normal to 118 per cent of normal.

These limits are based upon the condition that both the low voltage and high voltage terminals of the transformer are subjected to the same percentage of overvoltage or undervoltage. Operating conditions differ from this premise somewhat but in such a manner as to decrease the lower limit and increase the upper limit as specified above.

The upper voltage limit is that point to which the system voltage must be raised to cause the tube to become conducting even though a ground fault does not exist.

The lower voltage limit is that point to which the system voltage must be lowered to cause failure of the relay to pick up in the event of a ground fault. Although the tube will function properly for system voltages as low as 70 per cent, the relay itself begins to chatter at about 78 per cent of normal voltage and does not make a definite pick up.

It should be borne in mind that the lower voltage limit depends upon which phase is grounded. The limits specified above apply to the worst phase (i. e., the phase having the highest value of lower voltage limit).

High Voltage Cable Test

As has been stated, it is common practice to test feeder cables, particularly network feeders, periodically at high voltage direct current. A common test for 13.8-kv cables is an impressed 35-kv direct current for 5 min from the 3 conductors to ground. Since the high voltage coupler unit is permanently connected to the feeder—and there may be as many as 60 such units per feeder—it is essential that:

1. Each coupler unit be able to withstand the high potential without overheating or suffering a change in characteristic; and that
2. The total current load imposed by all of the coupler units on a feeder shall not exceed the permissible loading of the vacuum tube test set.

With an impressed voltage of 35-kv direct current, the current flowing through the coupler unit to ground will vary somewhat with the type of test set used, with the temperature of the transformer oil (the resistor units and their porcelains assume the temperature of the transformer oil under normal conditions), etc. However, in general, the ground current through the unit will not exceed 400 μa (rms) with an impressed 35-kv direct current. In Fig. 12 is shown the voltampere characteristics of the various elements of the coupler unit. An over-all characteristic of the resistor elements as they are connected for the 35-kv d-c test is also shown (i. e., the 2 thyrite resistors paralleled and in series with resistor O, and with resistors P and Q paralleled as shown in the insert). Note that, although resistor P is grounded only through the tube, the resistance of the tube is small and may be ignored. This over-all characteristic is a theoretical curve and shows that for an impressed voltage of 35-kv direct current the ground current will be about 450 μa. Actually, tests have shown that this value is never reached.

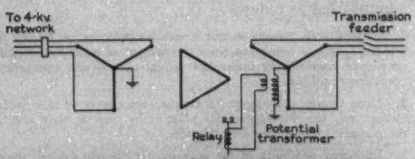


Fig. 8. A conventional method of obtaining ground fault protection on an ungrounded wye-connected feeder

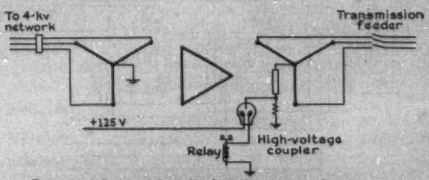


Fig. 9. A modified high voltage coupler for ungrounded wye-connected transformers

This arrangement is a modification of the high voltage coupler and relay assembly for ground fault protection on wye-connected transformers. It is preferred to the scheme shown in Fig. 8 owing to its reliability and low cost

Applications to the Secondary Network

As has already been pointed out, perhaps the most important application of the new ground fault protective scheme is on secondary network feeders. The value of the scheme in this particular case is augmented by its function in normal network operation apart from its function of ground fault protection. A distinct improvement in network operating efficiency and reliability has been obtained by applying the new device.

Consider for a moment the particular network operating characteristics and problems which are pertinent to the present application:

The secondary network consists of a number of primary feeders (13.2 or 13.8 kv in most cases), up to 50 or 60 protector and transformer units tapped to each feeder, and the 125/216-volt secondary grid. The network transformers usually have delta-connected primaries and wye connected secondaries. The conventional network relay equipment consists of a master network relay and a phasing relay which are arranged to function as follows:

1. A reverse power flow in the transformer of the order of magnetizing current will be sufficient to trip the protector. This so-called sensitive tripping is desirable since it allows the feeder to be taken out of service by the simple operation of opening the station circuit breaker, and furthermore, it provides feeder protection in the event of ground faults as well as the current-bearing phase faults.

2. A feeder which is out of service will automatically be restored to service if its voltage is of proper magnitude and is leading the voltage of the network grid.

Sensitive tripping has been found objectionable in certain cases since it results in excessive and unnecessary protector operations owing to feed-backs from regenerating elevator motors or to circulating currents arising from slight differences in feeder voltages.

Therefore, in view of the above general requirements and of the objections to sensitive tripping in some cases, the specific problem is to provide a supplementary relay device which will (1) permit the network feeder to be removed from service automatically by some simple operation at the station, (2) provide nonsensitive protector operation under normal conditions, and (3) provide sensitive protector operation in the event of a ground fault. It should further be stipulated that any scheme adopted must not interfere with or be affected by the high-voltage d-c cable test to which the feeder and all connected equipment is periodically subjected.

If a network protector be made sensitive to ground faults, it is evident that a plausible and simple method of taking the feeder out of service at the station is to open the station circuit breaker and ground one conductor. Thus, requirements 1 and 3 noted above may be accomplished by exactly the same device and in the same manner. At least one solution to the problem, then, consists of a ground sensitive relay which renders a normally nonsensitive power-directional relay sensitive in the event of a ground fault.

The high voltage coupler and relay unit described above offer an ideal solution to these network operating problems. The coupler is especially attractive for this application since it is not only highly reliable as a unit but it in no way impairs the reliability of the feeder itself.

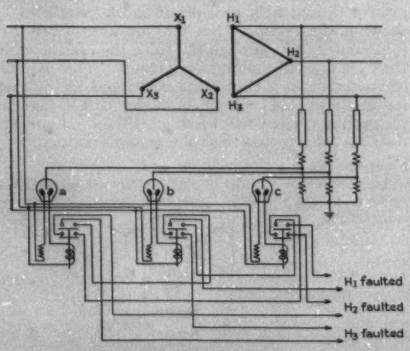


Fig. 10. Scheme for indicating which phase is grounded

This arrangement is a modification of the high voltage coupler and relay assembly shown in Fig. 4, and is designed to give not only ground fault protection but also an indication of the particular phase which is grounded

Fig. 11. The new cold cathode tube

This new 3-electrode tube was designed especially for the new ground protection scheme. It functions to control the relay circuit as dictated by the high voltage coupler

The particular advantages of the new relay combination for secondary network applications may be summarized as follows:

1. Ground fault protection over a wide range in system voltage is assured. This is important since the voltage of a network feeder may vary considerably under the several normal and emergency operating conditions.

2. Even though as many as 100 couplers are connected to a single feeder, they are not appreciably affected by, nor do they affect, the periodic high-voltage d-c cable test.

3. Improved reliability of the network is definitely assured since the ground relay permits nonsensitive tripping of the protector, thereby eliminating excessive operations.

4. Complete control of the feeder at the station is possible by the

simple expedient of opening the station circuit breaker and grounding one conductor.

5. The equipment will operate successfully over an unusually wide temperature range and a wide variation in system voltage.

6. The coupler unit may be mounted directly in the transformer tank or ground-switch compartment (under oil) of either a single-phase or a 3-phase transformer without the necessity for any external high-voltage cable connections. The relay unit will usually be mounted in the protector; and if the protector is attached to the transformer, as is frequently the case, the installation becomes a very simple one. (See Fig. 6 for a typical installation of the coupler unit.)

Applications to the Primary Network

The application of the new relay equipment to primary networks is of particular importance because it permits the use of a delta-wye transformer instead of the more costly wye-wye or wye-zigzag with delta tertiaries. In some of the early primary network installations, the transformers were wye-wye, delta tertiary with solidly grounded neutrals. Ground fault protection was insured with this arrangement since all ground faults drew sufficient current to operate the phase current relays. The wye-wye transformer is not acceptable in many cases, however, owing to the desirability of tying the network in with an existing delta-wye radial substation.

In the past, where such tie-ins have been expedient, wye-zigzag transformers have been adopted.

It has not always been desirable to ground the neutral of the high voltage windings, in which cases a neutral potential transformer has been used for ground fault protection as shown in Fig. 8. This arrangement is costly, especially at the higher voltages.

All of these difficulties and expensive expedients are removed by application of the new ground relay. The simple delta-wye transformer may be used with ample ground fault protection assured.

If for any reason a wye-wye transformer should be preferred, the new scheme may be applied in a simplified form as shown in Fig. 9. This arrangement is less expensive and probably more reliable than the potential transformer arrangement shown in Fig. 8.

The high voltage coupler and relay assembly is directly applicable for ground fault protection on primary network feeders in a manner similar to the secondary network application described above.

However, whereas in the secondary network application the relay functioned indirectly to isolate a grounded feeder by removing the restraint from the master relay, in the primary network application the relay functions directly to trip the circuit breaker; or, if desirable, it may operate directly to trip the circuit breaker through an auxiliary time-delay relay. Unlike the secondary network feeder the primary network feeder serves relatively few network units and there is no need for control of the feeder at the station and, therefore, no need for highly sensitive power-directional relays. In the primary network, therefore, the ground relay scheme serves only to isolate ground faults.

There is another fundamental difference in the application of the ground relay to the 2 types of network. In the secondary network, excitation for the relay circuit is obtained from the 216/115-volt grid as shown in Fig. 4. In the primary network, the network potential is 4,000/2,300 volts and excitation for the relay circuit must be obtained from the auxiliary power transformers which are standard equipment with each network unit.

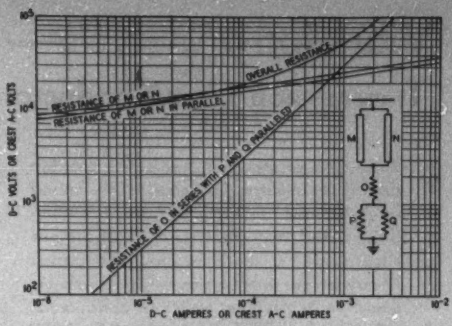


Fig. 12. Resistance characteristics of the high voltage coupler unit

These curves show the resistance characteristics of the 5 elements of the high voltage coupler unit designed for 13,800 volts. The over-all resistance curve is that resistance which limits the current in the unit when the cable to which it is connected is tested at 35-kv direct current to ground

Other Applications

The foregoing applications have been concerned with the primary and secondary networks. There are obviously many other applications on ungrounded line sections such as sections in loop circuits and tie lines.

It should be borne in mind that, by simply changing the resistor constants and insulation clearances, the coupler unit may be designed for any line voltage. Thus, for even the highest voltage, the new relay provides a relatively inexpensive and highly reliable device for isolating or detecting ground faults.

In some cases it will not be desirable to trip a circuit breaker to isolate a ground fault but only desirable to give an indication of the presence of the fault. For detecting ground faults, the new equipment has an advantage over conventional ground detectors in that it permits relaying the signal to a point remote from the grounded bus or line.

In addition to detecting a ground fault on a line, it may be desirable to detect also the particular phase which is grounded. A modification of the fundamental circuit to accomplish this result is shown in Fig. 10. Note that 3 relays and 3 tubes are required and that an additional high voltage resistor unit is required. If phase H_1 is faulted, relays *b* and *c* operate; if phase H_2 is faulted, relays *a* and *c* operate, etc.

Vibration Analysis—
Transmission Line Conductors

A method of measuring the stress distribution in transmission line conductors caused by vibrations under actual service conditions, and the effect thereon of various attachments, is outlined in this paper. Measurements have been made of the attenuation of traveling waves in conductors, reflection factors of supports, ratio of the bending at a clamp to that in mid span, effect of vertical rigidity of the support, impact effect of traveling waves, stress division effected by a rocking clamp, and other items. Some records of aeolian vibrations are included which indicate a periodic recurrence of similar groups of waves at time intervals equal to the double-span time-interval of a traveling wave.

By
W. B. BUCHANAN Hydro-Electric Power Commission of Ontario, Toronto
MEMBER A.I.E.E.

CAREFUL reading of much of the best literature on the subject of vibrations of transmission lines and their harmful effects, supplemented by field records and observations, indicated that while the over-all effects reported with respect to various devices for suppressing vibrations might be quite satisfactory there was still much to be desired in the rigor of the methods of analyses and a scarcity of the types of measuring or recording devices which would furnish the basis from which such analysis could be made.

The immediate and most pressing need called for decisions based upon the conditions existing in hundreds of miles of lines already installed and operating. Hence equipment by which a line could be tested with not more than a few hours' interruption seemed to be the first objective. The specific problem thus reduced to: First, the development of a satisfactory method of testing lines and attachments in place, as to vibration characteristics, with the measuring equipment adapted therefor; and second, testing with the view to determining quantitatively the relative merits of various devices that have been tried or might be proposed for the purpose of mitigating harmful effects of vibrations.

This paper deals with the method of testing and the equipment used. Some data of considerable value are also included, the purpose at this time being to demonstrate the validity of the method and to point out some of the most important principles involved in the protection of lines already built.

The facilities subject to requisition by the investigating staff included not only the extensive electrical and mechanical equipment of the laboratories of the Hydro-Electric Power Commission of Ontario, Canada, but a line of towers was available where at 2 convenient locations any type of line conductor and assembly could be mounted and tested as desired. One of these locations was quite favorable to the development of the so-called "natural vibrations" and such vibrations were observed and recorded on several occasions.

First efforts were directed to establishing standing waves on conductors in such a manner that the characteristics of conductors and devices could be observed and evaluated by test. Great difficulty was experienced in obtaining any satisfactory method of controlling such waves by any scheme suitable for field testing. Moreover, it was observed that in natural vibration the standing wave was a rather transient phenomenon, node points were continually changing and wave lengths changed within short periods and considerable agitation of the conductor was apparent prior to the observation of any standing waves.

Without commenting adversely at all on the very valuable work that has been done theoretically and practically on the formation of eddies, it did seem quite improbable that eddy currents of air could be so highly selective in space as to determine where node points should or should not occur. Observation indicated and subsequent tests tended to prove that any major disturbance of the conductor in space resulted in a traveling wave in each direction from that point, reflections occurred at points of support or where appreciable masses of material were rigidly attached, and in a few seconds these and subsequent reflections passing in opposite directions gave the appearance temporarily of standing waves.

Mathematically it can be shown that a standing wave is the result of 2 traveling waves equal in magnitude but of opposite direction of motion, hence to set up any large number of standing waves in a line conductor it would be necessary to have a succession of waves with practically undiminished reflections. This difficulty doubtless accounts for the constant shifting of node points and generally unstable conditions noted previously. It thus appears that since a standing wave is only one special case involving 2 traveling waves, any solution therefor could only be accepted as a special and not as a general solution without further consideration.

Such observations led to the conclusion that for the present purpose, testing with a single traveling wave should provide the means leading to a more thorough study of the stresses involved. Given suitable recording devices, a traveling wave could be applied to a conductor and its attenuation would

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Aug. 31, 1934; released for publication Sept. 19, 1934. *Not published in pamphlet form.*

be a definite measure of the energy loss in such conductor at that tension, amplitude, and wave length. The behavior of various suppressors or absorbers could also be determined by similar means in exact quantitative terms.

Methods of measuring energy loss from the decrement of electric or mechanical oscillating circuits are generally accepted. A similar analysis made from the attenuation of a mechanical wave as it travels from point to point on a conductor should be equally valid providing there be no appreciable distortion of wave shape.

It has been suggested that because the view that all vibrations on transmission lines originate as traveling waves is quite radical, an extra effort should be made to establish the validity of such an hypothesis. It may be accepted more readily if brief reference be made to some of the better known cases of vibration of strings as they behave in stringed instruments. It might be stated here that on actual tests on the lines quite high reflection factors have been measured; from 92 to 98 per cent is reflected from supports which are, according to present practice, considered to be among the best types. Hence the condition is more nearly comparable with that of the stringed instrument than might at first appear to be the case.

A piano wire is struck, a guitar, banjo, or mandolin string is plucked and obviously the displacement is initiated in the same manner as is adopted to apply a traveling wave on the line. The order and magnitude of the harmonics of the initial wave (transient) depend upon the force of the blow, the hardness of the materials at the point of impact, and the distance from one support where the string is struck or plucked. The mechanical oscillation (sustained) is determined by the mechanical characteristics of the system and some acoustic modification by the form of the sound box. In the present tests we are not interested in a sound box but all the other components enumerated have a part in dictating where and how the wave should be applied so that the record might be suitable for computation.

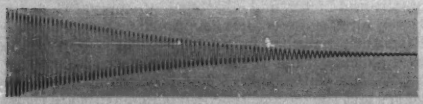


Fig. 1. Damped oscillation record of a solid steel rod taken by a carbon pack curvature recorder

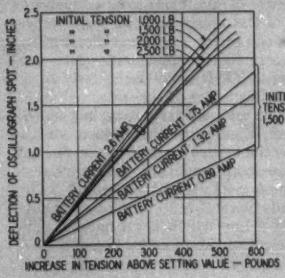


Fig. 2. Calibration curves of a carbon pack tension recorder on 3/8-in. diameter ground cable

Fig. 3. Carbon pack curvature recorder

The same analysis applies to stringed instruments which are excited by a bow, with the additional complication that the string is subjected to a series of minute impacts resulting from a high ratio of static to moving friction between the bow and string. Thus a very wide range of tone, color, pitch, and volume can be obtained by varying the magnitude and character of the component noted above as transient relative to the sustained component. Practically this is done by varying the pressure and velocity of the bow, the contact area, and the distance from the bridge. The conclusion then seems justified that in this more complex case the result is derived from the summation of a series of traveling waves and their reflections.

Test Apparatus Which May Be Used

After a critical review of such methods as had been used elsewhere it was decided that to obtain satisfactory records in permanent form at locations remote from the occurrence of any event at the frequencies used it would be necessary to use an oscillograph in combination with suitable devices for supplying the current. A portable 2-element oscillograph which operated from a 6-volt storage battery was available and has been used throughout the tests to date.

Some practical work had been done in the laboratory on carbon pack resistors and their application to remote measurements of stress and displacements but such development work is slow, uncertain, and expensive. The information obtained from the U.S. Bureau of Standards Technologic Paper No. 247 was of considerable value, especially in the preparation of the carbon disks for the resistance units. These units have been very satisfactory, as is shown, for example, by the damped oscillation record (Fig. 1) of a solid steel rod (taken by a curvature recorder) and that of a tension recorder (Fig. 2) calibrated up to 2,500 lb in 5 stages of 500 lb each.

Analysis of the transient stress to which a conductor is subjected by vibrations indicates a component or unbalancing due to bending and an average longitudinal component. Hence if direct measurement could be made of these quantities inde-

Fig. 4. Assembly of the equipment used with the carbon pack curvature recorder for use in the field

pendently of all other influences they should give a direct measurement of the actual duty imposed on the conductor.

Two arrangements are therefore used. The curvature recorder (see Fig. 3) is mounted with its carbons in the plane in which the wave is applied, and in the present form weighs 11 oz. The tension recorder is mounted with its carbons at right angles to the conductor and to the plane of the wave travel. In each case the opposing carbons are connected as adjacent arms in a Wheatstone bridge circuit, the oscillograph being the detector and the common lead to the carbons from the supply circuit. Suitable rheostats are used for changing the current supplied to the network and thereby the sensitivity of the recorders. The equipment has been assembled in a carrying case in a manner very convenient for use in the field. (See Fig. 4.) This is the first time we have heard of such a curvature recorder having been used and its merits will be discussed more fully in connection with the interpretation of some records.

One other special device for use with the oscillograph should be mentioned, *viz.*, a slide wire resistance placed vertically against the conductor and giving a measure of the amplitude of the wave at that point at any instant. This is useful in demonstrating the relation that exists between the actual wave and the curvature recorder but is less useful than the latter because the actual elevation of the conductor at any instant is unimportant compared with the manner of its progress to that point.

Location and Method of Applying Traveling Waves

It seemed advisable to determine and use for test such wave fronts, etc., as might most nearly duplicate those occurring through the action of wind. Various schemes were tried, sharp hammer blows, mechanical devices, and by hand, and thus far the most satisfactory, in fact the only usable records, have been those obtained when the wave was applied by hand. Some skill and experience is necessary to develop the proper "sleight of hand" to duplicate results; this phase of the problem at present is something of an art.

Keeping the records of various events separated so that valid measurements might be made requires certain precautions in placing recorders and choosing the point of application of the wave. When a wave is initiated by vertical displacement of the conductor, at, say, the center of the span, 2 waves are started, one in each direction, of identical shape. The steepness of the wave front depends upon the relative velocity of the vertical displacement and the longitudinal velocity of this lateral wave. The amplitude depends on how far it is displaced, and the shape of the tail on the rate of restoration to its initial position. It is advisable to force this return in order that the length of the wave be limited, otherwise the tail would be a long taper, similar to that of a lightning stroke, and interfere with the recording of reflections in their correct magnitude.

A "lattice" diagram has been so useful in visualizing what occurs and such an aid in identifying the various components that it seems advisable to discuss briefly its construction at this point and note some of the important features of the problem before undertaking the solution of any given set of test results.

One axis of a plane rectangular coördinate system is assumed to represent distances along the length of the conductor and all items of apparatus, *e. g.*, tower supports, recorders, suppression devices, etc., have their positions indicated to scale. The other axis indicates time as measured from the instant of application of the wave. The progress of the main waves and the various reflected components are then represented by lines of uniform slope depending upon the velocity of the waves and the scales represented by the 2 coördinates. A typical diagram has been drawn for a 1,400-ft span, curvature and amplitude recorders at 500 ft from the easterly tower and wave applied at the center of the span. (Fig. 5.) Initially the easterly and westerly traveling waves, denoted by E and W, are on the bottom of the conductor but reflections are thrown back on the top of the conductor, i. e., components of $-E$ travel westward while those of $-W$ travel eastward. This reaction corresponds to the reflection of a voltage wave at the end of a line which is grounded. The transmission coefficient of the recorder is noted as T, therefore its reflection factor is $(1 - T)$. The reflec-

tion factor of the tower support is indicated as R. Use of these symbols as coefficients permits the identification of the various transmitted components of the main waves and the various reflections therefrom. For simplification the coefficient indicating attenuation due to distance traveled is not written in the diagram but must always be considered in evaluating results.

Inspection of such a diagram identifies clearly the various waves as they pass the point C (location of the recorders) in either direction and also aids in the interpretation of unusual results obtained when waves of opposite direction of travel interfere at this point.

It has been implied that the velocities of these waves are independent of the actual wave lengths and that there is no interference between waves traveling in the same direction. The formula for this velocity is $v = \sqrt{T/m}$ where T is tension and m is mass per foot length. This does not involve wave length. Practically, it is found that the time of travel of a wave from one support to the next and back is the same regardless of whether the wave be applied by a hammer blow or by hand. Also it is deduced from records that unless a wave is subjected to some distorting interference, *e. g.*, reflected components, etc., it will pass through several reflections back and forth in a span without appreciable change in wave shape, the change being one of amplitude only. The latter fact has rather greater significance than might at first be apparent, for the following reason:

The wave is initiated as a lateral displacement of material, traveling lengthwise of the conductor in space at an approximately constant velocity. The record interprets this as a displacement with respect to time. Hence, the record, properly interpreted, indicates the form of the wave at any instant while traveling freely in space. It is usually distorted, that is, not sinusoidal, but might be represented between certain limits, by a Fourier series. The higher terms in such a series would indicate components of shorter wave length and if the velocity of travel of such components were different from that of the fundamental some appreciable change in wave shape should be evident. Any change that has been detected so far has been traceable to some other agency and it appears to be definitely established that for the conductors, spans, and other conditions involved, the transmission of the traveling wave is distortionless.

During periods of testing it is frequently difficult to obtain a quiet condition in the conductor due to oscillations continuing from a former test or to natural vibrations. At such times it is necessary to use waves for test which are substantially greater in value than the interference waves just as in communication it is necessary to maintain the energy level of communication well above that of the background of interference. Such phenomena are fairly common and require very little comment other than to point out that very erratic results might be obtained if due attention be not paid to this feature.

Progress to this point justifies a restatement of the problem, *viz.*—given the means of faithfully recording the components of the stresses it is desired to investigate, and a means of initiating a disturbance approaching the character and magnitude of those considered most hazardous it should be possible to analyze the distribution of loss and learn the direction in which improvement in equipment might be expected. The quantities it is desirable to measure include the attenuation due to loss in the conductor itself, reflection factors at supports or other attached masses, and the distribution or concentration of stress at such reflection points.

No general rule can be given but each test must be planned in accordance with the information required. A variety of examples will be given to indicate the great possibilities of this method of analyzing the transient components of stresses due to vibrations of line conductors.

Example 1—Relation of Curvature to the Amplitude of a Wave

Initially it was planned to measure the rate of loss of energy by noting the decrease in amplitude of a wave after it would have passed through one or more types of experience. Obviously, there would be practical difficulties in mounting an amplitude recorder 50 or 75 ft in the air at 200 ft distance from a tower, but it is possible to do this with the curvature recorder. It is necessary then to determine if the values, as indicated by the latter, could be used as a measure of the rate of energy absorption or dissipation taking place in the system.

The radius of curvature is usually expressed by a rather complex differential equation of the second order. The physical conditions of this test, however, permit the calculations to be based upon values at instants when the first derivative becomes zero and the curvature itself becomes equal to the second derivative which is directly proportional to the amplitude, *e. g.*, if $Y = A \sin X$ then $d^2y/dx^2 = -A \sin X$.

Reference to Fig. 5 will aid in visualizing the relation between the curvature and amplitude records

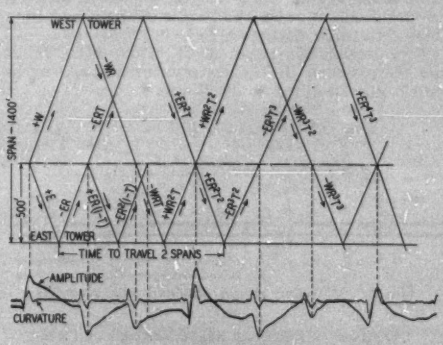


Fig. 5. A typical "lattice" diagram drawn for a 1,400-ft span

under conditions nearly ideal. It may be observed on close inspection that a long tail on a preceding wave may affect both amplitude and curvature records. The former would be also affected seriously by a slow sway of the conductor. The latter is practically independent of any swing of the conductor, recording only the changes in curvature from instant to instant. For the traveling wave this is usually consistent. It will be evident that considerable care is necessary to identify the registrations which are comparable for analysis. Though difficult this has not been found to be impossible if certain precautions have been taken in planning and carrying out the test.

Example 2—Calculation of Attenuation and Reflection Factors

The tests resulting in this series were devised to check line attenuation and reflection factors by sufficient readings to set up the simultaneous equations which would evaluate these quantities. The general principle and method of solution is as follows:

The record, Fig. 6, was obtained by applying an impulse at P_2, the wave W_1 traveled through recorder T_2 to S_1 and was there reflected. Wave W_2 first traveled west and was reflected at S_2.

Wave W_1 first gave record A, then after reflection at S_1 it gave C then traveled to S_2, was reflected, and on its return gave A' and C' etc.

Wave W_2 first traveled to S_2 was reflected and gave record F when passing through T_2, was reflected at S_1 giving record H. This wave continued to travel back and forth in the span until it was dissipated.

Recorder T_1 shows practically no component whatever transmitted past the support so that in this case the total loss occurs within the conductor of the span and at the 2 supports.

The distance S_1T_2 should be known or it could be estimated from the record by assuming uniform film speed and uniform wave velocity, neither of which were strictly true. The length of film A to A' is proportional to twice the length of span, and from A to C to twice distance S_1T_2.

The attenuation ratios A'/A, C'/C, F'/F, H'/H are the result of the waves traveling 2 span lengths and being subjected to 2 reflections.

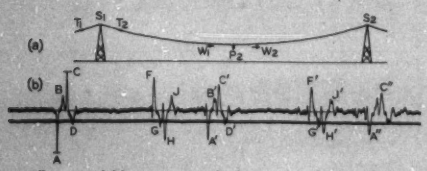


Fig. 6. Vibration record obtained with recorders at T_2

1,400-ft span of 795,000-cir mil aluminum cable steel reënforced conductors
Recorders 87.5 ft from east support
West span plucked by hand, 500 ft from support

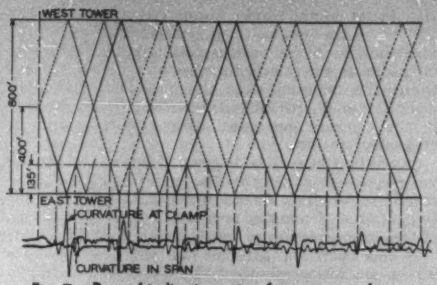


Fig. 7. Record indicating ratio of curvature at clamp to curvature in mid span

Record taken on a 5/16-in. steel-conductor 1,800-ft span at approximately 650-lb tension

The attenuation ratios C/A, H/F, C'/A', H'/F' are due to the travel of the wave along 175 ft of conductor and one reflection.

Using R to indicate the reflection factor of the support and with similar construction assuming that these factors for each end are equal, also J to indicate the attenuation due to conductor loss in the length of conductor indicated by the subscript, there are obtained by scaling the records:

$$RJ_{175} = 0.93$$
$$R^2J_{1,000} = 0.70$$

From which are obtained

$$R = 0.945$$

and

$$J_{1,000} = 0.92$$

These figures indicate that for this particular conductor at the tension given there is a reduction in amplitude of the wave of 8 per cent in 1,000 ft of travel, and it may be assumed to be uniformly distributed. There is also indicated an energy loss at the clamp sufficient to reduce the amplitude of the reflected component by 5.5 per cent. The stress distribution at the support, however, is extremely variable and requires a special series of tests for its determination.

Example 3—Ratio of Curvature at Clamp to Curvature in Mid Span

This phase of the general problem has been studied with the aid of the curvature recorders on several types of conductors and with various types of clamps and other modifications in the supports. The record shown in Fig. 7 was taken on a $^5/_{16}$-in. steel-conductor 800-ft span at a tension of approximately 650 lb. The corresponding lattice diagram serves to identify the various components as they appear at 2 locations, at the support and at a distance of 135 ft. The relative sensitivities of the 2 measuring elements is such that this recorder indicates a curvature at the clamp 20 times as sharp as that occurring at 135 ft from the clamp. A corresponding record after the installation of a

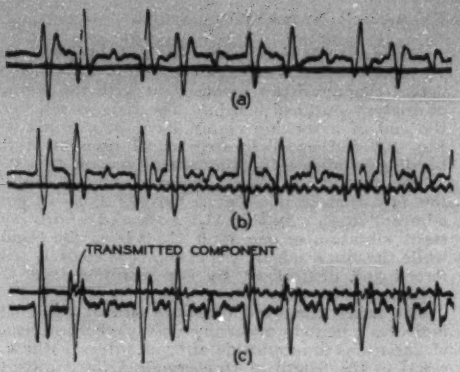


Fig. 8. Recording indicating effect of vertical rigidity of support

festoon gives a reduction of this ratio to 11, or about 55 per cent of its former value. The attenuation factor for 2 reflections and 2 span lengths of wave travel is not so pronounced, dropping from 0.871 to 0.61.

These ratios should not be taken as a criterion of the best results that can be obtained by festoons, but are submitted in order that a perspective may be obtained as to the duty imposed on the conductor at this point.

Example 4—Effect of Vertical Rigidity of Support

Since a high reflection factor is one of the elements tending to increase the stress due to bending at a support, some consideration was given to the essential features involved in developing a transmission factor for wave travel through the clamp. Oscillogram Fig. 8*a* taken with conductor arrangements similar to those in Fig. 6 and rigid suspension shows that the transmitted wave is negligible.

A spring suspension with limited travel was used to support the clamp, and oscillogram Fig. 8*b* was obtained. An increase in the oscillations in the adjacent span is apparent and this can be traced to the transmitted component through the clamp. The relation, however is much more definitely indicated by oscillogram Fig. 8*c* taken under similar conditions but with the clamp having 3 times as much freedom in a vertical line as in the previous case. During this test the wave was applied in the east span and the transmitted wave would appear on the record for the west at the same time as the reflected wave would appear on the record for the east span. In this case it is of appreciable magnitude and can be identified in wave shape with the original wave.

Other investigators have sought to discover some relation between the vibrations on opposite sides of a support but as far as we are aware they have been shown to be mutually independent. This experiment suggests the reason, namely, that unless there is elasticity of the support the synchronizing force between oscillations in adjacent spans is negligible.

Example 5—Longitudinal Component of Traveling Wave; Impact

The longitudinal components of the 2 traveling waves which result in a standing wave may be assumed to neutralize each other and the net effect of such components is to tend to reduce the effective length of the conductor. This action has the general effect of slightly reducing the sag of the span.

The unbalanced traveling components, however, are likely to produce an impact effect at supports or other masses. In fact, what appear to have been oscillations of a longitudinal wave between supports have been set up by the impact of a traveling wave of steep front. Such oscillations have been highly damped and are not likely to be of much practical importance.

In Fig. 9 is a record taken on a $^3/_8$-in. steel-conductor 1,400-ft span at 1,420-lb tension. The curvature recorder was mounted 75 ft from the tower and gave the upper record. A tension recorder at the support gave the variation in the total tension and the calibration in this case indicates a variation of plus and minus 75 lb. The magnitude of the wave was such as to approach the conditions involved in dancing or galloping conductors so might be assumed to represent the result of rather severe conditions.

Example 6—Flexibility of Conductor; Variation of Attenuation With Tension

A special type of hard-drawn copper conductor of section equivalent to about No. 4/0 was strung on a line of towers using 6 10-in. suspension units per support, and attenuation tests were made by checking the curvature record at one support during 10 spans of wave travel.

With an initial tension of 2,000 lb an attenuation coefficient of 0.94 per double span was estimated. This value includes both reflection factors of the supports and reduction due to loss in the conductor itself. Similar readings at 1,770-lb tension resulted in a coefficient of 0.895.

Greater per cent loss in amplitude at the lower tension is indicated but the figures do not give the complete story of the test. In the latter case a series of waves were slowly built up, following the main

Fig. 9. Record indicating impact effect at support

a. Curvature record 75 ft from tower
b. Tension record at tower
1,400-ft span of 3/8-in. steel conductor at 1,420-lb tension

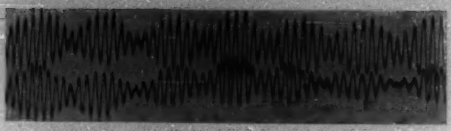


Fig. 10. Records with curvature recorders at opposite end of a flexible suspension clamp

wave, which doubtless were derived from the main wave and represent part of the energy loss from the main wave. Except for change in tension, which would affect the velocity of the wave travel, the conditions of the 2 tests were identical. Tentatively, therefore, the suggestion was advanced that the natural period of oscillation of the insulator string would have an important part in determining the magnitude and frequency of such detached components and that it might under certain conditions be very effective as a dissipator of energy from the main wave. It would be difficult, however, if not impossible, to rely on such action at all times since the tension changes with temperature, hence also the velocity of wave travel changes, and if this mechanical system were to depend upon resonance conditions for its operation, its behavior might be altered materially by slight change in wave velocity.

It is expected that tests made on conductors which are attached to rigid supports would be free from such difficulty and such tests are being continued to determine the relation between energy loss of a traveling wave in the conductor and the tension.

Example 7—Rocking Clamps

Some tests had been made mechanically which indicated that a rocking clamp, i. e., a clamp free to swing in a vertical plane with its axis passing horizontally at right angles through the cable at its point of suspension, would tend to divide the duty imposed by bending, between the 2 ends of the clamp. With restrained motion or large moment of inertia of the clamp this might be modified but the maximum benefit that should be expected would not be more than a 50 per cent reduction of the stress component due to transient curvature.

An opportunity was offered to check the bending at the 2 ends of a clamp on a 795,000-cir mil aluminum-cable steel-reinforced conductor suspended from a flexible string of insulators. The oscillogram, Fig. 10, of such curvatures confirms the earlier mechanical tests very definitely. The recorders have approximately the same sensitivity and the record indicates that the vibration stresses at the 2 ends of the clamp remained in step and with approximately the same amplitude throughout the length of the film.

Under example 4 it was pointed out that there need be no very definite relation between the vibrations in one span and those in the adjacent span. This conclusion was based upon conditions at some distance on either side of the clamp and is consistent with the records discussed in this example.

Example 8—Natural Vibrations

A few records have been obtained due to aeolian vibrations which have been carefully examined to detect characteristics inconsistent with the method of analysis outlined herein. The stresses set up at the end of a rocking clamp have been noted (see Fig. 10) and approximately equal division of the bending is indicated on a number of records.

The duty at the clamp, however, is intensified by the fact that it is affected by vibrations in both adjacent spans. In Fig. 11 is indicated a fairly constant vibration in one span 275 ft from the clamp, while the amplitude at the clamp is alternately reinforced and neutralized by the vibration from the adjacent span.

The latter film (and others of similar type) also indicates a periodic recurrence of a definite sequence of variations in amplitude after an interval which is equal to the length of time required for a wave to travel the length of the span and return. Such a definite repetition can be accounted for on the theory of 2 continuous series of vertical waves traveling in opposite directions along the span and being transmitted and reflected with very little loss of amplitude.

It would seem to be conclusive from this record alone that such an erratic sequence of amplitudes could not be repeated so faithfully after such an interval of time unless the time interval of the traveling wave for the 2 spans were the controlling factor.

This being the case, testing by the use of a pair of traveling waves should be the rational and most direct method of analyzing into its simplest components the problem of vibrational stresses in conductors.

Further Studies

According to this method of analysis the criterion of the effectiveness of any device in mitigating the harmful effects of vibrations might be determined by its effectiveness in (*a*) reducing the ratio of the curvature at the clamp to that in the conductor, (*b*) increasing the rate of dissipation of energy per cycle of operation, and (*c*) decreasing the impact or longitudinal component.

These elements of protection can now be isolated and each treated on its own merit without the delay necessary to carry out endurance tests. Much work, of course, remains to be done to coördinate the

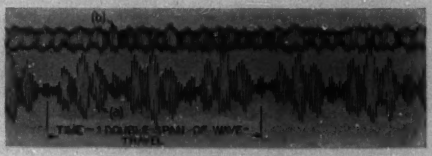


Fig. 11. Curvature records of vibrations in 795,000-cir mil aluminum cable steel reinforced conductors

a. At clamp
b. In span 275 ft from suspension clamp

results with the working stresses and strength of materials to determine what limiting conditions might be set in practice. It has been evident for some years that some factor of safety should be provided to take care of the fatigue due to vibrational stresses but the question of how much has not been determined.

References

An extensive bibliography has been prepared by the power transmission and distribution committee of the Institute and has been made available to members interested. It would be difficult to select even a limited number of references and do justice to those who have been actively interested in the problem for several years. This method of analysis, however, appears to be new and if this scheme has been published, even in part, the author and his associates have not been aware of such fact; hence the treatment has been developed directly from fundamentals of physics which are generally accepted and it is trusted will be clear to the reader without supplementary references.

Theory of Multielectrode Tubes

Physical principles underlying the characteristics and performance of multielectrode vacuum tubes are presented in simple form in this paper. The subject is presented from the viewpoint of those having an understanding of the physical principles of the ordinary triode or 3-element tube, but not having a similarly clear understanding of the more complex structures. Detailed analyses of the characteristics of several types of multielectrode tubes are given.

By
H. A. PIDGEON
MEMBER AM. PHYS. SOC.

Bell Tel. Labs.,
New York, N. Y.

INTRODUCTION of the 3-electrode vacuum tube into the field of communications and in other applications represented such a tremendous advance over the possibilities of any other known device that, despite some of its rather obvious limitations, it proved entirely adequate for the service required until comparatively recent years. However, with increasing demands made by service requirements for larger power output at higher efficiency, reduced distortion, higher gain, amplification at higher frequencies and greater frequency discrimination, it eventually became necessary to investigate the possibilities of making changes in vacuum tubes enabling them to meet these requirements more satisfactorily. Measures taken to meet this situation have included improvements in the 3-electrode tube that reduce the effects of some of its limitations, and the development of vacuum tubes having more than 3 electrodes.

The purpose of this paper is to present, in simple form, the physical principles underlying the characteristics and performance of multielectrode vacuum tubes. For present purposes, such tubes may be defined as those having more than the 3 electrodes of the conventional triode. The procedure will be to show that the definitions of electrical tube parameters applicable to triodes are, with certain modifications in their interpretation, also applicable to tubes having more than 3 electrodes; and, utilizing the theory of the triode, to analyze the characteristics of a few typical multielectrode structures that illustrate the types of characteristics found in many such tubes. No attempt is made to present new material in the paper or to discuss in detail the many different types of multielectrode tubes now in use. The author has attempted to present the subject from the viewpoint of those readers who have a satisfactory understanding of the physical principles, characteristics, and operation of the triode, but who do not have a similarly clear analysis available for the more complex structures.

Multielectrode tubes may be divided conveniently into 2 classes. In the first class are those the purpose of which is to perform some function that cannot be performed readily by a triode, or which perform some function better by reason of the elimination or reduction of some limitation in triodes. The second class includes those structures in which additional electrodes are introduced to permit them to perform simultaneously more than one function, or to permit them to function in 2 or more ways, depending on the voltages applied to the various electrodes and on the manner of their operation. This paper will deal exclusively with typical structures of the first class.

Fundamental Definitions and Tube Equations

Regardless of the type of multielectrode tube considered, the space current to any electrode may be ex-

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Sept. 13, 1934; released for publication Oct. 5, 1934. *Not published in pamphlet form.*

pressed as some function of the voltages applied to the various electrodes. However, in the operation of any multielectrode device, or any section of such a device performing a single function, one usually is concerned with variations in the voltages and corresponding currents of only 2 of the electrodes, the other electrodes being maintained at fixed potentials. One of these 2 electrodes, which usually is maintained at a negative operating potential, is connected to the input circuit and acts as a control electrode. The second of these 2 electrodes, which is maintained at a positive potential with respect to the cathode, acts as an anode or collector of electrons and is connected in the output circuit. Just as in the case of the triode, then, a study of the characteristics of multielectrode tubes is concerned with variations in the current collected by the anode with variations in the potential applied to the control grid.

This anode or plate current may be expressed as a function of the various electrode voltages by the following equation:

$$I_p = f(E_p, E_{g1}, E_{g2}, E_{g3}, \text{etc.}) \tag{1}$$

in which E_p is the operating voltage applied to the output anode or plate, and E_{g1}, E_{g2}, E_{g3}, etc., are the operating voltages applied to the various grids numbered outward from the cathode. The variation in the anode current, neglecting second and higher order terms, is given by

$$dI_p = \frac{\partial I_p}{\partial E_p}\,dE_p + \frac{\partial I_p}{\partial E_{g1}}\,dE_{g1} + \frac{\partial I_p}{\partial E_{g2}}\,dE_{g2} + \frac{\partial I_p}{\partial E_{g3}}\,dE_{g3} + \text{etc.} \tag{2}$$

The partial differential coefficients in eq 2 have the physical dimensions of conductances and, if these conductances be designated by the letter S with appropriate subscripts, the equation may be written

$$dI_p = S_{pp}\cdot dE_p + S_{g1}\cdot dE_{g1} + S_{g2}\cdot dE_{g2} + S_{g3}\cdot dE_{g3} + \text{etc.} \tag{3}$$

The plate or output anode conductance of a multielectrode tube is defined in the same manner as for the 3-electrode tube. It is the rate of change of plate current with plate voltage, that is, it is the slope of the plate current-plate voltage characteristic at the selected operating point, the potentials of all the other electrodes remaining constant. Under this condition, from eqs 2 and 3

$$\text{Plate conductance} = \frac{\partial I_p}{\partial E_p} = S_{pp} = S_p \tag{4}$$

Obviously, the plate resistance also must be defined in the same manner as in the triode, that is

$$\text{Plate resistance} = R_p = \frac{1}{\dfrac{\partial I_p}{\partial E_p}} = \frac{1}{S_p} \tag{5}$$

In a similar manner, the transconductance from the control grid to the output anode or plate of a multielectrode tube is defined, as it is in the triode, by the rate of change of plate current with variation of the control-grid voltage; that is, it is the slope of the plate current-grid voltage characteristic at the given operating point, the potentials of all electrodes other than the control grid remaining constant.

In conventional screen grid tetrodes and pentodes, the grid next to the cathode is the control grid. Consequently, for such structures, the transconductance is defined from eqs 2 and 3 by

$$\text{Transconductance} = \frac{\partial I_p}{\partial E_{g1}} = S_{g1} \tag{6}$$

In space-charge grid tetrodes and pentodes, the grid next to the cathode is maintained at a fixed positive potential and the second grid acts as the control grid. Consequently, in these and similar structures

$$\text{Transconductance} = \frac{\partial I_p}{\partial E_{g2}} = S_{g2} \tag{7}$$

Similarly, considering the control grid (assumed to be the first grid) and the output electrode of a multielectrode tube, the amplification factor is defined, as it is in the triode, by the ratio of the transconductance to the plate conductance. It is expressed by

$$\text{Amplification factor} = \mu_{pg1} = \frac{\dfrac{\partial I_p}{\partial E_{g1}}}{\dfrac{\partial I_p}{\partial E_p}} \tag{8}$$

Or, assuming that E_{g1} and E_p are varied in such a manner that I_p remains constant, the amplification factor is expressed in the usual form by

$$\mu_{pg1} = -\left.\frac{dE_p}{dE_{g1}}\right]_{I_p = \text{constant}} \tag{9}$$

Combining eqs 5 and 6 with eq 8 gives

$$\text{Transconductance } S_{g1} = \frac{\mu_{pg1}}{R_p} \tag{10}$$

just as in the case of the triode. Exactly similar equations apply if g2 is used as the control grid.

Obviously, the currents to the other electrodes in a multielectrode tube may be expressed by functions of the electrode voltages, similar to eqs 1 and 2. The various differential coefficients of these equations define transconductances, electrode resistances, and amplification (or reflex) factors analogous to those just given. Since these quantities are not used in this paper, they will not be given further consideration here. The voltage applied to the control grid will be designated by E_g, regardless of the grid employed for the purpose; and the transconductance (or mutual conductance) and the amplification factor, applying to the control grid and plate, will be designated by S_m and μ, respectively.

If a load resistance, R, is inserted in the plate circuit of a multielectrode tube, and if the potentials of all of the elements other than the control grid and plate are maintained constant, eq 3 reduces to

$$dI_p = S_p\cdot dE_p + S_m\cdot dE_g = \frac{1}{R_p}\cdot dE_p + \frac{\mu}{R_p}\cdot dE_g \tag{11}$$

In this case, the only independent variable is E_g, and E_p varies by reason of the changing potential drop across the external load resistance, R, due to variations in the plate current, I_p, produced by the varying grid potential. Consequently

$$dE_p = -dI_p\cdot R \tag{12}$$

Substituting eq 12 in eq 11 and reducing

$$dI_p' = \frac{\mu}{R_p + R}\cdot dE_g \tag{13}$$

For vacuum tubes having curvilinear characteristics, eq 13 applies rigorously, of course, only to infinitesimal variations in I_p and E_p. However, as in the case of the triode, the output from multielectrode tubes may be expressed by a power series in terms of finite voltage variations applied to the elements, and whose coefficients are functions of the static characteristics. If these finite variations in I_p and E_p are designated by i_p and e_p, respectively, the output current is expressed to the first order by

$$i_p = \frac{\mu e_g}{R_p + R} \tag{14}$$

which is identical with the equation expressing the output current from a triode.

Letting e_p represent the variable voltage across the load resistance, R, the voltage amplification is given by

$$A_v = \frac{e_p}{e_g} = \frac{i_p \cdot R}{e_g} = \frac{R}{R_p + R} \cdot \mu \tag{15}$$

It may also be written in the following form which will be found useful later

$$A_v = \frac{R_p \cdot R}{R_p + R} \cdot \frac{\mu}{R_p} = \frac{R_p \cdot R}{R_p + R} \cdot S_m \tag{16}$$

It should be emphasized, perhaps, that the electrical parameters of multielectrode tubes and the output current, as defined by the foregoing equations, are subject to the condition that the voltages applied to all of the electrodes other than the plate and control grid are maintained constant. The satisfactory operation of multielectrode tubes in circuits also usually requires that this condition be fulfilled. It requires that the impedance to alternating current components in each of these circuit branches be very low. This is accomplished in practice by connecting these electrodes to ground, so far as alternating currents are concerned, through reasonably large capacitances.

From the foregoing analysis it is apparent that, with proper interpretation, the definitions of plate resistance, transconductance, and amplification factor applicable to triodes are also applicable to multielectrode tubes; in addition, the same expressions for output current and voltage amplification are applicable. This follows from the fact that these quantities are expressed in terms of the differential coefficients of the static characteristics, that is, they depend only upon the slopes of these characteristics at the given operating voltages and not upon their form. However, as will appear later, the difference in the shape of the static characteristics of multielectrode tubes from those of triodes is very important in determining great differences not only in the magnitude of the electrical parameters, but also in the character and amount of distortion resulting when the tubes are operated under conditions such that large portions of the characteristics are traversed.

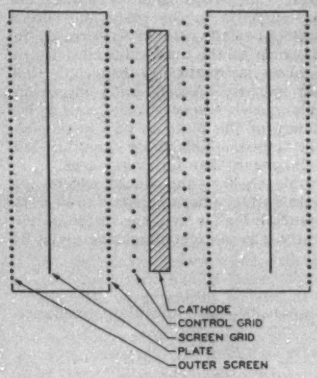


Fig. 1. Schematic diagram showing the arrangement of electrodes in a screen grid tetrode

In multielectrode tubes, as well as in triodes, the total space current drawn from the cathode is determined by the extent to which the resultant field, due to the electrodes, overcomes the opposing field produced by space charge. While space charge extends throughout the interelectrode space, it is relatively so much more dense in regions of very low electron velocity that, as a first approximation, its effect usually may be neglected in other regions. Except in space-charge grid tubes and a few other special tubes, the only important space charge region is confined to a relatively thin sheath near the cathode surface. Consequently, in such structures the total space current is determined largely by the extent to which the resultant positive field due to the electrodes neutralizes the negative field near the cathode surface produced by space charge. An appreciation of this fact is essential to a clear understanding of the characteristics of multielectrode tubes.

Screen Grid Tetrode

Utilizing the simple theory of triodes, which has been shown to be applicable to multielectrode tubes also, the characteristics of a multielectrode tube will be analyzed next. For this purpose the screen grid tube is chosen, since it admirably illustrates the type of characteristics found in several types of multielectrode tubes.

The objective in this case is to reduce the direct capacitance between the plate and control grid through which energy is fed back from the plate to the input circuit. This is accomplished by inserting an electrostatic shield between the plate and control grid of what otherwise would be a 3-electrode tube. The condition that such a screen must allow an electron stream to flow through it to the plate, is satisfied by making it of fine mesh or in the form of a finely wound grid structure. To be effective, it must be maintained at some constant potential with respect to ground.

The arrangement of the electrodes in such a tube is shown diagrammatically in Fig. 1. The screen structure outside the plate is added for the purpose of completing the electrostatic isolation of the plate and its leads from the grid, thus reducing the ca-

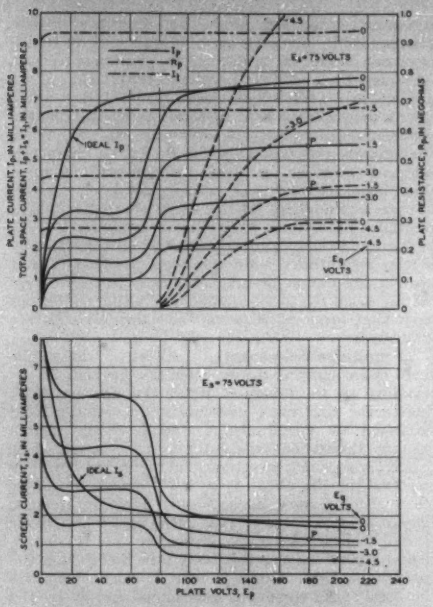


Fig. 2. Characteristics of a screen grid tetrode

The curves show the plate current, I_p, screen current, I_s, total space current, $I_t = I_p + I_s$, and plate resistance, R_p, as functions of the plate voltage. Control-grid voltage, E_g, is indicated on the curves. Screen voltage, E_s, is maintained constant at 75 volts throughout

pacitance between these 2 elements to the lowest practicable value. This outer screen is of no further concern, since it has no effect on the static characteristics of the tube. The usual characteristics of a typical screen grid tetrode are shown in Figs. 2, 3, and 4. In this case, as is usual in screen grid tubes, the shielding is very complete, reducing the direct capacitance between the plate and control grid to a few thousandths of what its value would be in the absence of the screen.

First, the characteristics of Fig. 2 will be considered. Since the direct capacitance between the plate and the control grid, $g1$, is extremely small, the electric field in the immediate vicinity of the latter, produced by any potential on the plate, also must be extremely small. The cathode is electrically even more remote from the plate than the control grid, because it not only is shielded from the former by the screen grid, but also has some additional shielding from the control grid. Consequently, the field produced by the plate at points between the cathode and control grid is smaller even than the field produced at the control grid and, hence, is negligibly small. Since, as previously discussed, the total space current is determined almost wholly by the field very near the cathode surface, the plate in this case can have practically no effect on the total space current drawn from the cathode. This is shown by the curves giving the total space current, I_t, in Fig. 2. These curves are seen to be so flat as to be almost entirely independent of variations in the plate voltage.

The plate, then, in a screen grid tube plays an essentially passive rôle which is to collect those electrons that succeed in passing through the screen. The remainder of the space current is collected by the screen, the sum of the plate and screen currents remaining nearly constant with changes in plate voltage.

There is nothing in the theory of the triode by which to determine the ratio in which space current divides between 2 or more positive electrodes in a multielectrode tube. As a rough approximation, one might assume that when their potentials are nearly equal the currents to the plate and screen would be proportional to the ratio of the area of the openings in the screen to the area subtended by its lateral wires. Also, it might be expected that this ratio would increase slightly with increasing voltage of the plate with respect to the screen, because of a tendency of the plate to pull more electrons through the screen. This effect should be less for very fine mesh screens than for coarse ones.

From this simple theory, one would expect the plate current-plate voltage characteristics to be very flat for plate potentials higher than the screen potential. Consequently, the plate conductance given by

$$S_p = \frac{\partial I_p}{\partial E_p} = \frac{1}{R_p}$$

is a very small quantity; and the plate resistance, given by

$$R_p = \frac{1}{\frac{\partial I_p}{\partial E_p}}$$

is a very large quantity compared with its value in triodes, and increases with the fineness of mesh of the screen grid. The plate current curves of Fig. 2 are seen to be in general accord with this simple theory at the higher values of plate voltage, although they are not quite as flat as might be expected from the theory. This, and the rapid falling off in the vicinity of 100 volts, will be discussed later.

Taken alone, the extremely high resistance of a screen grid tube would seem to be a very serious disadvantage. From eq 14, the tube may be considered as analogous to a generator the electromotive force of which is μe_g and the internal resistance of which is R_p, working into an external load resistance R—a generator with extremely high internal resistance. Why this is not fatal to the usefulness of the tube will be pointed out later.

While the plate current in a screen grid tube is nearly independent of plate voltage for values of the latter higher than the screen potential, this obviously cannot hold at low values of plate voltage. At zero plate voltage, the plate current must be zero. At this point the screen collects the entire space current and $I_s = I_t$. As the plate potential increases from zero, the plate current would be expected to rise

rapidly, with a corresponding drop in the screen current, as the plate collects more and more of the electrons passing through the screen. However, 2 factors tend to prevent an abrupt rise in the plate current to its nearly constant value when the plate becomes slightly positive. The first of these is space charge in the region closely adjacent to the plate produced by the electrons that pass through the screen, reach zero velocity in the region adjacent to the plate, and return to the screen. Some of them may perform several oscillations to and fro through the screen before being captured by it. This space charge effect is largely masked by the more important second factor which is the deflection of the majority of the electrons from their normal paths by the intense electric fields about the lateral wires of the screen. This results in large differences in the components of velocity of the electrons normal to the surface of the plate and, consequently, in the distance to which they approach the plate in their trajectories before being turned back to the screen. As a result, the plate must become positive by several volts with respect to the cathode before it captures substantially all of the electrons that pass through the screen.

From this simple theory, the plate current and screen current curves would be expected to have the form shown by the ideal curves of Fig. 2. Obviously, the screen current curves must be complementary to the plate current curves since the sum of the 2 currents is substantially constant.

The difference between these ideal curves and the actual characteristics, in the region extending from a few volts to potentials somewhat higher than the screen voltage, is attributed to the phenomenon of secondary electron emission. When electrons strike a metal surface with velocities equivalent to more than a few volts, other electrons, known as secondary electrons, are liberated from the surface. The number of electrons so liberated varies not only with the velocity of the primary bombarding electrons, but also with the character of the metal surface, the amount of adsorbed gases and other materials on the surface, and other factors. The number of such electrons leaving the surface may even exceed the number of primary electrons striking it, in which case the net current to the metal surface is negative. The velocity of the secondary electrons varies greatly. A very few have velocities approaching that of the primary electrons. The great majority, however, have low velocities equivalent to only a few volts.

In the screen grid tube, an appreciable number of secondary electrons is liberated from the plate at potentials between 5 and 10 volts, and they increase in number with plate voltage. For plate potentials lower than the screen potential, in this case 75 volts, the secondary electrons from the plate are drawn to the screen, thus increasing the screen current by the amount the plate current is decreased. When the plate reaches a potential equal to that of the screen, secondary electrons no longer can escape from the plate to the screen, except those emitted with appreciable velocities; consequently, the plate current rises rapidly to its normal value.

At plate potentials higher than the potential of the screen, secondary electrons emitted from the latter are drawn to the plate. Consequently, in this region the plate current is slightly higher than it would be in the absence of secondary electron emission from the screen. The gradual rather than abrupt rise in the plate current curves at 75 volts is attributed primarily to the distribution of velocities with which the secondary electrons are emitted; to a lesser extent, it is dependent also on the combined effects of space charge, intensity, and distribution of the field at the surface of the screen wires.

Normal operating conditions for the screen grid tube the characteristics of which are shown in Fig. 2 are: $E_p = 180$ volts, $E_s = 75$ volts, and $E_g = -1.5$ volts. At this operating point P in Fig. 2, the plate current is 5.5 ma and the plate resistance is 400,000 ohms. The operating range is confined to the flat portion of the characteristics. If the tube is operated with plate voltage swings sufficiently large that the instantaneous values of the plate potential extend into the region of rapidly falling plate current, serious distortion of the output results. This is a serious limitation in screen grid tetrodes, because it requires that the operating plate potential be much higher than the screen potential. How this limitation may be removed by the introduction of an additional electrode in the tube will be shown later.

Curves showing the variation of plate resistance with plate voltage are shown in Fig. 2. The plate resistance decreases with plate voltage, falling off

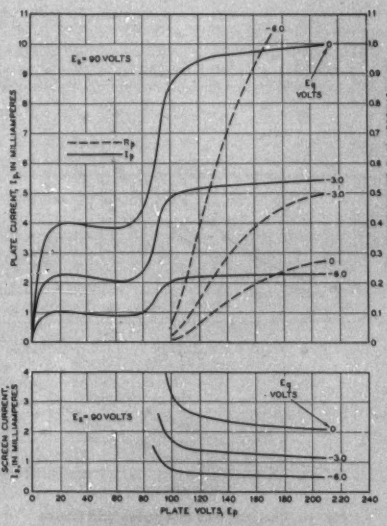


Fig. 3. Characteristics of a screen grid tetrode similar to those shown in Fig. 2 except that E_s = 90 volts

very rapidly as the plate voltage approaches the screen voltage. The ordinates of the plate resistance curves give a measure of the flatness of the plate current curves. That the latter are not as flat as the total-space-current curves, thus resulting in values of plate resistance approaching infinity, is attributed to 2 factors: secondary electron emission from the screen, and an increasing ratio of plate current to screen current with increasing plate voltage. The increasing percentage of the primary space current drawn to the plate with increasing plate voltage is an involved and undetermined function of several factors including: the ratio of the openings in the screen grid to the total conducting area subtended by it, the intensity and distribution of the field at the screen grid, the velocity and directional distribution of the electrons arriving at the screen grid, and space charge effects in its vicinity.

Thus, there is the interesting situation in screen grid tubes that, for any given set of operating voltages, the magnitudes of the plate resistance and amplification factor are determined largely by factors not directly determined by the geometry and design of the tube. This is quite different from triodes in which the plate resistance and amplification factor both are determined directly by geometrical dimensions and the arrangement of the electrodes.

Obviously, the number of electrical parameters in vacuum tubes increases rapidly with the number of electrodes. The curves of Fig. 2, which correspond to the usual plate current-plate voltage characteristics for a triode, were obtained with the screen maintained at a constant potential of 75 volts as a fixed parameter. To obtain a complete charting of the characteristics would require several such families of curves taken with different screen voltages. One such additional family of characteristics, in which E_s is maintained at 90 volts, is shown in Fig. 3.

Since the plate in a screen grid tube has practically no effect on the total space current, so far as consideration of the latter is concerned one may regard the plate as being removed from the structure and consider only the remaining elements. The cathode, control grid, and screen then may be regarded as constituting an ordinary triode. By maintaining the screen at a positive potential, it is enabled to perform the function usually performed by the plate of a triode, *viz.*, that of supplying the positive field necessary to produce the flow of space current against the opposing resistance due to space charge. This function does not interfere with its screening action, so long as its potential is not allowed to vary. In fact, there is an actual gain in efficiency, as will be shown later, in having the electrode that provides the main driving field for the space current maintained at a fixed potential instead of varying over the operating cycle as it must in the triode.

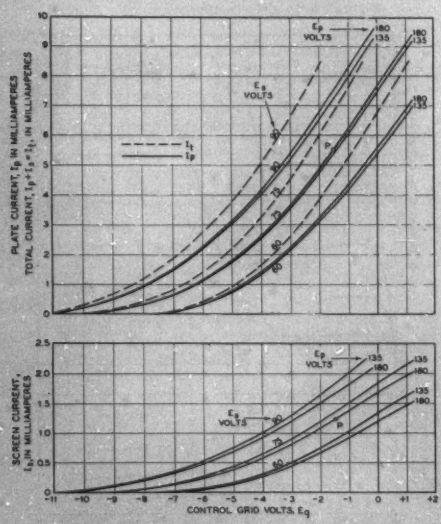


Fig. 4. Characteristics of a screen tetrode

Plate current, I_p, screen current, I_s, and total space current, I_t, as functions of the control-grid voltage, with various values of plate voltage and screen voltage as parameters

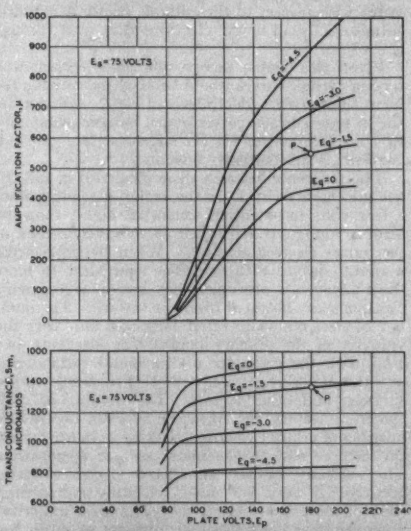


Fig. 5. Amplification factor and transconductance of a screen grid tetrode as functions of the plate voltage

Usual design principles and equations applicable to triodes are also applicable to screen grid tetrodes. By making the spacings between the electrodes small,

particularly that between the cathode and control grid, a high transconductance can be obtained. Using the subscript t to designate total space current, the transconductance is given by $S_t = \frac{\partial I_t}{\partial E_g}$ and has the same value as that for a triode of the same dimensions. Let f represent the fraction of the total space current that passes through the openings in the screen and is collected by the plate, which is assumed to be at a higher potential than the screen. By proper design, f can be made large, say from 0.7 to 0.9, in the normal operating range. The transconductance from the control grid to the plate is given by

$$S_m = \frac{\partial I_p}{\partial E_g} = f \cdot \frac{\partial I_t}{\partial E_g}$$

which is 0.7 to 0.9 of the normal value of transconductance for the 3-electrode tube.

The amplification factor, μ, for the tetrode, is given by

$$\mu = \frac{\frac{\partial I_p}{\partial E_g}}{\frac{\partial I_p}{\partial E_p}} = S_m \cdot R_p \qquad (17)$$

Since the transconductance, S_m, has a value not greatly different from the normal value for a triode, and since R_p is very large, μ, which is proportional to R_p, also must be very large. Referring to eq 14 and its analogy with the generator equation, it may be seen that, despite the fact that the screen grid tube considered as a generator has a very high internal resistance, it gives normal output because it is provided also with a very large electromotive force, μe_g.

From this analysis of the characteristics of the screen grid tube, based upon the simple theory of triodes, one would expect that families of characteristics corresponding very closely with those of ordinary triodes would be obtained if the total space current, or the plate current, were plotted as functions of the control grid voltage and screen grid voltage, with the plate maintained at any fixed potential higher than the screen potential. It would be expected further that the family of curves showing total space current would remain practically invariant with variations in plate voltage. The plate current family of characteristics should show only small variations with plate voltage (so long as E_p is higher than E_s), depending on the magnitude of the change in the ratio of I_p to I_s.

Families of such characteristics are shown in Fig. 4. They are seen to correspond very closely indeed with similar characteristics for a triode. The I_t curves vary so little with plate voltage that the families of characteristics taken at $E_p = 135$ volts and $E_p = 180$ volts, coincide within the breadth of the curves. The plate current curves show a small variation with E_p, as was discussed previously.

In Fig. 5 the transconductance and amplification factor are shown as functions of the plate voltage for 4 different values of grid bias and with the screen potential maintained constant at 75 volts. At the normal operating point P, the transconductance is 1,375 micromhos and the amplification factor is 550.

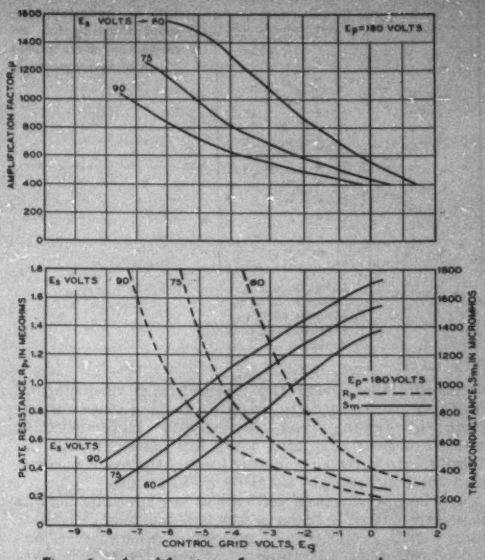


Fig. 6. Amplification factor, transconductance, and plate resistance of a screen grid tetrode as functions of the control-grid voltage

The shape of these curves is typical of that for screen grid tubes and pentodes. Throughout the normal operating range, the transconductance curves have about the same degree of flatness as the plate current curves. This is to be expected from consideration of the plate current curves of Fig. 4. Since these curves change only slightly with variations in plate potential, their slopes or transconductance values also change but slightly. The amplification factor curves are very similar in form to the plate resistance curves of Fig. 2. This follows at once from eq 17, for since S_m remains nearly constant with variations in E_p, μ must vary in the same manner as R_p.

In Fig. 6 the transconductance, plate resistance, and amplification factor are shown as functions of grid voltage for 3 different values of the screen voltage and with the plate voltage maintained constant at 180 volts. These curves are also typical of those found for several multielectrode tubes. The transconductance curves agree in form with those for a triode, as would be expected from the plate current curves of Fig. 4. The plate resistance curves are similar in form to those for a triode, but rise more rapidly with increasing negative grid bias. The amplification factor curves, however, are entirely different in form from those for a triode, since they rise with increasing negative grid bias, whereas in triodes the amplification factor decreases with increasing negative grid bias. The reason for this difference is that the plate resistance in many multi-

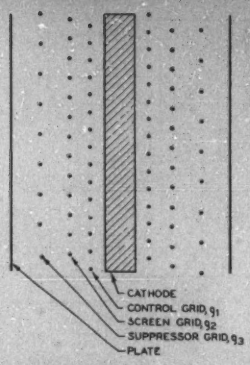


Fig. 7. Schematic diagram showing the arrangement of electrodes in a power pentode

electrode tubes, over the normal range of operation, increases more rapidly with decreasing plate current than in triodes. At sufficiently large negative values of grid bias and very low plate currents, the amplification factor curves frequently reach maxima and then fall rapidly as they do in triodes.

In the operation of triodes as voltage amplifiers, it is usually possible to have the external load resistance large with respect to the plate resistance. Consideration of eq 15 shows that this results in a voltage amplification ratio approaching the amplification factor. In the operation of screen grid tubes and conventional pentodes as well, which have high plate resistances, it is usually necessary that the load resistances be much smaller than the plate resistances. This limitation is imposed by circuit coupling requirements and sometimes by restrictions on the permissible harmonic content in the power output. This limitation results in an amplification ratio that is much smaller than the amplification factor; but even so, a considerably higher amplification ratio usually can be obtained than with triodes. This is apparent from consideration of eq 16 which may be written in the form,

$$A_v = S_m \cdot \frac{R}{1 + \frac{R}{R_p}} \tag{18}$$

Since in screen grid tubes and pentodes R/R_p is small, the voltage amplification is given approximately by

$$A_v = S_m \cdot R \tag{19}$$

Now, in a comparable triode the transconductance will have a value comparable with S_m, and it may be assumed that a load resistance could be used comparable with R. However, the ratio R/R_p for the triode is not small and may be greater than unity. Hence, from eq 18, the amplification obtained with the triode is correspondingly smaller.

It has been shown that the presence of the electrostatic screen in the screen grid tetrode results in a high plate resistance and a high amplification factor, but that the ratio of μ to R_p (transconductance) remains normal. Such tubes yield high amplification and, with suitable associated circuits, are relatively free from feed-back; but they are limited in their range of operation because of the fold in the plate current-plate voltage characteristics resulting from secondary emission from the plate.

Power Pentodes

In order to deliver a large power output, a vacuum tube must be capable of large variations in plate current and plate voltage from their normal operating values. Both of these conditions are fulfilled by the power pentode. The arrangement of the electrodes, shown schematically in Fig. 7, corresponds to that in a screen grid tube except that an additional grid, $g3$, is inserted between the plate and screen grid, $g2$. As in the screen grid tube, the first grid, $g1$, has a negative voltage applied to it and acts as the control element. The second grid, $g2$, is maintained at a fixed positive potential, E_s, and provides the main driving field for the space current.

As in the screen grid tube, the total space current is determined almost wholly by the geometrical dimensions and spacings of the cathode, $g1$ and $g2$, and by the voltages applied to these electrodes. Consequently, in the design of this portion of the structure, the same considerations apply as in the design of an ordinary triode to deliver large power

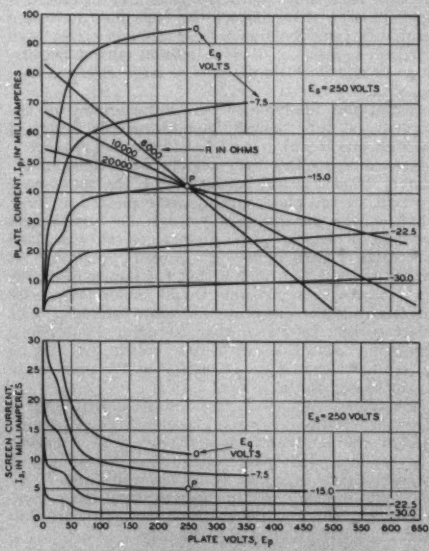


Fig. 8. Characteristics of a power pentode

Plate current, I_p, and screen current, I_s, as functions of the plate voltage with various values of the control-grid voltage, E_g, as parameters. Screen voltage, E_s = 250 volts throughout. Load lines are shown for resistance loads of 6,000, 10,000, and 20,000 ohms

output. By making the inner grid comparatively coarse and by designing the second grid to operate at comparatively high potentials, a structure having a low amplification factor is obtained which draws a large space current from the cathode at a control grid bias sufficiently negative to permit relatively large swings of the control grid voltage. In pentodes designed to operate at low frequencies, screening between the plate and control grid is unimportant; hence, the second grid can be comparatively coarse thus permitting as large a portion as possible of the space current to pass through it to the plate.

To permit the largest possible swings in plate voltage, it is necessary to remove the "fold" in the plate current characteristics, caused by secondary electrons emitted from the plate. This is accomplished by the insertion of a third grid, g3, between the plate and second grid, g2. This grid, known as a suppressor grid, must be maintained at a lower potential than the lowest instantaneous potential reached by the plate, and is usually maintained at the cathode potential by connecting it to the cathode inside the tube. The suppressor grid exerts a retarding force on the primary electrons flowing toward it from the cathode, but, because of its coarse structure, all but a small fraction succeed in passing through it and are accelerated again, finally reaching the plate with the same velocity they would have if the suppressor grid were absent. On the other hand, secondary electrons emitted either by the plate or screen grid find themselves in a retarding field, which they are unable to traverse because of their low velocity, and are constrained to return to the electrode from which they came.

Plate current-plate voltage characteristics and screen current-plate voltage characteristics for a power pentode of the indirectly heated cathode type, are shown in Fig. 8. The secondary emission "fold" in the characteristics is almost completely eliminated by the suppressor grid.

The effectiveness of the suppressor grid is shown by the characteristics of Fig. 9. These curves were obtained from a tube of the same type as that for which the characteristics are shown in Fig. 8. One

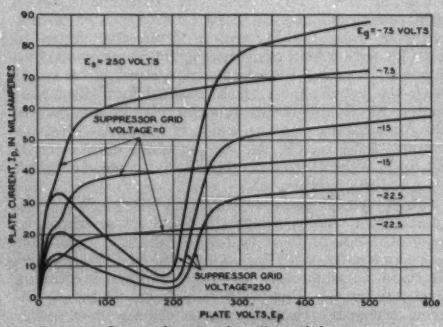


Fig. 9. Curves showing the effect of the suppressor grid in a power pentode

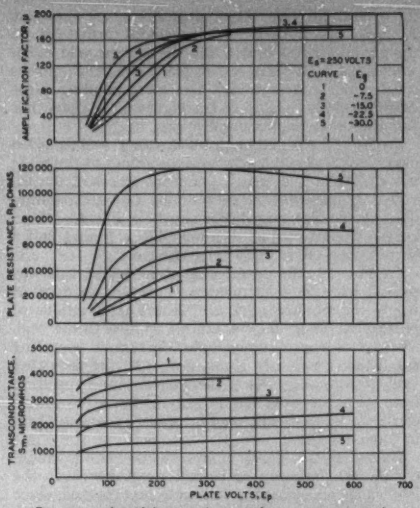


Fig. 10. Amplification factor, plate resistance, and transconductance of a power pentode as functions of the plate voltage, with various values of control-grid voltage as parameters

Screen voltage, E_s, is maintained constant at 250 volts

set of curves was obtained with the suppressor grid operating in the normal manner. The other curves were obtained with the suppressor grid tied to the screen grid and maintained at a positive potential of 250 volts. In this latter case, the number of secondary electrons escaping from the plate is practically the same as if the suppressor grid were removed from the tube. The presence of the suppressor grid not only permits the plate to swing to very much lower potentials than otherwise would be possible, but also permits the plate and screen to operate at the same potential, which is 250 volts in this case.

The characteristics of Fig. 8 closely approach the form that would be expected from simple theory. As is usual with power pentodes, the curves are not quite as flat as those for screen grid tubes. This is because of the more open character of the grids which permits the plate to have a slightly greater effect on the magnitude of the space current. This is evidenced also by the tendency of the curves to turn up at the higher plate voltages.

The normal operating point for this tube is at point P in Fig. 8, at which the plate and screen potentials are both 250 volts and the control grid potential is -15 volts. Under these conditions, the average characteristics are: $I_p = 42$ ma, $I_s = 5$ ma, $\mu = 156$, $R_p = 52{,}000$ ohms, and $S_m = 3{,}000$ micromhos.

Curves showing the amplification factor, μ, the plate resistance, R_p, and the transconductance, S_m,

for several different values of grid bias, are shown in Fig. 10. They correspond in general form to those shown in Figs. 3 and 5 for the screen grid tube. The maxima in some of the plate resistance curves result from the fact that the corresponding plate current curves turn up at the higher plate potentials and thus have points of inflection.

In Fig. 11, the plate current is shown as a function of control grid voltage for various values of the plate voltage, with the screen potential constant at 250 volts. The curves are very similar to corresponding ones for the screen grid tube shown in Fig. 4. Here, curves are included at such low plate voltages that a large falling off in plate current occurs.

In Fig. 12, the power output in watts, and the second and third harmonics, expressed in decibels below the fundamental, are shown as functions of peak volts for a sinusoidal input applied to the grid. These data were obtained under the normal operating conditions previously given, and with the indicated load resistances. Since the curves are typical in form of those obtained in several types of multi-electrode tubes, it will be of interest to examine them in some detail.

Except at the higher inputs, the power output increases continuously with load resistance over the load range considered. This is to be expected, since the highest load resistance of 12,000 ohms is much smaller than the plate resistance of the tube, which is 52,000 ohms. For small inputs, the maximum power output would be obtained, as it is in triodes, when the load resistance is equal to the plate resistance of the tube. The decrease in power output with increasing load resistance, at the higher inputs, results from the progressive turning over of the dynamic characteristics as shown by the curves of Fig. 11.

The second harmonic decreases continuously with increasing load resistance at small inputs. At large inputs, it decreases at first, then increases with

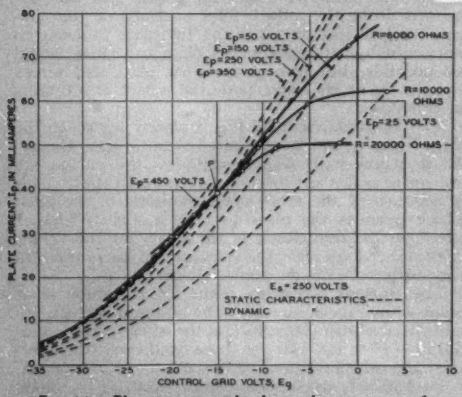
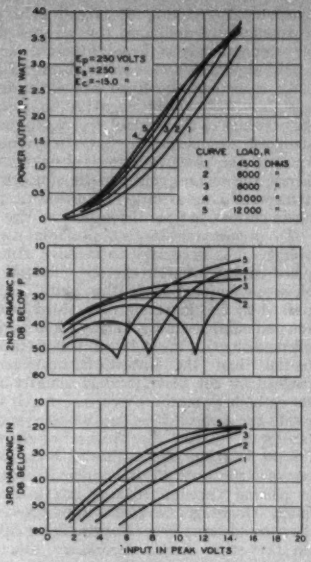


Fig. 11. Plate current-grid voltage characteristics of a power pentode, with dynamic characteristics for resistance loads of 6,000, 10,000, and 20,000 ohms

Fig. 12. Characteristics of a power pentode

Power output, P, in watts, second and third harmonics in decibels below the fundamental, as functions of the peak input when a sinusoidal voltage is applied to the control grid



increasing resistance. At very low resistances, the second harmonic increases continuously with input. At higher load resistances, it rises to a broad maximum, then falls to a very sharp minimum, after which it again rises rapidly with increasing input. The explanation of these phenomena will be given later.

The third harmonic increases continuously both with increasing input and with increasing load resistance. At load resistances that are small compared with the plate resistance of the tube, it rises to a higher level than the second, over a certain range of input. Relatively high levels of third harmonic are characteristic of pentodes, screen grid tubes, and also of some other types of multi-electrode tubes. For example, from the curves of Fig. 12, with a load resistance of 6,000 ohms and an input of 15 peak volts, the power output is 3.8 watts with the volume level of the second and third harmonics 31 db and 26 db, respectively, below that of the fundamental. At an input of 10 peak volts, the volume level of the second harmonic rises to 27 db and of the third harmonic falls to 36 db below that of the fundamental.

These results are quite different from those obtained with triodes where the third harmonic is, in general, 10 db or more below the second. Furthermore, in triodes, both the second and third harmonics decrease continuously, as a rule, with increasing load resistance. There are exceptions to this, however, where the third harmonic curves show minimum points or cusps, similar to those shown by the second harmonic curves for pentodes.

The reason for the relatively large harmonic content in the output of pentodes is apparent from consideration of the load lines drawn through the operating point P in Fig. 8. At the lower values of plate voltage, the load lines cut across the rapidly descending portions of the plate current characteristics. This effect is more marked and begins at more negative values of grid bias as the load resistance increases and the slope of the load lines becomes correspondingly less. The effect of this is to produce current variations through the external load resistance that are not proportional to the variations in grid voltage, thus resulting in distortion of the output.

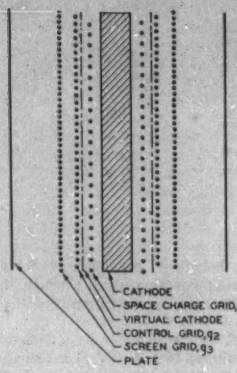


Fig. 13. Schematic diagram showing the arrangement of electrodes in a space-charge-grid pentode

The character of the distortion is made clearer by reference to the dynamic characteristics of Fig. 11, for resistance loads of 6,000, 10,000, and 20,000 ohms. All the curves show a flattening out at the top which increases progressively with load resistance. It readily is shown that such dynamic characteristics, having points of inflection at which the curvature changes sign, give rise to peculiarities in the harmonic output.

If such a characteristic be expressed by a power series in terms of grid voltage variations from the operating point P, there usually is found a relatively large contribution by third and higher odd-power terms the coefficients of which are predominantly negative in sign. Since odd-power terms yield odd harmonics, this accounts for the relatively high levels of third harmonic at input voltages sufficiently large that the flat portion of the characteristic is traversed. However, positive and negative signs are about evenly divided among the coefficients of the even-power terms, which yield even harmonics. At some value of the input voltage, which varies with the load resistance, the contributions to the second harmonic by positive and negative terms are approximately equal, resulting in a very small value of this harmonic. This accounts for the cusps in the second harmonic curves of Fig. 12. For inputs less than the value at the cusp, the contribution of positive terms (largely the second-power term) prevails over that of negative terms, while at higher inputs the reverse is true. Consequently, there is a reversal in the phase of the second harmonic at the cusp.

If the point of inflection were at the operating point P and, if the dynamic characteristic were symmetrical about P, then only odd-power terms would appear in the equation of the curve. Consequently, in this special case, even harmonics would vanish from the output and only odd harmonics would remain.

Plate circuit efficiency of pentodes is higher than that usually found in triodes. The underlying physical reasons for this difference are as follows: In the triode, the plate simultaneously performs 2 functions. First, it is the element in the output circuit whose fluctuating potential is impressed across the load resistance. Second, assuming that the grid potential is not positive, the plate is the only positive electrode providing the necessary driving force for the space current. These 2 functions militate against each other to a certain extent, for, as is evident from consideration of the dynamic characteristic of either a triode or a pentode, the plate voltage reaches its minimum value at the instant when the plate current reaches its maximum value. This minimum voltage, which must be sufficiently large to draw the peak current through the tube, is a very

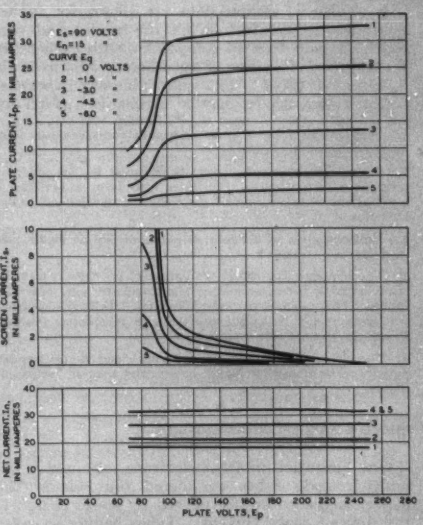


Fig. 14. Characteristics of a space-charge-grid pentode

Plate current, I_p, screen current, I_s, and net (space-charge-grid) current, I_n, as functions of the plate voltage with the indicated values of control-grid voltage as parameters. Screen-grid voltage, E_s = 90 volts. Net (space-charge-grid) voltage, E_n = 15 volts

Table I—Comparative Data for Typical Triodes and Pentodes

	Triodes			Pentodes		
	A	B	C	D	E	F
Plate voltage, E_p	200	250	325	180	250	250
Screen voltage, E_s				180	250	250
Grid voltage, E_c	−45	−50	−68	−18	−16.5	−15
Plate current, I_p, ma	45	34	60	14.5	34	42
Screen current, I_s ma				2.8	6.5	5
Transconductance, S_m, micromhos	2,610	2,175	5,200	1,050	2,200	3,000
Amplification factor, μ	2.9	3.5	3.8	105	220	156
Plate resistance, R_p, ohms	1,030	1,610	730	100,000	100,000	52,000
Load resistance, R, ohms	2,060	3,900	2,750	12,000	7,000	6,000
Input, peak volts	45	50	68	18	16.5	15
Power output, watts	1.9	1.9	7.8	1.2	3.0	3.8
Second harmonic, %	7.4	5.7	5.0	5.0	2.3	2.8
Third harmonic, %	0.7	1.2	1.1	7.5	6.6	5.0
Total harmonic, effective %	7.45	5.9	5.1	9.0	7.0	5.7
Plate efficiency, %	21	22	40	46	35	36
Plate-grid capacitance, $\mu\mu f$	12	7.2	20	1.2	0.8	0.2
Plate-ground capacitance, $\mu\mu f$	3.2	3.0	5.5	7.8	8.5	15
Grid-ground capacitance, $\mu\mu f$	6.8	4.5	9	6.4	8.4	9

substantial fraction of the operating plate voltage, particularly when the latter is comparatively low.

In pentodes and in some other multielectrode tubes, the positive grid, maintained at a constant voltage, provides the necessary driving force for the space current, thus relieving the plate from performing this function. Consequently, the plate is free to swing to lower voltages than otherwise would be possible, which results in a corresponding increase in efficiency.

In Table I, similar data are shown for typical pentodes and triodes. While the triodes and pentodes are not directly comparable with each other, the data are indicative of the differences between the 2 types of tubes. The chief differences between pentodes and triodes may be summarized as follows:

1. Pentodes yield higher gain and require correspondingly lower input voltages to drive them.

2. Pentodes have much higher amplification factors and plate resistances than triodes. The latter constitutes a handicap in coupling the tube to its circuit, particularly if transformer coupling is employed.

3. Pentodes yield high power output, generally at higher plate efficiency than triodes.

4. The harmonic content in the output of pentodes is high, the third harmonic being particularly high compared with its level in triodes. This requires that pentodes work into load impedances that are very low compared with the plate resistance. Ratios of R to R_p of $^1/_3$ to $^1/_{10}$ are common.

5. The plate-grid capacitance is much lower and the plate-ground capacitance is somewhat higher in pentodes than in comparable triodes.

Space-Charge-Grid Pentodes

One limitation in the 3-electrode tube and in the multielectrode tubes considered thus far in this paper, is the resistance offered by space charge to the flow of space current. Tubes having so-called space-charge grids overcome this limitation to some extent by having a positive grid close to the cathode, which partially neutralizes the negative field very near the cathode surface due to space charge. A comparatively large current is drawn from the cathode by the space-charge grid. A portion of this current (usually about half of it) is collected by this grid, while the remaining portion passes through it and is acted on by the remaining elements of the tube.

The arrangement of the electrodes in a space-charge-grid pentode is shown in Fig. 13. The space-charge grid, $g1$, is maintained at a relatively low positive potential with respect to the cathode, usually in the range from 10 to 20 volts. The second grid, $g2$, is the control grid and is maintained at a negative potential with respect to the cathode.

Ideally, at some cylindrical surface between these 2

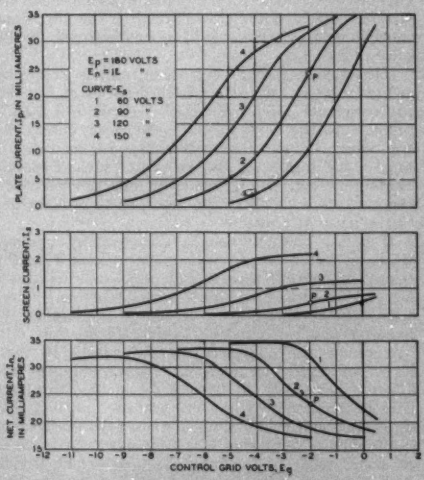


Fig. 15. Characteristics of a space-charge-grid pentode

Plate current, screen current, and net current as functions of the control-grid voltage, E_g, with the indicated values of screen voltage as parameters. Plate voltage, E_p = 180 volts. Net voltage, E_n = 15 volts

grids (assuming the structure to be cylindrical) the electrons are retarded to nearly zero velocity forming a second space-charge region which may be regarded as a virtual cathode. Since this space-charge sheath is larger in area than the original cathode and is very close to the control grid, it results in very large values of transconductance. Practically, the ideal condition is not fully realized, largely because velocity components other than radial are imparted to the electrons in passing through the space-charge grid. Consequently, these electrons reach any given cylindrical surface outside the space-charge grid with rather widely varying radial components of velocity. This, as will be seen later, places a rather serious limitation on the performance of such tubes.

The arrangement and functioning of the other electrodes in Fig. 13, outward from the virtual cathode, corresponds with that of the screen grid tetrode. The screen grid, $g3$, is maintained at a fixed positive potential necessary to accelerate the electrons from the region of the virtual cathode. The plate must be maintained at a potential higher than that of the screen for the same reason as in the screen grid tetrode. It will be shown that the characteristics of this pentode correspond roughly with those of the screen grid tube previously discussed.

If $g3$ were omitted, the structure outside the virtual cathode would correspond to that of a triode and the characteristics in the resulting tetrode would correspond roughly to those of a triode. In Fig. 14, characteristics are shown for a pentode of this type, the cathode and general dimensions of which are the same as those of the power pentode, the characteristics of which were shown previously. The plate current and screen current curves are seen to correspond very closely with those previously shown for a screen grid tube. The characteristics exhibit the same "folds" due to secondary electrons, although this portion of the characteristics is not shown. The net or space-charge-grid current I_s increases as the plate current decreases with increasing negative control grid voltage. This is to be expected since, as the control grid becomes more negative and reduces the current passing through it to the plate, the excess current returns to the net rather than to the cathode as in the screen grid tube.

If values of the amplification factor, plate resistance, and transconductance are plotted as functions of the plate voltage, families of curves are obtained similar in all respects to those for a screen grid tube as shown in Figs. 3 and 5. These characteristics are not shown for this tube.

In Fig. 15, plate current, screen current, and net current characteristics are shown as functions of the control grid voltage with different values of the screen voltage as parameters. As in the case of the screen grid tube, only a slight displacement of the characteristics results from variation of the plate voltage. It is of interest to note the high values of net current, particularly as the plate current drops toward zero with increasing negative grid bias. For example, if the operating point is chosen at P in Fig. 15, with a screen potential of 90 volts and a grid potential of -2 volts, the plate current, screen current, and net current are 24, 0.5, and 23 ma,

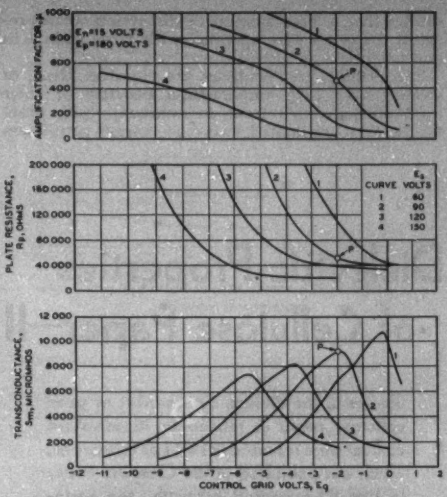


Fig. 16. Amplification factor, plate resistance, and transconductance of a space-charge-grid pentode as functions of the control-grid voltage

respectively, making a total space current of 47.5 ma drawn from the cathode, nearly half of which is collected by the space charge grid.

Another point of interest in Fig. 15 is the flattening out of the plate current characteristics at the higher values of plate current, in a manner very similar to that exhibited by triodes of low cathode emission. In fact, this phenomenon is caused by the partial exhaustion of the space charge in the region of the virtual cathode. This is a fundamental characteristic of space-charge-grid tubes, caused largely by the imperfect character of the virtual cathode, which results from electrons entering the space charge region with widely varying normal components of velocity. It constitutes a serious limitation on the practicable range of operation of such tubes, since it prevents the plate potential from swinging over a sufficiently large range to obtain a large power output without resulting in prohibitive distortion.

In Fig. 16, the amplification factor, plate resistance, and transconductance are shown as functions of control grid voltage, with the same parameters as were used in obtaining the curves of Fig. 15. Of particular interest in these curves, are the unusually high values of transconductance for a tube of this size. For example, at the selected operating point P it is 9,200 micromhos. Also of interest is the peaked character of the transconductance curves. Since transconductance is defined by the slope of the plate current-grid voltage curves, which for this tube have points of inflection in them, maximum points must occur in the transconductance curves. The rapid falling off in transconductance on either side of the maxima, with change in grid voltage, also in-

dicates that a large amount of distortion would result if the tubes were operated with large swings in grid potential.

Space-charge-grid pentodes are capable, then, of yielding very high amplification because of their extraordinarily high transconductance; but, practically, they are limited to use as voltage amplifiers for fairly small inputs, since operation over the wide range necessary for large power output results in prohibitive distortion. These statements apply also to space-charge-grid tetrodes. These tubes have the advantage over ordinary triodes, however, of yielding high values of transconductance at comparatively low voltages applied to the plate.

Dielectric Properties of Cellulose Paper—II

Studies of the dielectric properties of pure cellulose paper as related to its moisture content were reported in Part I of this paper, which was published in the October issue. In Part II, presented herewith, the variations in dielectric properties as related to temperature are discussed. These investigations not only throw additional light on the theoretical aspects of dielectric absorption, but also reveal information of practical importance to cable manufacturers.

By
J. B. WHITEHEAD
FELLOW A.I.E.E.

E. W. GREENFIELD
ASSOCIATE A.I.E.E.

The Johns Hopkins University, Baltimore, Md.

IN PART I of this paper, studies of the electrical properties of cellulose paper as related to the moisture content have been reported. In Part II, presented herewith, these studies have been extended to the variation of the electrical properties as related to temperature when the paper is in a state of extreme dryness. These matters are of interest because the electrical properties of the paper during the vacuum drying process are used by manufacturers for determining the proper condition for impregnation, and further, because it has been shown[1] that the properties of the paper before impregnation constitute an important factor in the final behavior of cable insulation of the best type.

Part II of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted July 12, 1934; released for publication Aug. 24, 1934. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

Further grounds for interest are the additional light thrown on the uncertain question of the nature of dielectric absorption and dielectric loss in dry paper and the fact that no satisfactory explanation has been offered for observed increases with temperature of the apparent dielectric constant of cable insulation both before and after impregnation.

In the portion of the investigation reported in this part of the paper, samples of dry kraft cable paper were studied over the temperature range from 20 to 100 deg C. At each temperature the dielectric properties were measured for both alternating and continuous stresses and the results used for an analysis of the measured values. The chief conclusions are:

1. Power factor and capacitance as measured under alternating stress may be predicted accurately from short-time charge and discharge curves under continuous stress.

2. Reversible absorption is found to account for the whole of the measured power factor from 20 to 70 deg C; from 70 deg C the component due to irreversible conduction becomes appreciable.

3. Over the whole range of temperature studied, the component of capacitance attributable to reversible dielectric absorption is found to be approximately equal to the difference between the apparent capacitance and the geometric capacitance.

4. A large increase in measured capacitance observed between 20 and 100 deg C has been found to be caused principally by a concurrent increase in geometric capacitance occasioned by thermal expansion of the electrode system.

5. A separate study of the change in the dimensions of the electrode system has permitted derivation of the variations with temperature of the true capacitance and dielectric constant.

6. Over the range from 20 to 100 deg C there is little change in the measured dielectric constant or in the geometric dielectric constant of dry paper. Within the upper range of temperature, there is a slight falling off in these values which is attributed to a decrease of density caused by thermal expansion of the dielectric.

Specimen and Measurements

Test Sample. A photograph of the experimental sample is reproduced in Fig. 15. Dimensions and other details of the sample, together with those of the drying tanks, and pumping and temperature control equipment, have been given in foregoing papers.[1,2,3] For measuring the temperature of the sample, 2 carefully calibrated resistance thermometers were used, one fitting closely inside the brass cylinder electrode, the other mounted immediately adjacent to the outer lead electrode. The whole assembly was enclosed within a vacuum tank equipped with close temperature control. By these arrangements, the temperature of the insulation could be determined within 0.1 deg C.

Experimental Procedure. The sample was dried at 105 deg C and under vacuum of 0.25 mm (of mercury) until the final conductivity, as measured at a continuous potential of 1,500 volts had reached the low constant value of 3×10^{-16} mho per cm.[3] The tank then was filled with well dried air at atmospheric pressure and sealed off. From power factor measurements, and by the method described in Part I of this paper, the sample then had a moisture content of approximately 0.08 per cent of its total volume.

In this condition, the following measurements were made:

1. Capacitance-frequency from 60 to 20,000 cycles.
2. Power factor, capacitance, and loss at 60 cycles and 500, 1,000, and 1,500 volts, respectively.
3. Short-time measurements (amplifier oscillograph) of charge and discharge currents at a continuous potential of 1,500 volts for the time interval 0.001 to 0.030 sec.
4. Long-time measurements of charge and discharge currents at a continuous potential of 1,500 volts, extending to 40 min.

These measurements were made in the order given, at each of 6 different temperatures from 100 to 20 deg C, the order being from higher to lower temperatures. Normally 2 complete sets of measurements were made at each temperature and their average taken. A period of 24 hr or more was allowed between each successive pair of temperatures to insure equilibrium conditions.

Experimental Results

Capacitance and Power Factor at 60 Cycles. In Fig. 16 is shown the observed 60-cycle power factor and capacitance as functions of the temperature. The power factor exhibits the conventional minimum at about 70 deg C, with rise thereafter commonly attributed to increase in conduction.

The capacitance increases from 752 $\mu\mu$f at 23 deg to 787 $\mu\mu$f at 100 deg C, an over-all increase of about 5 per cent. This type of increase has been noted in earlier papers and also by cable manufacturers, but never has been completely understood. It now is explained for the first time, the authors believe, by measurements reported in this paper.

Frequency-Capacitance. Measurements of capacitance as related to frequency up to 20,000 cycles are shown in Fig. 17. These curves show the well-known decrease of capacitance with frequency resulting from the diminishing effect of dielectric absorption with increasing frequency. The decrease is more rapid at high than at low temperatures, but the magnitude of the total change is greater at the lower temperatures. In all cases the capacitance in the regions of higher frequency, where it is apparently constant over a wide range, is assumed to be the true geometric capacitance of the paper sample. Note that the geometric capacitance so measured, as well as the 60-cycle capacitance, increases with increasing temperature—an unexpected result.

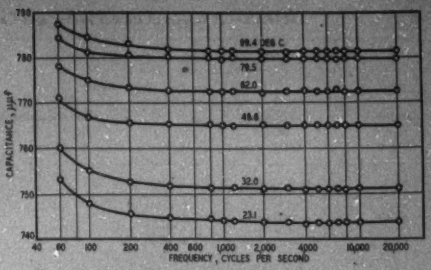


Fig. 17. Variation of capacitance with frequency at different temperatures

D-C Measurements. The discharge curves plotted from the amplifier oscillograph records are shown in Fig. 18. Below 70 deg C no difference between the charge and discharge curves could be detected, indicating the absence of measurable conduction. No great difference in the shapes or positions of these curves below 60 deg C is evident. Above 60 deg C, the well-known tendency to a steep initial portion and a higher final portion with increasing temperature begins to be evident. Using the von Schweidler method of computation, as extended by Whitehead and Banos,[4] these short-time curves may be used for computing the separate components of the dielectric loss due to dielectric absorption and to conduction, and also the component of capacitance due to absorption. An example of the photographic record has been given in Fig. 6 of Part I of this paper.

The results of the long-time d-c measurements are given in Table III. At low temperatures the 40-min charge and discharge currents at 1,500 volts can scarcely be detected and are extremely small at

[redacted]

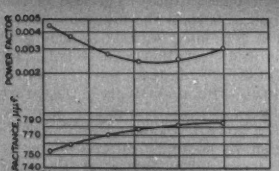


Fig. 15 (above). Completed paper sample

Fig. 16 (left). Variation of apparent power factor and capacitance with temperature

Table III—Results of Long-Time D-C Measurements

Temperature, Degrees C	1,500-Volt Charge Current at 40 Min, Amperes	1,500-Volt Discharge Current at 40 Min, Amperes
23.5	0.05×10^{-10}	
32.8	0.09×10^{-10}	0.07×10^{-10}
48.4	0.5×10^{-10}	0.5×10^{-10}
62.6	1.7×10^{-10}	1.0×10^{-10}
79.0	117×10^{-10}	46×10^{-10}
99.8	650×10^{-10}	125×10^{-10}

Table IV—Analysis of Power Factor and Capacitance of Paper Samples Versus Temperature

1	2	3	4	5	6	7	8	9
	Power Factor				Capacitance, μμf			
		D-C Short-Time Analysis						
Temperature, Deg C	60-Cycle Bridge Measurement	Absorption	Conduction	Abs. + Cond.	60-Cycle Bridge Measurement C	Geometric Capacitance (∞ frequency) C_∞	Absorption Capacitance $C - C_\infty$ or ΔC_T	D-C Analysis, Absorption Capacitance ΔC_T
23.5	0.004408	0.00442		0.00442	752.7	743.5	9.2	8.83
33.8	0.003693	0.00369		0.00369	759.5	751.8	7.8	8.02
48.4	0.00276	0.00274		0.00274	770.3	764.8	5.5	5.06
62.6	0.002418	0.00242		0.00242	777.3	772.8	4.5	4.27
79.0	0.002512	0.00243	0.00007	0.002503	783.9	779.3	4.6	4.15
99.3	0.003127	0.00296	0.000215	0.00316	786.5	781.3	5.2	4.7

63 deg C. No appreciable difference was found between them. For higher temperatures, however, both charge and discharge currents are greater, the former increasing more rapidly with temperature so that the difference, which is the conduction current, is correspondingly greater. Briefly, this means that the leakage conduction is negligibly small at low temperatures, but becomes appreciable at higher temperatures.

Variation of Capacitance and Power Factor With Voltage. At a-c potentials of from 500 to 1,500 volts (8 to 25 volts per mil), 60 cycles, both power factor and capacitance were constant at each value of temperature.

Discussion of Results

A-C D-C Correlation. Table IV, which contains a summary of the experimental results, indicates the excellent agreement between the measured values of power factor and those computed from the d-c measurements of absorption and conduction. A similar agreement is found between the 60-cycle capacitance and the capacitance computed from the geometric value and the component due to absorption as computed from the d-c observations. Column 6, giving the sums of the computed power factor components of absorption and conduction is to be compared with column 2, the measured values of power factor. Column 8 gives the differences between the apparent capacitances at 60 cycles and the geometric capacitances. Column 8 agrees quite closely with column 9 in which is given the component of capacitance attributable to absorption, as computed from the d-c discharge curves.

Analysis of Power Factor. Variation of the separate components of the power factor with temperature is shown in Fig. 19. The upper curve is the measured or apparent power factor and the next lower curve is the power factor component attributable to absorption. The lowest curve is the component due to conduction and its ordinates are equal to the difference between the ordinates of the 2 upper curves. As already noted, the conduction component is absent below 70 deg C, showing that in the dielectric loss below this temperature the leakage conduction is negligible compared with the effect of dielectric absorption. Above 70 deg C, conduction becomes appreciable and increasingly so with further rise of temperature. The rise in this familiar type of curve, beyond the minimum value, commonly has been attributed entirely to increasing conduction. It is of interest, therefore, to note that in dry paper a substantial and in fact the greater part of this rise is due to absorption, certainly in the earlier stages. A qualitative explanation of this may be found in Wagner's 2-layer development of Maxwell's theory of absorption, by assuming suitable shapes of the conductivity temperature curves of the constituent dielectrics.[8]

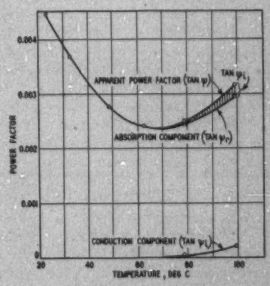


Fig. 19. Analysis of power factor

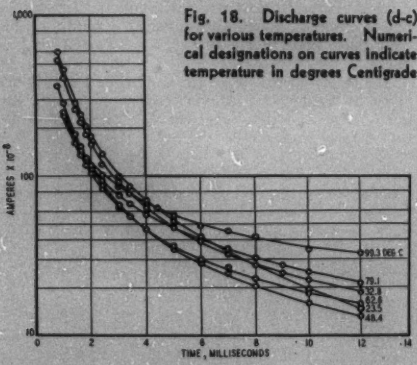


Fig. 18. Discharge curves (d-c) for various temperatures. Numerical designations on curves indicate temperature in degrees Centigrade

Analysis of Capacitance. Variation of the apparent capacitance and that of the geometric capacitance with temperature is shown in Fig. 20. The difference between these 2 curves is the component of capacitance attributable to dielectric absorption which may be computed from the d-c measurements; the values so computed agree closely with the differences between curves 1 and 2 in Fig. 20, as shown in Table IV. These differences are plotted in Fig. 21; the component of capacitance due to absorption is seen to pass through a minimum at about the same temperature at which a similar minimum of power factor was observed.

The increase in the geometric capacitance with temperature, as shown in Figs. 17 and 20, was quite unexpected, and it immediately suggests an obvious explanation of the heretofore unexplained increase with temperature in the measured values of capacitance both in laboratory samples and in cables as manufactured. It is well known that under certain conditions, increasing temperature may cause an increase of capacitance due to dielectric absorption, and elsewhere this has been suggested as a possible cause of the temperature increase of capacitance of impregnated insulation. The geometric capacitance, however, should show either a constant value with increasing temperature, or a very slow decrease due to a change in density. It is suggested immediately, therefore, that these large changes must be caused by changes in the dimensions of the sample due to thermal expansion. This is found to be the correct explanation, proceeding as follows:

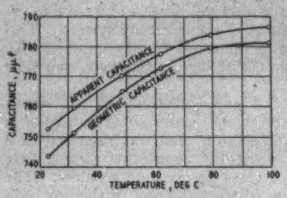


Fig. 20. Variation of components of capacitance with temperature

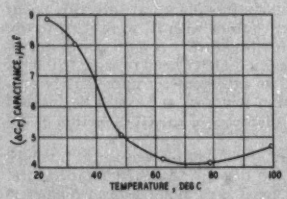


Fig. 21. Variation of absorption component of capacitance with temperature

Let

C_a = the electrode system capacitance (in vacuum and with no dielectric)

ΔC_a = the increase in electrode system capacitance due to temperature expansion

C_∞ = the geometric capacitance of the composite paper sample

ΔC_∞ = the increase in geometric capacitance of the paper sample corresponding to the temperature increase

$$C_a = K \frac{0.2416\,l}{\log_{10}\frac{b}{a}} = \frac{6.17}{\log_{10}\frac{b}{a}}$$

The point on the curve indicated by a cross (⊗) indicates the values for the test specimens used in these studies; at that point C_a = 311.7 μμf at 25 deg C; b = 2.61567 in.; a = 2.5 in.; b/a = 1.0467

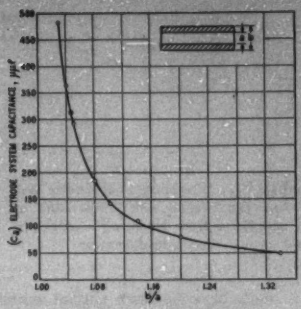


Fig. 22. Capacitance of electrode system as a function of the ratio of outer and inner electrode diameters

K_∞ = the geometric dielectric constant of the paper sample

Then

$$C_a K_\infty = C_\infty \tag{1}$$

and further

$$(\Delta C_a + C_a) K_\infty = C_\infty + \Delta C_\infty \tag{2}$$

Hence

$$\Delta C_\infty = K_\infty \cdot \Delta C_a \tag{3}$$

Equation 3 indicates that any increase due to temperature in the geometric capacitance of the sample, divided by the geometric dielectric constant of the dielectric gives the change in the capacitance of the electrode system that must take place if this change is to account for the increase in the measured values. Since the geometric dielectric constant of paper is approximately 2.5, a change of 4 μμf for example, in the value of C_a is sufficient to account for a change of 10 μμf in the value of C_∞. In other words, a relatively small change in the electrode dimensions is reflected in a larger over-all change in geometric capacitance due to the dielectric constant.

In the foregoing studies, test samples always have been enclosed in constant temperature vacuum tanks and accurate measurements of changes in dimensions resulting from changes in temperature were not possible. In view of the foregoing, however, it becomes important to make an accurate study of these changes.

Expansion of Test Sample With Temperature

Dimensions of Sample. The inner cylinder of Fig. 15 forming the high voltage electrode is of brass having inside and outside diameters of 2.2 in. (5.6 cm) and 2.5 in. (6.35 cm), respectively, giving a section of 0.15 in. (0.38 cm). Fifteen layers of paper form a wall of about 0.06 in. (0.152 cm). Over this is the close fitting lead sheath forming the measuring electrode. This sheath has a longitudinal slot about 6.3 mm wide to allow for temperature expansion (a thin strip of lead foil under this slot closes it electrically). The sheath is held in place by

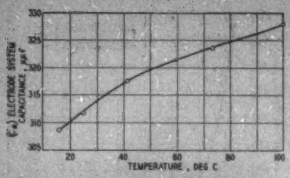


Fig. 23. Variation of electrode system capacitance with temperature as computed from observed changes in electrode diameters

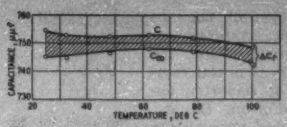


Fig. 24. Capacitance as a function of temperature, corrected for electrode expansion

C = Apparent capacitance
C_m = Geometric capacitance
ΔC_a = Absorption component of capacitance

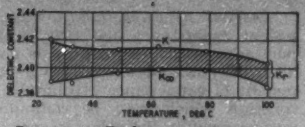


Fig. 25. Dielectric constant as a function of temperature

K = Apparent dielectric constant
K_m = Geometric dielectric constant
K_a = Absorption component of dielectric constant

a single layer of linen thread wound at a tension of about 15 lb.

Of these concentric elements, the lead has the highest coefficient of thermal expansion, while that of the thread is very small. Almost equally as small is the expansion coefficient of the paper in a radial direction. The expansion coefficient of the brass cylinder, although not so great as that of the lead, is still considerably greater than that of the dry paper. Bearing these things in mind it is noted that the diameter of the inner cylinder increases linearly with temperature. The lead electrode experiences a considerable circumferential expansion; but because of the negligible expansion of the binding layer of thread, the net result is that with increasing temperature, the slot in the lead sheath closes up and the over-all diameter of the sample remains practically the same. The paper insulation thus is caught between an expanding inner cylinder and a nonexpanding outer cylinder, and necessarily suffers a contraction of wall thickness approximately determined by the increase in diameter of the inner electrode. In this picture a slight volumetric expansion of the paper itself has been neglected; this seems a not too inaccurate assumption in view of the low thermal coefficient of expansion of the paper. It remains to be seen whether this picture is sufficient to account for the observations.

In Fig. 22 are plotted as ordinates values of capacitance of a cylindrical capacitor and as abscissas the ratio, b/a, of the outer to the inner diameters. The point on the curve marked with a cross indicates the corresponding values for the test specimen used in these studies. It may be seen that this point is in a region where a relatively small change in the value of b/a is accompanied by a very large change in the value of capacitance. As a matter of fact, simple computation using the formula shown in the figure indicates that an increase in the diameter of the inner cylinder of about 0.2 per cent without corresponding increase in the diameter of the outer cylinder will completely account for the 5-per cent increase in geometric capacitance observed between 25 and 100 deg C. Moreover, using an average value for the coefficient of expansion for brass, as taken from technical literature, an increase of the diameter of the cylinder of about 0.2 per cent was to be expected over the temperature range studied. Therefore, the large increase in geometric capacitance of the sample apparently is explained on the basis of an increase of electrode diameter. It remains only to check these assumptions and the conclusions by direct measurement.

It should be noted that the longitudinal expansion of the lead electrode also will cause an increase in the geometric capacitance of the electrode system. This increase, however, is relatively small compared with that resulting from the change in diameter, as will be seen later.

Measurement of Thermal Expansion. A sample was cut in 2 parts at the center so as to expose a clean circular cross section, and was mounted in a thermostatically controlled constant temperature box having a large glass observation window. The sample was suspended from the roof of the box by a pendulum type of support in order to minimize local vibration. Thermometers placed at intervals about the sample and in contact with it, were used to obtain the average temperature. A high power microscope fitted with a micrometer head reading to 0.0001 mm was mounted as cathetometer immediately outside the observation window, and could be focused on any point of a diameter of the cross section of the sample.

The temperature of the sample was set at 5 values between 16 and 100 deg C. At each temperature, the shifts from a fixed zero along a fixed diameter, of the surfaces of separation between brass and paper and paper and lead were measured accurately for both ascending and descending temperatures and along 2 different diameters of the specimen. The results of these 4 sets of measurements then were averaged to give the final results which appear in Table V. It may be noted that the column marked "b" indicates no change in the inside diameter of the lead sheath, and column "a" indicates a progressive increase in the outer diameter of the brass cylinder. The succeeding columns show the progressive decrease in the ratio b/a, and the last column shows the corresponding increases in the geometric capacitance of the electrode system. During these observations, the expansion and contraction in the longitudinal slot in the outer electrode were easily seen.

Values given in the last column of Table V have been plotted as related to temperature in Fig. 23, which thus shows the increase in capacitance resulting from diametral expansion. A small increase resulting from longitudinal expansion of the lead sheath is included in this curve although its contribution to the total change is very small. Comparison

Table V—Thermal Expansion of Component Parts of the Paper Specimen

Avg Temp, Deg C	A Mm	B Mm	h Mm	ΔA Increase in A From 25°C Value, In.	a In.	b In.	b/a	log b/a	C_a μμf
16.2	0.4640	1.9470	1.4830	−0.00035	2.4989	2.61567	1.04673	0.019837	308.66
25.0	0.4780	1.9470	1.4690		2.5000	2.61567	1.04627	0.019643	311.7
41.8	0.5043	1.9470	1.4427	+0.001035	2.50207	2.61567	1.045408	0.0192853	317.17
73.5	0.5309	1.9471	1.4162	0.002085	2.50417	2.61568	1.044524	0.0189209	323.33
100.3	0.5466	1.9471	1.4005	0.002701	2.5054	2.61568	1.0440	0.018700	327.5

A = } Expansion shifts along a diameter of brass and lead
B = } edge, respectively, from a fixed arbitrary zero
$h = A - B$
a and b are as shown on Fig. 22

At 25 deg C $a = 2.5000$ in., $b = 2.61567$ in. } measured with micrometer calipers (averaged values)

$a_t = 2.5000 + 2\,\Delta A$ (at temperature "t")

$$C_a = \frac{6.1739}{\log_e b/a_t} \text{ (at temperature "t")*}$$

* Assuming test electrode length to remain constant. Longitudinal thermal expansion of the lead sheath causes an additional increase in electrode system capacitance, C_a, amounting to a total of 0.66 μμf which is about 4 per cent of the increase resulting from radial expansion from 25 to 100 deg C. The curve of C_a in Fig. 23 and the curves in Figs. 24 and 25, however, include the effects of both radial and longitudinal expansion.

of Fig. 23 with Fig. 20 indicates at once that the greater part of the temperature variation shown in the latter may be accounted for by thermal expansion. If the values given in Fig. 20 be corrected for change of electrode capacitance by the values given in Fig. 23 the values shown in Fig. 24 are obtained. Noting the extended scale on which the capacitance is plotted in Fig. 24, it may be seen that when corrected, the changes indicated for both geometric capacitance and apparent or measured capacitance over the entire temperature range are exceedingly small.

The same conclusion may be expressed in terms of dielectric constants. If the observed geometric capacitance at each temperature be divided by the corresponding capacitance of the electrode system as given in Fig. 23, a value is obtained that may be called the geometric dielectric constant of the paper. The result is shown in Fig. 25 which also contains a similar corrected curve for the apparent dielectric constant as measured at 60 cycles. Again the over-all changes in the dielectric constants, both geometric and total, of the paper itself are very small over the temperature range studied.

Although as indicated, the total changes in the values of dielectric constant and over-all capacitance are not great, they nevertheless are of apparently definite character. The measurement of capacitance was very accurate and there seems to be no reason to question the actuality of the changes indicated in the curves of Figs. 24 and 25. It may be seen that at first the geometric dielectric constant increases with temperature up to about 70 deg C and thereafter decreases. Nothing definite can be said as to the causes of these variations, but the following is suggested: In the lower range, compression of the paper results in an exclusion of air and a consequently greater ratio of fiber to air, that is, an increase in density greater than the decrease resulting from the change in temperature. Beyond a certain point, however, this effect must cease and the longitudinal thermal expansion of the paper wall thereafter causes a decrease in density giving the descending portion of the curve in the higher range of temperature. This latter type of variation with temperature from the cause suggested is well known for liquid and plastic materials.

With reference to the initial descending portion of the curve for K, the over-all measured dielectric constant, from Fig. 21 the rapidly descending value of the component of capacitance due to dielectric absorption within the range 30 to 60 deg C may be noted. This is reflected in the curve of Fig. 25. The further tendency to lower values in the upper range of temperature may be accounted for on the same grounds as proposed for the geometric dielectric constant, namely, decreasing density resulting from longitudinal expansion. In Part I of this paper were reviewed briefly the suggestions that have been made for the mechanism of dielectric absorption as resulting from residual moisture, and as accounting qualitatively for the observed behavior of power factor and capacitance.

As a general result of the foregoing, it should be noted that in the use of cylindrical condensers for the study of dielectrics over any considerable temperature range, large errors in measured and computed values may arise from thermal expansion of the electrode system. These errors are greater the smaller the ratio of diameters of outer to inner electrodes. Although no measurements of the magnitudes of these temperature changes have been made on impregnated samples, temperature variations of measured capacitance have been found for such samples and a similar variation frequently has been noted in the capacitance measurements on high voltage cables. It appears highly probable from the results here reported that within the range from 20 to 100 deg C the dielectric constant of impregnated paper insulation undergoes little if any change, and further, that the increases of capacitance with temperature frequently noted in both cables and laboratory samples are caused by corresponding temperature changes in the dimensions of the electrode systems.

References

1. The Dielectric Losses in Impregnated Paper, J. B. Whitehead. A.I.E.E. Trans., v. 52, 1933, p. 667–81.
2. Fundamental Properties of Impregnated Paper, J. B. Whitehead and W. B. Kouwenhoven. A.I.E.E. Trans., v. 50, 1931, p. 699–704.
3. Half Degree Temperature Control, W. B. Kouwenhoven and S. K. Waldorf. *Elec. World*, v. 95, 1930, p. 1214–17.
4. Predetermination of the A-C Characteristics of Dielectrics, J. B. Whitehead and A. Banos, Jr. A.I.E.E. Trans., v. 51, 1932, p. 392–402.
5. Lectures on Dielectric Theory and Insulation, J. B. Whitehead. (McGraw-Hill Book Co., 1927).

Vacuum Tubes as High Frequency Oscillators

By
M. J. KELLY
FELLOW A.I.E.E.

A. L. SAMUEL
Membership Application Pending

Both of the Bell Tel. Labs., Inc., New York, N. Y.

Vacuum tubes as oscillators and amplifiers at frequencies greater than 100 megacycles (3 m) are considered in this paper. The type of construction used in a large number of different tubes, and the characteristics of the tubes, are presented. Circuits for operating the tubes also are considered and the theory of operation and the factors limiting ultra-high frequencies are discussed. Principal attention is given to the tubes as oscillators, with brief consideration of the problem of amplification.

THE 3 types of oscillation generators which at present are the most efficient in the range from 100 megacycles to 3,000 megacycles per second will be discussed in the following survey. These are: the negative grid tube which at lower frequencies is the conventional regenerative oscillator, the positive grid or Barkhausen oscillator, and the "magnetron" oscillator. The amplification problem will be briefly discussed. Because of the present unsettled state of the theory, only the most elementary and generally accepted part will be included. Much theoretical and experimental work remains to be done before knowledge of the mechanism of oscillation and amplification in this frequency range will be satisfactory. As is often the case, the empirical knowledge of some of these mechanisms has outdistanced the theoretical interpretation.

The Negative Grid Oscillator

The conventional thermionic vacuum triode, whether it be a large water cooled power tube or a small receiving tube, may be used as a generator of oscillations varying in frequency from a few cycles per second to some 20 or 30 megacycles with substantially undiminished efficiency and output. In this range the frequency at which a tube is to be employed is a factor of almost negligible importance in the determination of its characteristics and its form. Beyond this range, however, frequency plays an increasingly important part, and as one approaches 300 megacycles, it becomes the most important factor in the determination of tube design.

When an attempt is made to operate a standard triode at increasingly high frequencies it is found that the output and efficiency begin to decrease. The frequency at which this is first observed will depend upon the design of the tube but it will usually be in the 10 to 60 megacycle range. By successive modifications of the circuit arrangement and size this decrease in power output and efficiency can be minimized. With optimum circuit arrangements, however, this decrease continues until finally a frequency is reached beyond which oscillations can no longer be produced.

In Fig. 1 are shown typical data for a standard 75-watt tube, the Western Electric type 242*A*, operated with reduced potentials over the frequency range from the point where oscillation frequency noticeably affects performance to the point where oscillations can no longer be produced. The plate potential was held constant at 750 volts throughout the entire frequency range. The oscillation circuit was modified at each point in order to obtain maximum output and efficiency, keeping the anode dissipation within the maximum rating of 100 watts and the anode current within the maximum rating of 0.150 amp. It can be seen from the curves that the output and efficiency are independent of the frequency until about 20 megacycles is reached, when they begin to decrease. At 100 megacycles the output power is only 2.5 watts and the efficiency only 2 per cent. The tube will not oscillate at 105 megacycles.

Effect of Energy Losses on Performance

A tube operating in the range where frequency affects performance must withstand energy losses, and the resulting heating within its structure, which occur to only a negligible degree at the lower frequencies. Some of these losses are due to dielectric hysteresis in the insulating materials of the tube, particularly in the portions of the glass supporting stem or bulb which lies between the tube leads. The

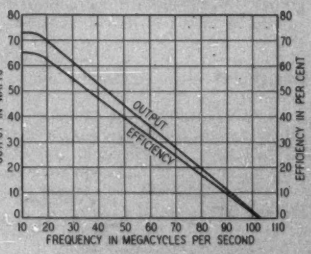


Fig. 1. Power output and anode efficiency as a function of frequency for a standard triode

These curves are typical of all tubes as they approach their upper limiting frequency

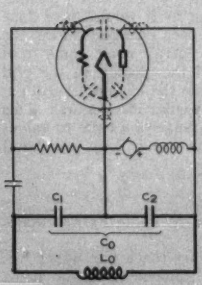
Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Sept. 25, 1934; released for publication Oct. 3, 1934. *Not published in pamphlet form.*

glass is sometimes so softened by the heat thus developed that it is punctured by the outside air pressure. Losses also occur in the auxiliary metallic parts of the tube structure due to the increased eddy currents that occur at high frequencies. Losses in the tube electrodes and their lead-in wires are also greatly increased due to skin effect which increases their resistance, and due to the increased charging current required by the interelectrode capacities. The increased lead temperature, depending upon its amount, will cause a more or less rapid deterioration of the lead-to-glass seals which may ultimately destroy the vacuum. In order to protect the tube from damage because of these new types of energy dissipation, the operating potentials and currents must be reduced to values less than those established for low frequency operation. Some manufacturers are now giving special ratings on such of their standard tubes as may be used at ultra-high frequencies. These ratings should be adhered to when operating in this range.

Effect of Circuit on Performance

The decrease in output power and plate efficiency which sets in with the increase in frequency, while due in part to the losses described above, and to the rapid increase in radiation losses, is also due to 2 additional effects of fundamental importance. The first to become evident, with increasing frequencies, is circuital in nature. This can be explained by reference to the conventional oscillator shown in Fig. 2. The frequency of such an oscillator is given by

$$f = \frac{1}{2\pi\sqrt{LC}},$$



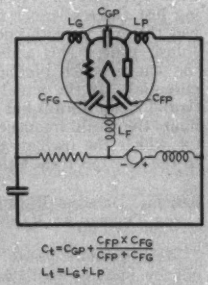


Fig. 2 (left). A standard Colpitts oscillator circuit

The heavy lines indicate the main oscillating circuit. The dotted portions represent the interelectrode capacities and lead inductances which play a minor rôle at low frequencies

Fig. 3 (right). The limiting circuit with the external tuning capacity eliminated and the external inductance reduced to a short circuiting bar between the grid and plate leads

The main oscillating circuit, indicated by the heavy lines, is seen to include the interelectrode capacities and lead inductances

where L and C are the effective inductance and capacity of the oscillating circuit. In the lower frequency range, the LC product which determines the frequency is substantially equal to L_0C_0, that is, to the product of the inductance and capacity of the external circuit. The inductance of the tube leads and the capacity between its electrodes (indicated by the dotted lines in the figure) play a negligible rôle. In order to tune the circuit to higher and higher frequencies, the capacity C_0 is first reduced and finally eliminated, leaving the interelectrode capacity as the only capacity in the oscillating circuit. The tube leads then form a part of the main oscillating circuit, in which large circulating currents must exist for stable operation. For a further increase in frequency the external inductance L_0 must be reduced and, in the limit, it becomes the shortest possible connection between the grid and plate terminals. The oscillating frequency for this limiting circuit, shown in Fig. 3, is determined by the product of the lead inductance L_t and the interelectrode capacity C_t; that is,

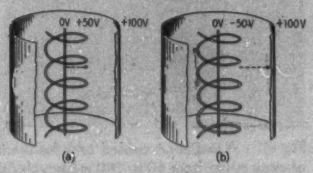


Fig. 4. Illustrating the mechanism which enables electrons to take energy from the oscillating circuit

$$f_0 = \frac{1}{2\pi\sqrt{L_tC_t}},$$

where L_t is the sum of the grid and plate lead inductance and C_t is the total grid-plate capacity. Even before this frequency limit is reached the output power and plate efficiency are seriously reduced by the lack of full control over the relative amplitude and phase of the alternating grid and plate potentials. Whereas the ratio of these amplitudes is controlled in the circuit shown in Fig. 2 by the condensers C_1 and C_2, it is determined in the limiting case primarily by the fixed ratio of the grid-filament to plate-filament interelectrode capacities. Most tubes made especially for ultra-high-frequency use are constructed so as to minimize these circuit limitations by a reduction in the interelectrode capacity and lead inductance and by adjusting the capacity ratio.

Effect of Transit Time on Performance

The second fundamental effect has to do with the time required for the electrons to travel from the cathode to the anode within the tube structure. This time, the so-called transit time, is very small in present-day commercial types of power tubes, usually much less than one microsecond. Obviously at low frequencies it can be neglected and, in fact, for many tubes it still plays a minor rôle either in determining the output and efficiency in the high

Fig. 5. A radiation cooled tube for use in the frequency range from 60 to 180 megacycles per second

Note the large ratio of the plate diameter to plate length and the special arrangement of the leads

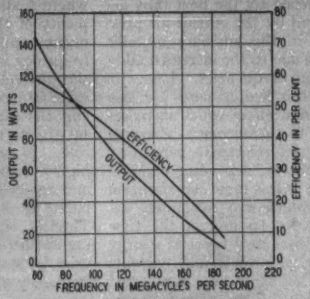


Fig. 6. Output and efficiency as a function of frequency for the tube shown in Fig. 5

A comparison of these curves with those shown in Fig. 1 illustrates the improvement obtained by taking account of those factors which become important at high frequencies

Fig. 7. A tube for use at frequencies up to 350 megacycles

frequency range or in establishing the limiting frequency for oscillations. When the frequency range of oscillation of a tube is extended by an adequate decrease in energy losses and by improvements in electrical design, transit time becomes a dominating factor in the reduction of output power and efficiency and in establishing the limiting frequency of oscillation.

This comes about in 2 ways. In the first place, the relative phase of the alternating grid and plate potentials for best operation must be altered to compensate for the time required for the electrons to travel from the region in which the grid has its greatest effect upon their motion to the region in which their motion has the greatest effect upon the plate current. The available control over these phases is usually insufficient to permit a realization of the optimum adjustment. In terms of the measured characteristics of the tube, the transconductance has become complex. But even with the optimum phase adjustment the efficiency is reduced by losses which occur because of the variations in grid and plate potentials during the transit time. Electrons arriving at the plate will in general have velocities greater than the velocity corresponding to the potential of the anode at the instant of their arrival. The excess energy corresponding to the greater velocity is obtained from the oscillating circuit and is dissipated at the plate in the form of heat. Again in terms of the measured characteristics, the input conductance has been increased above its low frequency value.

The mechanism which enables electrons to take energy from the oscillatory circuit in their passage across the tube is evident from a consideration of a somewhat simplified case as shown in Fig. 4. Assume that the anode is held at a constant positive potential of 100 volts, and that the grid is held at 50 volts positive just long enough to allow an electron to come from the cathode to the grid plane (very near one of the wires), where its velocity will correspond to a fall of 50 volts. The potential of the grid is then suddenly changed to 50 volts negative. The electron will then fall through an additional potential difference of 150 volts, arriving at the anode with a velocity corresponding to 200 volts, producing just twice as much heat as it would have done had the grid potential not been changed during the transit time. This added energy must come from the source which produced the change in the grid potential. In the actual case the change in grid potential is not abrupt but a similar loss occurs. This limits the useful frequency range of a tube to values for which the oscillation period is long compared to the electron transit time.

Special Designs Required for Different Ranges of High Frequencies

Most standard power tubes reach the upper frequency limit of oscillation somewhere in the 10 to 100 megacycle frequency range. For frequencies above this, specially designed tubes are required. The frequency range in which a given design is near the optimum is limited. Therefore, there is a succession of tubes, each rated for a band of frequencies. Characteristics such as a high mutual conductance and a sharp cut-off which make a tube a good oscillator at low frequencies, while still of importance at ultra-high frequencies, are apt to be secondary to the special frequency requirements. Although some progress has been made in the modification of conventially designed water-cooled tubes for use above 100 megacycles, more attention has so far been given

to the development of radiation cooled tubes for this frequency range.

A departure from conventional design with increasing frequency is illustrated by a radiation cooled tube described by McArthur and Spitzer[1] in which the ratio of the plate diameter to the plate length is much larger than for the conventional tube. Radiating fins are employed to compensate for the decrease in heat radiating ability of the plate which would otherwise occur because of its short length. In Fig. 5 is shown a photograph of this tube. It will be noted that the tube electrodes are supported directly from their leads. The complete absence of auxiliary supporting members either of metal or of insulating material and the large size of leads reduce radiation, eddy current, and conduction current losses. That portion of the interelectrode capacities due to the supporting structure is also made small by this method of support.

The interelectrode capacities are given below, together with the corresponding values for the type 242*A* tube, which has the same plate dissipation rating but is designed for use at lower frequencies:

	High Frequency Tube	242A
Plate to grid	3 μμf	13 μμf
Grid to filament	2 μμf	6.5 μμf
Plate to filament	1 μμf	4 μμf

The decrease in capacity by a factor of approximately 4 makes possible a much greater improvement in performance in the 60 to 150 megacycle per second frequency range than the corresponding degradation in performance due to the lower mutual conductance and the increased electron transit time resulting from the increased spacing. The material increase in plate impedance makes it necessary to employ an anode potential approximately twice as great with the high frequency tube.

Output and efficiency curves are shown in Fig. 6. (For the sake of uniformity, curves taken from published papers have, in most cases, been redrawn.) The particular shape of the output curve is due to the manner in which the applied anode potential was reduced with increasing frequency to minimize the danger of tube failure from the increased energy losses which occur at high frequencies. The limiting frequency as set by the interelectrode capacities and lead inductances is given by the authors as 230 megacycles. An extension of the efficiency curve to higher values indicates that the tube will probably fail to oscillate before this limit is reached. From this it can be inferred that the decrease in efficiency in the range from 150 to 200 megacycles is due largely to the effect of the relatively large transit time, since the authors' method of arriving at the output by taking the difference between the measured input and the measured plate losses includes circuit and lead losses as a part of the output. A comparison of the data of Fig. 1 and Fig. 6 shows that at 100 megacycles the output of the type 242*A* tube is 2 watts and the corresponding output of the high frequency tube is approximately 86 watts with substantially the same plate loss. This strikingly illustrates the improvement obtained by taking into account the factors which become important in the high frequency range.

1. For all numbered references see list at end of paper.

Transit Time Becomes More Important

In extending the frequency range to 300 megacycles the importance of electron transit time becomes relatively greater. It must be kept as low as possible even at the expense of relatively higher interelectrode capacities. In the tube just described for the frequency range around 100 megacycles the reverse procedure is followed; in order to make the interelectrode capacities as small as possible, transit times are increased. Fay and Samuel[2] in a recent paper presented before the International Scientific Radio Union (U.R.S.I.) describe a tube designed for use at 300 megacycles which well illustrates this point. The tube is shown in Fig. 7. It differs from the one previously discussed in the close spacings between elements, particularly between the grid and filament. The lead length is further decreased and lead diameter made considerably larger in order to decrease lead inductance and resistance. The interelectrode capacities are:

Plate to grid	2.5 μμf
Grid to filament	2.0 μμf
Plate to filament	0.67 μμf

While these capacities are substantially the same as for the tube shown in Fig. 5, the limiting frequency, as set by circuit resonance, is somewhat beyond 400 megacycles as contrasted with 230 megacycles for the other tube. This is due, primarily, to the material decrease in lead inductance. The decreased losses resulting from the minimized transit time more than compensate for the increased circuit loss resulting from the required higher charging currents to the interelectrode capacities. Its mutual conductance of 2,200 microohms and the sharp cut-off shown by the static characteristics indicate that those electrical characteristics which are important

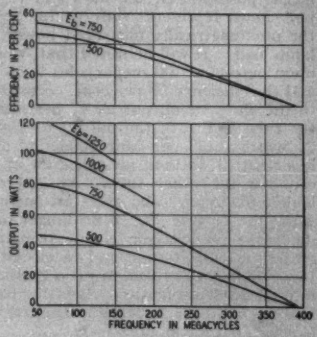


Fig. 8. Output and efficiency curves for 2 tubes of the type shown in Fig. 7

Fig. 9 (left). A typical push-pull circuit for use at ultra-high frequencies

A circuit of this type was used to obtain the data shown in Figs. 8 and 11

Fig. 10. This tube will oscillate at frequencies up to 740 megacycles

Note the absence of the usual press and the extremely small size of the elements

for efficient oscillators in the low frequency range have not been sacrificed in meeting the requirements of 300 megacycle operation.

Output and efficiency curves for this tube are shown in Fig. 8. These data are for 2 tubes operated in the push-pull circuit shown in Fig. 9. The output shown represents only useful power, since it is the photometrically measured power consumed in a lamp load. It will be noted that, whereas the maximum output at 100 megacycles is 55 watts per tube and the efficiency 50 per cent, corresponding roughly to the 86 watts output at 47 per cent efficiency for the tube of Fig. 5, the output at 200 megacycles is 34 watts at 33 per cent efficiency as compared to less than 10 watts at an efficiency of only a few per cent for the other tube. At 300 megacycles the higher frequency tube gives an output of 13 watts, while the tube of Fig. 5 no longer oscillates. This difference in behavior is due primarily to the decreases in transit time and in circuit losses, and to the more nearly optimum ratio existing between the interelectrode capacities. It is due to a considerably less extent to the increase in the frequency limit set by circuit resonance.

A Still Further Departure in Construction

The tube illustrated in Fig. 10 represents a still further departure from conventional construction with a corresponding increase in the frequency limit. Fay and Samuel report an output of 6 watts per tube at 500 megacycles and a frequency limit of 740 megacycles. Unusual features of the design are: The complete elimination of the usual press, the close spacing of the leads and the special construction of the tube elements, particularly the grid, made necessary by their small size. The grid is in the form of a number of straight wires (parallel and equidistant from the axial filament) supported by cooling collars at each end. The plate, in spite of its small size, can dissipate 40 watts with safety.

The interelectrode capacities of this tube are:

Plate to grid	1.8 μμf
Grid to filament	1.0 μμf
Plate to filament	0.75 μμf

The output and efficiency curves, shown in Fig. 11, were obtained with 2 tubes in a push-pull circuit. The efficiency of the tube is about 28 per cent at 300 megacycles, contrasting with only 18 per cent for the previously discussed tube, while the output is only 8 watts as compared to 13 watts. The higher efficiency suggests that above 300 megacyles 2 of the smaller tubes are preferable to one of the large tubes. The fact that the limiting frequency varies with the applied anode potential indicates that the transit time effect is largely responsible for the decreased efficiency. This suggests modulation difficulties if the tube is used near the upper limit of the frequency range. The outputs and efficiencies in the 400 to 600 megacycle range, although low, represent a substantial increase over the usual values obtained at these frequencies.

The relatively low efficiency at 200 megacycles is due to insufficient filament emission. In order to maintain space charge conditions near the filament, at high frequencies, the electron emission must be large enough to supply not only the actual electron current to the plate but also the charging currents to the grid-filament and plate-filament capacities. In a tube of this small size an increase in the filament emission is possible only by an impractical and unwarranted increase in the filament heating current.

The logical extension of these principles to increasingly high frequencies requires the use of closer and closer interelectrode spacings. Severe mechanical difficulties are encountered. Curiously enough the limiting factor in the power dissipating ability of the tube turns out to be the grid temperature rather than the temperature of the plate as might

be expected. This comes about because of the required close grid-filament spacing, and makes necessary the adoption of some method of cooling the grid. One of the writers has constructed a series of tubes in which the grid is a tungsten helix, each turn of which is attached to a common cooling fin projecting through a slot in the plate. This construction simplifies the mechanical problems involved and provides ample grid cooling. Two of these tubes are shown in Fig. 12. The larger one will deliver 10 watts at 670 megacycles with an efficiency of 20 per cent and the smaller one will deliver one watt at 1,200 megacycles with an efficiency of 10 per cent. These tubes are in no sense commercial, the results representing the limit that has been obtained by specially constructed tubes under controlled laboratory conditions at voltages and currents above those for which the tube would have a long life. With further advances it is reasonable to expect that outputs of this sort will be commercially realizable and that the frequency range of the negative grid oscillator can be extended beyond 1,200 megacycles.

Tubes for Receiving Purposes

For receiving purposes where large outputs are not needed, the ultra-high-frequency requirements are best met by shrinking all the tube dimensions in proportion to the desired wave length. Tubes constructed by Thompson and Rose[2] based upon this principle are shown in Fig. 13 compared in size with the conventional receiving type tube. These tubes make use of parallel plane electrodes, the cathode being oxide coated and indirectly heated, and the grid being in the form of a mesh. A cross-section view of the triode is shown in Fig. 14. This tube will oscillate at frequencies up to 1,000 megacycles in miniature replicas of the customary circuits used at longer wave lengths. A photograph of a complete oscillator is shown in Fig. 15 and the circuit diagram in Fig. 16.

Factors Limiting Ultra-High Frequencies

The limiting factor in the continued extension of the negative grid oscillator to higher and higher frequencies appears to be the dependence of physical size and output power on the operating frequency range. This dependence is well illustrated by the comparison in Fig. 17 of some of the tubes so far discussed with a standard one-kilowatt tube for which the frequency limit is approximately 75 megacycles. Dimensional considerations indicate that the linear dimensions of a series of tubes of optimum design must be decreased in proportion to the operating wave length. Since the heat dissipating ability depends upon the surface area of the plate, the output (assuming the same efficiency) will decrease as the square of the wave length. That this is approximately true for the tubes shown in Figs. 5, 7, and 10 may be seen by reference to Fig. 18 where the outputs as a function of frequency are plotted on a logarithmic scale. The sloping lines are for different values of the ratio of output to the square of the

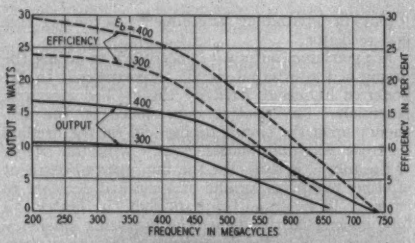


Fig. 11. Output and efficiency curves for 2 tubes of the type shown in Fig. 10

Fig. 12. These tubes represent a further extension in design according to the principles under discussion

The smaller one will oscillate at 1,200 megacycles per second

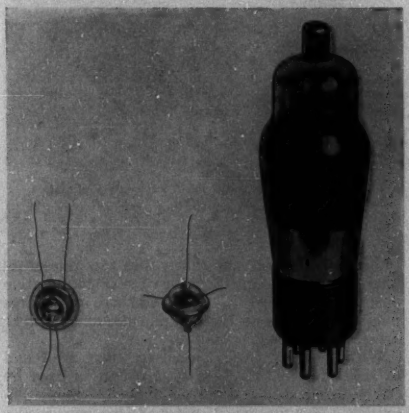


Fig. 13. Receiving tubes of extremely small dimensions

A conventional receiving type tube is shown at the right for comparison

wave length. With radiation cooled tubes patterned after those illustrated, outputs of only a few tenths of a watt at 3,000 megacycles can be expected. If larger outputs are to be obtained, innovations in tube design must be made.

Positive Grid (Barkhausen) Oscillator

As first reported by Barkhausen and Kurz[7] in 1920, oscillations at frequencies greater than 300 megacycles can be produced by most high-vacuum triodes having symmetrical cylindrical structures when the grid is operated at a fairly high positive potential and the plate is held at or near the cathode potential. When so used they are variously known as oscillators of the Barkhausen and Gill-Morell[8] types after the earliest experimenters, or oscillators of the positive grid or retarding field type to designate the arrangement of the electrode potentials. The relative ease with which such oscillations can be obtained at frequencies above 300 megacycles by

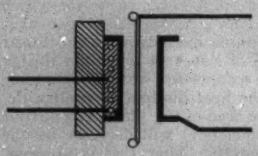


Fig. 14. A sectional view of the triode developed by Thompson and Rose

Fig. 15. A complete oscillator using a miniature receiving tube

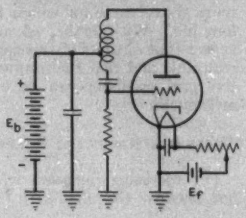
the use of conventional tubes, and the widespread interest in this frequency range for communication purposes, have led to the appearance of a large number of papers on the experimental and theoretical aspects of such operation.

With the positive grid oscillator there are found to exist preferred frequencies of operation fixed by the electrode spacings and the applied electrode potentials. For the lowest preferred frequency modes of oscillation the relationship is such that the period of one complete oscillation is approximately equal to the total transit time of an electron which fails to strike the grid on its first transit, is retarded and finally turned back by the plate potential, and again missing the grid, returns to the cathode. Under these conditions the relationship,

$$\frac{E_g}{n^2} = \text{constant},$$

is found to hold approximately, where E_g is the applied grid potential, n is the frequency, and the constant is a function of the tube geometry. Other high frequency modes of oscillation can be obtained. One of these is particularly easy to excite if the grid of the tube is in the form of a simple helix. The important rôle played by the electron transit time in determining the frequency of the positive grid oscillator contrasts sharply with the minor rôle

Fig. 16. The circuit diagram of the oscillator shown in Fig. 15



it plays in determining the frequency of the negative grid oscillator.

For maximum output it is necessary to adjust the tuning of the external circuit to correspond to the preferred frequency fixed by the applied electrode potentials. The relative dependence of the frequency upon the circuit tuning and on the applied electrode potentials varies greatly with the design of the tube. In any case the improper adjustment of either parameter results in a marked decrease in output. In general it appears that the better the tube design and the higher the operating efficiency the greater will be the dependence of frequency upon circuit tuning and the less will be its dependence upon the applied electrode potentials.

The most efficient operation of the positive grid oscillator is obtained when the space current is limited by the cathode emission, as contrasted with the most efficient operation of the negative grid oscillator when the current is limited by space charge. Not only must the space current be emission limited but it must have a fairly critical value. This makes it necessary to adjust the cathode temperature critically. Since the cathode emission characteristics are apt to change with time, frequent readjustments of the cathode temperature are usually required.

No completely satisfactory and generally accepted theory of the positive grid oscillator has as yet been given. Many theoretical papers dealing with the mechanism of oscillation have been published. Some of these papers resort to pictorial explanations which, from their very nature, must leave out certain basic factors. Readers interested in a résumé of the various theories are referred to the excellent review by Megaw[13] and to the original papers. It

Fig. 17. Some of the tubes, previously discussed, compared in size with a lower frequency tube on the left

is now recognized that any accurate theory must be based upon a general consideration of all the forces acting upon the electrons in their flight between the electrodes. This may take the form of either a particular solution of the classical electromagnetic equations for the conditions within the tube or an analysis of the energy contributions due to individual electrons in their passage across the interelectrode space.

Construction of a Positive Grid Tube

A representative positive grid tube of current design described by Fay and Samuel[3] before the International Scientific Radio Union is shown in Fig. 19. This tube differs from the conventional negative grid tube primarily in the construction of the grid and in the arrangement of the leads. While designed primarily for use in the frequency range from 500 to 550 megacycles, it illustrates the general problems encountered in the construction of the positive grid oscillator of this type for any frequency range.

The grid consists of a number of parallel wires supported by cooling collars at each end, the so-called squirrel cage construction. It will withstand 150 watts heat dissipation safely, and provides a minimum of circuit inductance and resistance. The grid diameter is fixed by the frequency for which the tube is designed and by the desired operating potential, such that the relationship

$$d_g = \frac{K_1\sqrt{E_g}}{n} \qquad (1)$$

is approximately satisfied, where d_g is the diameter of the grid, K_1 is a constant, n the frequency, and E_g the applied grid potential.

An indefinite increase in output at a fixed frequency by the simultaneous increase in the grid diameter and in the applied grid potential is not possible because of the limited permissible grid dissipation per unit area. The optimum grid current is found to follow roughly a $^3/_2$ power law, that is

$$I_g = K_2 \frac{E_g^{3/2}}{d_g} \qquad (2)$$

so that the grid power will increase as the fourth power of the grid diameter while the grid area and hence the heat dissipating ability only increases as the first power of the diameter. Because of this an upper limit in output exists, fixed by the maximum permissible heat dissipation per unit area for the grid structure. The optimum grid diameter will vary directly with the wave length for which the tube is designed, and if the ratio of the grid length to its diameter is maintained constant, the maximum available power output (assuming the same efficiency) will vary as the square of the desired wave length.

Circuit of a Positive Grid Oscillator

In Fig. 20 is shown a diagram of a positive grid tube of the straight-wire-grid type and its associated

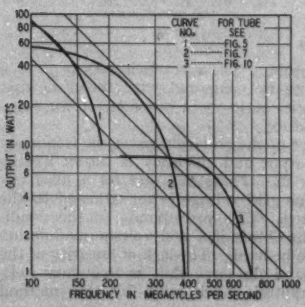


Fig. 18 (left). A comparison plot of the outputs obtained with the tubes of Figs. 5, 7, and 10

The sloping lines are fixed values of the ratio of output to the square of wave length

Fig. 19 (right). A positive grid oscillator designed for the frequency range from 500 to 550 megacycles

circuit. Tuned circuits, in this case in the form of so-called Lecher systems, are connected between the grid and plate leads, extending approximately a half wave length (30 cm) beyond the lead seals. Because of the existence of preferred frequencies of operation fixed by the potentials applied to the tube electrodes, distributed-constant circuits, if used, may be operated at frequencies corresponding to harmonic modes of oscillation. In this case the length of the leads within the tube envelope has been adjusted so that the glass seals come at or near potential nodal points for the Lecher systems of which the leads form a part. This minimizes dielectric losses in the glass. The effective paralleling of the 2 sets of leads greatly reduces the resistance losses,

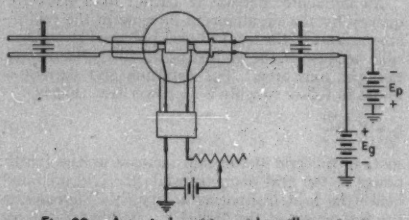


Fig. 20. A typical positive grid oscillator circuit

while the balanced arrangement decreases radiation losses. Strict attention to these details is required because of the already low efficiency of the mechanism of generation.

Characteristics of Positive Grid Oscillators

The dependence of output and anode efficiency on frequency is shown in Fig. 21. These data were taken by adjusting the circuit tuning, filament current, and the grid and plate potentials to their op-

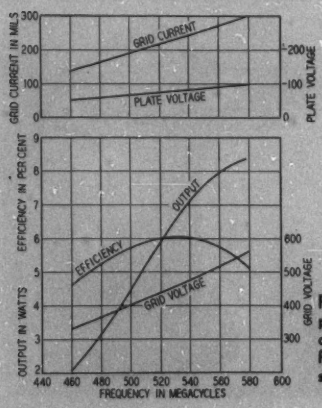


Fig. 21. Output and efficiency curves for the tube shown in Fig. 19

timum values for each frequency. The curve showing the grid voltage will be observed to follow eq 1 above, at least roughly, and a similar correspondence will be observed between the curve for the grid current and eq 2. Some variation in the required

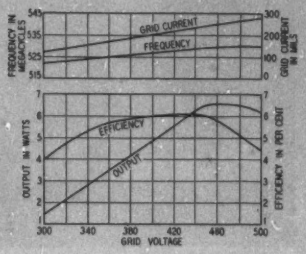


Fig. 22. Result of variation of grid voltage, tuning fixed, on tube of Fig. 19

negative plate potential is observed. A maximum efficiency will be noted at a frequency of approximately 530 megacycles. The output, however, continues to increase with increasing frequency, the limit in output as well as in frequency being set by the safe grid dissipation. The outputs over the 500 to 600-megacycle range vary from 4.5 to 8 watts, comparing with outputs from 6 to 3 watts for the

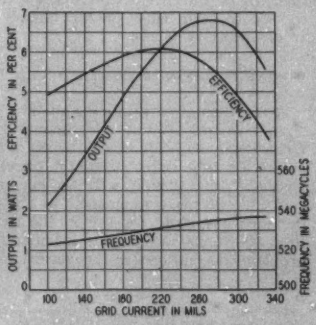


Fig. 23. Result of variation of grid current, other adjustments fixed, on tube of Fig. 19

f = 532 megacycles
E_G = 450 volts

negative grid tube. The low efficiencies of 5 to 6 per cent are to be compared with the somewhat higher efficiencies of 19 to 11 per cent for the negative grid type tube.

The influence of the grid voltage on the frequency and on the output and efficiency is shown by the curves in Fig. 22. These data are for a fixed circuit tuning, the grid voltage being adjusted to the values indicated. This corresponds to the condition that might obtain if a grid voltage modulation scheme were to be used. The lack of linearity of the output curve and the large shift in frequency indicate that amplitude modulation by this method

Fig. 24. Three optimum positive grid oscillators of the spiral grid type

Smallest tube designed for 2,500 megacycles, largest for 500 megacycles

would be unsatisfactory. The frequency shift, large as it is, is much less than the shift observed in tubes of poorer design and correspondingly lower efficiency.

The dependence of the output and efficiency as well as frequency upon the grid current is shown in Fig. 23. These data were taken with a grid potential of 450 volts and a fixed circuit adjustment corresponding roughly to a frequency of 532 megacycles. The current to the grid was varied by adjusting the temperature of the filament. The maxima observed in both the output and the efficiency correspond to conditions for which the grid current is limited primarily by the available emission rather than by space charge. As conditions corresponding to complete space charge are approached the output and efficiency fall off rapidly. The limit on the permissible grid dissipation prevents the extension of these curves to the condition of complete space charge. Because of this dependence of output on grid current, the adjustment of filament temperature is extremely critical.

At lower frequencies the efficiency of operation of a correctly designed positive grid tube is substantially the same as that exhibited by this tube. The negative grid oscillator on the other hand, as has been shown, increases both its output and efficiency rapidly with decreasing frequency. The positive grid oscillator is, therefore, at an increasing disadvantage at lower frequencies. With the present state of development, the negative grid oscillator will give larger outputs with higher anode efficiencies at all frequencies less than about 300 megacycles.

For frequencies much higher than 600 megacycles, it is found that the power input requirements for efficient operation of tubes having grids of the straight wire type are in excess of that which can be tolerated in the grid structures. Operation at very much less than optimum input results in considerable decrease in output as indicated in Fig. 25.

Spiral Grid Barkhausen Tubes

If the grid of a Barkhausen oscillator is in the form of a simple helix, oscillations at frequencies greater than those predicted by the relationship of eq 1 are readily obtained. When so constructed they are called spiral grid Barkhausen tubes. Some experimental models are shown in Fig. 24. The tubes used in the Lympne to St. Inglevert "micro-ray link" are of this general type.[14] Such tubes have been used to produce oscillations up to 3,000 megacycles.

Because of the fact that the severe limitation on the optimum grid diameter is modified by the presence of a tuned circuit within the tube formed by the helical grid helix, tubes of this type are particularly useful at frequencies above 600 megacycles. The former restriction on grid diameter is replaced by the requirement that the expanded length of the grid spiral be approximately 1.24 times the wave length at which the maximum output is required, and that there be a correct proportioning of the other dimensions of the tube. The dependence of wave length on the grid wire length is illustrated by the experimental data in Table I covering a frequency range from 460 megacycles to 2,220 megacyles. Graphic evidence of the independence of shape is shown by the largest and the smallest tube shown in Fig. 24 for which the dimensional ratios are nearly the same. The largest tube delivers several watts at 500 megacycles, while the smallest one delivers only a few tenths of a watt at 2,500 megacycles. The efficiency in both cases is about one per cent. These dimensional considerations lead to the conclusion that there exists a maximum output at any given wave length for a tube of a given design and that this output is proportional to the square of the optimum wave length. From this it appears that the only advantage offered by the spiral grid tube

Fig. 25. An experimental model of the split-plate magnetron showing a possible arrangement of the magnetic field

over the other type is the simplification in mechanical design which permits the construction of rigid grid structures capable of high energy dissipation for the higher frequency range.

The external tuned circuit for the higher frequency mode of oscillation takes the form of a Lecher system connected between the 2 grid terminals. When so connected the dependence of frequency upon circuit tuning is pronounced, as contrasted with the negligible dependence observed if the Lecher system is connected between the plate and the grid. When oscillating in the higher frequency mode the spiral grid tube shows only a comparatively small dependence of frequency on grid potential and this may be compensated by a proportional change in plate potential. This, coupled with the fact that the output increases rapidly with increasing grid potential, makes it possible to apply various schemes of amplitude modulation. Characteristics of the type shown in Figs. 21, 22, and 23 for the straight-wire-grid tube cannot be taken except for a limited portion of the range due to the inability of the grid to dissipate the energy required in the upper portion of the grid voltage or grid current ranges.

Table I—Dependence of Wave Length on Grid Wire Length for Barkhausen Oscillator With Helical Grid

Grid Wire Length in Cm.	Optimum Wave Length in Cm.	Ratio
16.3	13.5	1.21
18.6	18.6	1.00
19.7	14.5	1.36
20.4	18.0	1.13
21.4	17.5	1.22
21.8	25.0	0.85
22.3	20.2	1.10
25.2	18.6	1.35
30.6	25.0	1.22
32.0	23.8	1.36
32.0	25.5	1.25
33.4	25.0	1.33
42.6	29.0	1.47
42.6	29.5	1.44
42.6	30.2	1.41
42.6	30.7	1.38
53.2	43.5	1.22
80.0	65.0	1.23
Average		1.24

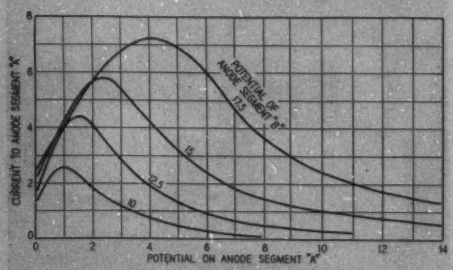


Fig. 26. Static characteristics of a split-plate magnetron

Magnetic field set for cut-off at potential of 1.45 volts. All values in arbitrary units

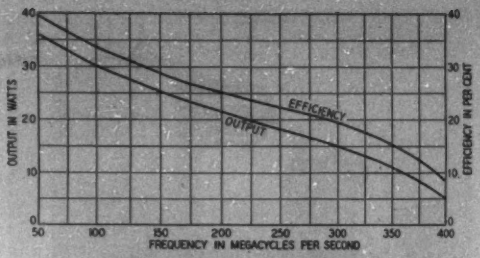
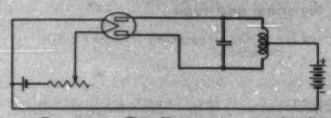


Fig. 27. Output and efficiency curves at different frequencies for split-plate magnetron

Anode potential—1,500 volts
Magnetic field—600–800 gausses



Data for Fig. 27 taken in this type of circuit

Fig. 28. Oscillation circuit of split-plate magnetron

While the spiral grid tube will also oscillate in the lower frequency mode, its efficiency and output are considerably lower than the corresponding values for the straight-wire-grid tube previously discussed. Its field of usefulness is, therefore, largely limited to the higher frequency mode of oscillation in the frequency range above 600 megacycles.

The "Magnetron" Oscillator

The "magnetron" in its simplest form consists of a cylindrical diode or 2-electrode tube, with a uniform magnetic field in the direction of the electrode axis. The original type of tube has been largely superseded for ultra-high-frequency generation by the so-called split-plate magnetron, first used by Okabe,[18] in which the cylindrical anode is divided longitudinally into 2 (or more) segments to the terminals of which is connected the tuned circuit. Such a tube is shown in Fig. 25.

In the frequency range from 300 to 600 megacycles the split-plate magnetron compares favorably with the negative grid tube both in output and in anode efficiency. Its use has been limited because of the complicating factor of the magnetic field, and the attending modulation difficulties. For frequencies higher than 600 megacycles the magnetron provides larger outputs than those so far reported by other means. It has been used at frequencies up to 30,000 megacycles, a value well above that so far reported for any other type of vacuum tube.

The magnetron depends for its operation upon the curvature of the electron orbits produced by the magnetic field. As first shown by Hull[15] in 1921, a

critical field exists beyond which the anode current falls off rapidly to zero. This field is given by the relationship

$$H = \frac{0.72}{R}\sqrt{V} \qquad (3)$$

where R is the anode radius and V is the potential of the cylindrical anode with respect to an axial filament. Although the original magnetron of Hull and Elder made use of variations in the magnetic field in its operation as a generator, it was soon discovered that oscillators could also be produced with steady fields by 2 somewhat different mechanisms. The one, first pointed out by Habann,[16] makes use of a negative resistance effect observable in the static characteristics and the other, first described by Zácek,[17] involves the electron transit time in a way quite analogous to the way in which it is involved in the positive grid triode. Both mechanisms have been used to produce oscillations at ultra-high frequencies.

Negative Resistance Type

Data reported by McArthur and Spitzer[1] on a split-plate magnetron tube are illustrative of the negative resistance type of behavior. Static characteristics taken by varying the potential of one anode with the magnetic field held constant for different values of the potential on the other anode are shown in Fig. 26. The pronounced negative resistance effect is obvious. This negative resistance characteristic can be utilized in producing oscillations.

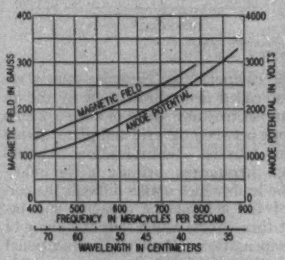


Fig. 29. Relation of magnetic field and anode potential to frequency of oscillation in magnetron oscillator of second type

Output and efficiency curves for this tube as an oscillator are shown in Fig. 27. These data were obtained by connecting a "tank" circuit, tuned to the desired frequency, across the 2 anodes, as shown in Fig. 28. Each anode delivers energy to the oscillating circuit during alternate half-cycles, so that in effect, it is equivalent to a push-pull oscillator. The limiting frequency as set by the interelectrode capacities and lead inductances (corresponding to the similar limit for the negative grid tube) is 450 megacycles. The decrease in output before this limit is reached is due to resistance and radiation losses and to the effect of electron transit time.

The magnetron, as contrasted with the negative grid tube, will oscillate with circuits having a high decrement. However, for its most efficient operation the effective anti-resonant impedance of the tuned circuit when loaded must be approximately 10 times the value required by a triode with the same anode dimensions. The load resistance that can be obtained at high frequencies is only a fraction of this value, so that the efficiency becomes increasingly less with higher frequencies. A further limitation is due to the fact that the electron current is concentrated on only a small part of the anode surface. This reduces the safe anode dissipation unless the anode is designed to have a high thermal conductivity. Because of these limitations, the ratio of output to the interelectrode capacity may be only slightly more favorable than the corresponding ratio for a triode of the same anode dimensions.

Type Depending on Electron Transit Time

When the magnetic field of a split-plate magnetron is adjusted to near the critical value given by eq 3, oscillations can be produced whose frequency will depend primarily upon the time of flight of electrons between filament and anode in a way closely resembling the behavior of the positive grid oscillator in its lower frequency mode of oscillation. For best output, the field must be above the critical value. To fix the time of flight and hence the frequency of oscillation, the magnetic field and plate voltage must be adjusted to certain values roughly expressed by the empirical relationship

$$\lambda H = 13{,}100 \qquad (4)$$

where λ is the wave length in centimeters and H is the field strength in gausses, which must also satisfy eq 3. It is found that for best operation the magnetic and electric fields within the tube should not be exactly perpendicular. This lack of perpendicularity may be achieved either by tipping the magnetic field relative to the tube axis or by introducing end plates within the tube and maintaining them at a fixed positive potential.

Kilgore[19] has given complete information concerning this type of oscillator. In Fig. 29, taken from his paper, is shown the dependence of field strength and anode potential on the desired frequency. The existence of a preferred frequency fixed by these values is confirmed by the data in Fig. 30 relating the output and wave length with the

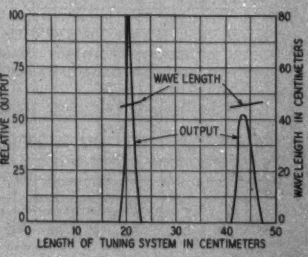


Fig. 30. Relation of wave length and output to length of tuning system in magnetron oscillator of second type

Anode potential —2,000 volts
Magnetic field—254 gausses

length of the attached Lecher system. The decreased output shown at the second peak is due to the added losses introduced by the extended length of the system. The outputs shown on these curves are not in watts, but represent relative readings of the field strength near the oscillator. With optimum adjustments 7 watts at 715 megacycles is reported, the efficiency being about 8 per cent. The dependence of output and frequency on the applied anode potential is shown in Fig. 31, and the dependence of frequency on the current in the magnetic field coil in Fig. 32. The importance of the adjustment of the field angle is shown by the data in Fig. 33.

An output of 2.5 watts at 3,160 megacycles has been reported by Wolff, Linder, and Braden.[22] They find that the efficiency of the tube is much improved by using end plates in place of the tipped magnetic field. Cleeton and Williams[21] have been able to obtain oscillations at 30,000 megacycles with a magnetron tube.

Amplification

The use of the conventional thermionic triode as an amplifier greatly exceeds its use as an oscillation generator in communication applications. Its ability to amplify has contributed much more to the development of our present-day long distance communication, whether by wire or by radio, than has its ability to oscillate. The complete utilization of ultra-high frequencies as carrier channels in communication will also, no doubt, be dependent upon the development of suitable amplifiers for this frequency range. Although certain forms of pseudo-amplification are possible with tubes of the Barkhausen and magnetron types, the negative grid triode and multi-element tubes derived therefrom are the only devices available for very high frequencies which will amplify in the sense that the output is an enlarged undistorted replica of the input.

As the frequency of operation of the negative grid triode is increased, difficulties in securing stable operation as an amplifier and in realizing the full gain indicated by the tube constants are encountered. These difficulties, as is well known, are in the main due to the tendency of the amplifier to oscillate or "sing" because of feed-back through the grid-plate capacity. This may be overcome either by the introduction of a compensating capacity somewhere in the circuit, so-called neutralization, or by the introduction of an electrostatic shield or screen within the tube envelope between the grid and plate, giving the screen-grid tetrode. Neutralization schemes fail at very high frequencies because of the inductance of the tube leads which makes difficult the correct location of the neutralizing capacity and because of transit-time effects which shift the phase of the needed compensation. However, conventional screen-grid tetrodes and pentodes are available which function satisfactorily over the major portion of the frequency range covered by the conventional 3-element tube as an oscillator.

For frequencies above approximately 60 megacycles specially designed tubes are required. Because of the similarity in the special frequency requirements, it is expected that there will be found a succession of multi-element tubes for amplification use, each rated for a band of frequencies, patterned after corresponding triode oscillators. The special frequency requirements for the amplifying tube are even more severe than those for the triode oscillator, so that the multi-element amplifying tube will in general cease amplifying at a frequency somewhat lower than the frequency limit of oscillation of the corresponding triode oscillator.

Thompson and Rose[3] have described small screen-grid tubes which will amplify at frequencies of 300 to 400 megacycles. One of these tubes is shown in Fig. 13. Their characteristics are similar to those of the conventional screen-grid tube in many respects. The very great reductions in interelectrode capacities, lead inductances, and transit time make

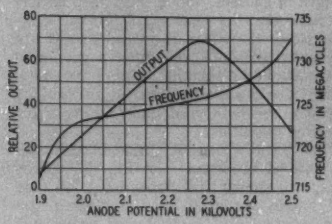


Fig. 31. Relation of output and frequency to anode potential in magnetron oscillator of second type

Field current—0.59 amp
Anode current—0.04 amp
Field angle—5 deg

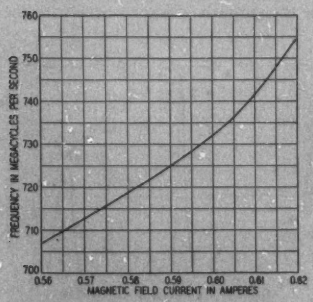


Fig. 32. Relation of frequency to magnetic field current in magnetron oscillator of second type

Anode potential—2,200 volts
Anode current—0.040 amp
Field angle—5 deg

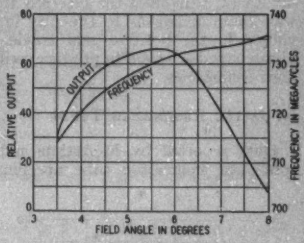


Fig. 33. Relation of output and frequency to field angle in magnetron oscillator of second type

possible the construction of receiving circuits using tuned radio frequency amplification at these very high frequencies. The ratio of the frequency limits of the corresponding triode as an oscillator (1,000 megacycles) to the frequency at which amplification was reported (400 megacycles) is typical and illustrates the apparently inevitable failure of the amplifier to keep pace with the oscillator in the struggle toward higher and higher frequencies.

References

NEGATIVE GRID TUBES

1. VACUUM TUBES AS HIGH-FREQUENCY OSCILLATORS, E. F. McArthur and R. E. Spitzer. I.R.E. *Proc.*, v. 19, 1931, p. 1971. (Bibliography of 28 titles.)

2. VACUUM TUBES FOR GENERATING FREQUENCIES ABOVE 100 MEGACYCLES, F. E. Fay and A. L. Samuel. I.R.E. *Proc.*, v. 22, 1934, p. 679.

3. VACUUM TUBES OF SMALL DIMENSIONS FOR USE AT EXTREMELY HIGH FREQUENCIES, B. J. Thompson and G. M. Rose. I.R.E. *Proc.*, v. 21, 1933, p. 1707.

4. AN EXPERIMENTAL STUDY OF REGENERATIVE ULTRA-SHORT WAVE OSCILLATORS, W. H. Wenstrom. I.R.E. *Proc.*, v. 20, 1932, p. 113.

5. A NEW TYPE OF ULTRA-SHORT WAVE OSCILLATOR, I. E. Mouromtseff and H. V. Noble. I.R.E. *Proc.*, v. 20, 1932, p. 1328.

6. ON THE PRODUCTION OF UNDAMPED OSCILLATIONS OF WAVE LENGTHS OF THE ORDER OF A DECIMETER IN A REACTION CIRCUIT I, W. Kroebel. *Ann. der Physik*, Series 5, v. 14, 1932, p. 80.

POSITIVE GRID TUBES

7. THE SHORTEST WAVES OBTAINABLE WITH VACUUM TUBES, H. Barkhausen and K. Kurz. *Phys. Zeits.*, v. 21, 1920, p. 1.

8. SHORT ELECTRIC WAVES OBTAINED BY VALVES, E. W. B. Gill and J. H. Morrell. *Phil. Mag.*, v. 44, 1922, p. 161.

9. CONTINUOUS ULTRA-SHORT ELECTRIC WAVES, K. Kohl. *Ergebnisse der exakten Naturwissenschaften*, v. 9, 1930, p. 276. (Bibliography of 135 titles.)

10. INVESTIGATIONS IN THE FIELD OF ULTRA-SHORT ELECTRO-MAGNETIC WAVES, G. Potapenko. *Phys. Rev.*, v. 39, 1932, p. 625; v. 39, 1932, p. 638; v. 40, 1932, p. 988; v. 41, 1932, p. 216. (Many references to the literature.)

11. INVESTIGATIONS OF VERY SHORT WAVE TUBES, H. Collenbusch. *Ann. der Physik*, Series 5, v. 13, 1932, p. 191.

12. A NEW CIRCUIT FOR THE PRODUCTION OF ULTRA-SHORT-WAVE OSCILLATIONS, H. N. Kozanowski. I.R.E. *Proc.*, v. 20, 1932, p. 957.

13. ELECTRONIC OSCILLATIONS, E. C. S. Megaw. I.E.E. *Jl.*, v. 72, 1933, p. 313. (Bibliography of 47 titles.)

14. PRODUCTION AND UTILIZATION OF MICRO-RAYS, H. G. Clavier. *Elec. Communication*, v. 12, 1933, p. 3.

MAGNETRON TUBES

15. THE EFFECT OF A UNIFORM MAGNETIC FIELD ON THE MOTION OF ELECTRONS BETWEEN COAXIAL CYLINDERS, A. W. Hull. *Phys. Rev.*, v. 18, 1921, p. 31.

16. A NEW VACUUM TUBE GENERATOR, E. Habann. *Zeit. f. Hochfreq.*, v. 24, 1924, p. 115.

17. A METHOD FOR THE PRODUCTION OF VERY SHORT ELECTROMAGNETIC WAVES, A. Žáček. *Zeit. f. Hochfreq.*, v. 32, 1928, p. 172.

18. PRODUCTION OF INTENSE EXTRA-SHORT ELECTROMAGNETIC WAVES BY SPLIT-ANODE MAGNETRON, K. Okabe. I.E.E. *Jl.*, Japan, 1928, p. 284. See also I.R.E. *Proc.*, v. 17, 1929, p. 652; and I.R.E. *Proc.*, v. 18, 1930, p. 1748.

19. MAGNETOSTATIC OSCILLATORS FOR GENERATION OF ULTRA-SHORT WAVES, G. R. Kilgore. I.R.E. *Proc.*, v. 20, 1932, p. 1741.

20. AN INVESTIGATION OF THE MAGNETRON SHORT WAVE OSCILLATOR, E. S. C. Megaw. I.E.E. *Jl.*, v. 72, 1933, p. 326. (13 references.)

21. A MAGNETOSTATIC OSCILLATOR FOR THE GENERATION OF 1 TO 3-CM WAVES, C. E. Cleeton and N. H. Williams. *Phys. Rev.*, v. 44, 1933, p. 421.

22. TRANSMISSION AND RECEPTION OF CENTIMETER WAVES, I. Wolff, E. G. Linder, and R. A. Braden. I.R.E. *Proc.*, v. 22, 1934, p. 555.

GENERAL

23. VACUUM TUBE ELECTRONICS AT ULTRA-HIGH FREQUENCIES, F. B. Llewellyn. I.R.E. *Proc.*, v. 21, 1933, p. 1531.

24. THEORY OF THE INTERNAL ACTION OF THERMIONIC SYSTEMS AT MODERATELY HIGH FREQUENCIES, W. E. Benham. Part I—*Phil. Mag.*, March 1928, p. 641. Part II—*Phil. Mag. A*, v. 11, 1931, p. 457.

25. ON TRANSMITTER TUBES FOR PRODUCING WAVES ONE METER LONG, L. Rohde. *Hochfreq. und Elektroakustik*, v. 40, 1932, p. 3.

26. THE SELECTION OF TYPES OF VACUUM TUBES AS SOURCES OF HIGH FREQUENCY POWER, W. C. White. *G.E. Rev.*, v. 36, 1933, p. 394.

27. HISTORICAL REVIEW OF ULTRA-SHORT-WAVE PROGRESS, W. H. Wenstrom. I.R.E. *Proc.*, v. 20, 1932, p. 95. (Bibliography of 54 titles.)

The "Thyratron" Motor

A new type of motor in which a scheme involving electronic tubes is used to perform a function similar to that of a commutator is described in this paper. The motor operates at variable speed and is supplied from a 3-phase power system. A 400-hp motor of this type has been built and is ready for commercial use.

By
E. F. W. ALEXANDERSON
FELLOW A.I.E.E.

A. H. MITTAG
ASSOCIATE A.I.E.E.

Both of the General Elec. Co., Schenectady, N. Y.

THE newly developed "thyratron" motor described herein is analogous to a commutator motor because a group of "thyratron" tubes takes the place of the commutator and functions to commutate the current. It belongs to the group of developments which are based upon the discovery that the starting of the anode current in a gas arc rectifier could be controlled by a third electrode. Vapor electric devices such as grid-controlled gas-filled or mercury-vapor-filled electronic tubes, based upon this principle, are on the market under the trade name of "thyratron."

The thyratron set which is an essential part of the motor equipment has 2 distinct functions. One is grid controlled rectification and the other is commutation. Each of these functions of the thyratron set has a significance in the practical application of the motor. Through the commutator functions, a motor is made available which operates on an a-c power supply but has smooth variable speed torque characteristics like a d-c motor without any reference to synchronism with the a-c system. The grid controlled rectifier function gives a motor which has continuous power control from standstill to maximum speed. This power control has delicacy, quickness, and accuracy which is superior to anything heretofore available. It may be operated manually or with remote control, and lends itself well to automatic control for regulating speed and power for coördination with other machinery.

ARRANGEMENT OF THE THYRATRON MOTOR

The functioning of the thyratron motor can be best understood if it is looked upon as a species of d-c motor. The elements of a d-c motor are a d-c

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Sept. 27, 1934; released for publication Oct. 4, 1934.

power supply, a commutator, an armature, and a field. In the new motor each of these elements can be identified. A set of thyratron tubes takes the place of the commutator. The armature is stationary and the field is rotating, and the motor has a structural resemblance to the synchronous motor, but nevertheless the functioning of the armature and the field can best be explained in terms of the d-c motor. The d-c power supply can also be identified although it is not so apparent on the surface.

The actual power supply used in the developmental arrangement as shown in Figs. 1 and 2 is 4,000 volt, 3 phase, 60 cycle. With reference to this power supply the thyratron tubes act as a rectifier with an output which appears in the form of direct current. The same set of tubes serve to guide the flow of direct current successively through the different sections of the armature windings like the brushes and segments of a d-c commutator. This double functioning of the thyratron tubes may seem a little confusing at the first instant but this matter can be cleared up by considering for a moment an arrangement as shown in Fig. 3 in which one set of tubes is used for rectification and another set of tubes is used for commutation. Motors have been operated successfully in this way, but the first arrangement is preferable for the practical purpose which is now being considered because of its high torque starting characteristics, which will be explained later under the theory of commutation.

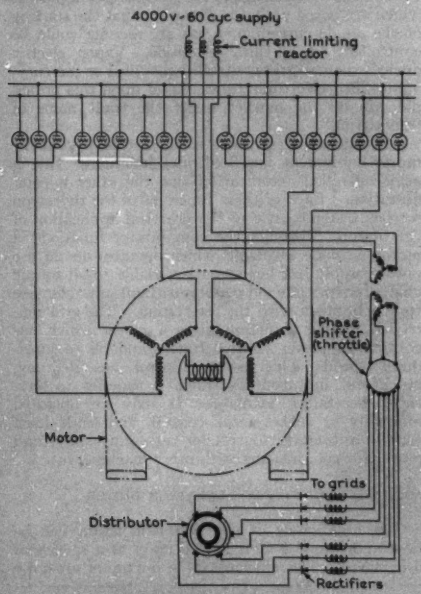


Fig. 1. Simplified diagram of connections of thyratron motor with grid circuit omitted

Consideration of the second arrangement with one set of rectifying tubes and one set of commutating tubes is, however, helpful for the purpose of explanation. The rectifier tubes functioning with the conversion ratio of this type of rectifier transforms the 3-phase a-c power into about 5,000-volt direct current. The rectifier is grid controlled so that the output voltage may be adjusted by the operator to any desired value between zero and full voltage. In this respect the new motor has a distinct advantage over the conventional d-c motor which always consumes power at full voltage unless part of this power is wasted in resistance. The controlling grids of the rectifier, on the other hand, vary this voltage from zero to maximum without any loss of power.

The commutating tubes have a function corresponding to the brushes and segments of the commutator making contacts successively to different portions of the armature winding. Each tube has a cathode and an anode, one of which may be considered as a commutator segment and the other as the brush. The brush and the commutator segment are in contact only at certain times and in analogy

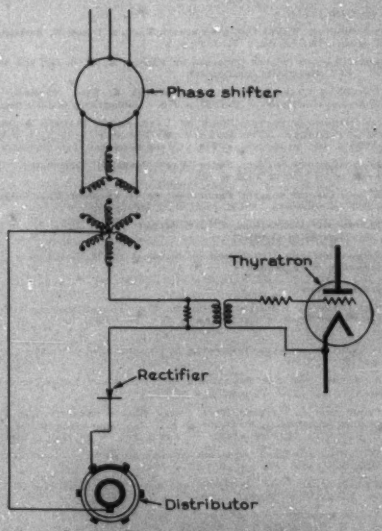


Fig. 2. Thyratron motor grid circuit

with this the grid control functions in such a way that electrical contacts between the cathode and the anode are established only when desired.

When these separate functions of rectification and commutation are understood it becomes easier to analyze the arrangement which is being used whereby each tube performs all these functions at the same time. As seen by the diagram in Fig. 1, the tubes are arranged in groups of 3 with reference to the

power supply and each of these groups functions exactly like a single rectifier tube in Fig. 3. With reference to the motor the tubes are also arranged in groups of 3 but in a different order; and with reference to the motor, the tube groups function like the commutator tubes in Fig. 3. While each tube has only one grid, it has 2 distinct grid controls, one of which functions as a rectifier control and the other as a commutation control. To accomplish this result it was necessary to find some method of combining these 2 grid controls in such a way that

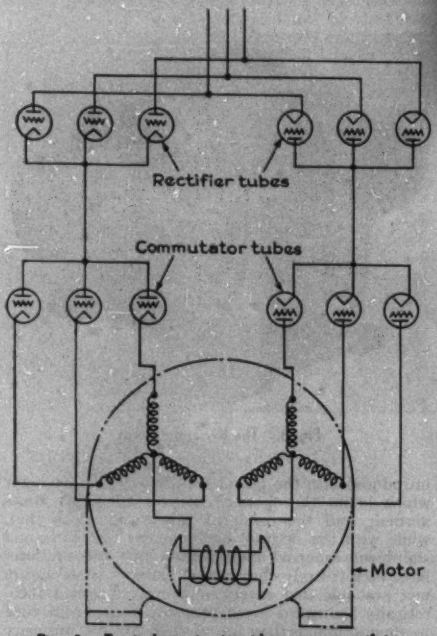


Fig. 3. Equivalent circuit with separate rectifying and commutating tubes

the 2 functions do not conflict with each other. This has been accomplished by the grid control circuit shown in Fig. 2. The rectifier control is of the nature of a phase shifter and the commutation control is in the nature of a distributor. When the phase shifter delivers a positive voltage and the distributor at the same time makes contact, a circuit is closed which impresses a positive voltage on the grid and thus makes the tube conducting. Whenever the phase shifter delivers a positive voltage but the distributor does not make contact, or whenever the distributor makes contact while the phase shifter delivers a negative voltage the tube remains nonconducting.

The choice of the tube which is to be conducting

Fig. 4. Thyratron control unit

at any instant is thus determined by the rectifier control and the commutation control in combination in such a way that those 2 controls do not conflict with each other, but the rectifier control determines the path of the current flow exclusively in the power supply circuit, and the commutation control determines the path of the current in the motor circuit.

The assembly of the thyratron tubes of a 400-hp thyratron motor designed for commercial use is shown in Fig. 4. In Fig. 5 is shown the operation board and controller, while the motor proper with the distributor mounted at the end of the shaft is shown in Fig. 6. Figure 7 shows the air core current limiting reactor which is indicated on the diagram, Fig. 1.

Theory of Operation

When in the elementary explanation given above it is stated that a positive grid voltage makes the tube conducting and the negative voltage makes it nonconducting, this statement applying to present-day commercial tubes should be qualified: A positive voltage makes the tube conducting and a negative voltage prevents it from becoming conducting but it does not interrupt a current which has already been established.

The transfer of current from one tube to another is called commutation in analogy of transfer of current from one commutator segment to another. In a d-c motor with sparkless commutation the current is transferred from one segment to another by the electromotive forces in the windings acting between those 2 segments and not by the breaking of the contact between the brushes and the segment. This analogy between the d-c motor and the thyratron motor is accurate because the transfer of current takes place as a result of electromotive force in the motor winding. If these electromotive forces are not adequate to complete the commutation, there is a commutation failure which is analogous to the sparking of the commutator. It has been the ob-

Fig. 5. Operating panel

ject of the present development work to establish methods for designing thyratron motors so that commutation failures do not occur in normal operation and if they do occur due to some abnormal circumstances, they are only of minor consequence and do not cause a shutdown of operation.

The principal sources of failure in a thyratron circuit can be classified as those originating in the power circuit, those originating in the grid circuit, and those originating within the tubes. The oscillogram reproduced in Fig. 8 illustrates a failure of a type which should not occur, and for which there have been found means to avoid. The oscillogram shows first an increase of current from the operating current to an abnormal value. This increase was due to a failure of grid control and may have originated within the tube or may have originated in the grid circuit by imperfect contact on the distributor. The excessive current caused by this commutation failure runs along for several cycles and then there appears a still more excessive current in a reverse direction which indicates a tube failure of the nature that is called arc-back, meaning that a tube conducts in the direction in which it should always be nonconducting. The arc-back, however, lasts only one-half cycle after which normal operation is resumed and the circuit breaker opens shortly afterward only because the tripping mechanism had been set in motion. The tube used in these tests had a continuous rating of 12.5 amp and a maximum rating of 75 amp, and it is therefore significant to know that the arc-back current shown in the oscillogram has a magnitude of 1,200 amps. Nevertheless, the tube was not damaged.

Another important observation may be made from this oscillogram. The arc-back current lasts only $^1/_2$ cycle, although the circuit was closed for several cycles before the circuit breaker opened. From this it has been concluded that the occurrence of the arc-back serves as a cleaning process which removes from the anode accumulated contamination which was the cause of formation of a cathode spot and conductivity in the wrong direction. Thus, it may be observed that the arc-back not only did not damage the tube but on the contrary improved it. It is evident, however, that a failure of this sort illustrated by this oscillogram and a consequent shutdown is not permissible in practical operation. All electrical apparatus must somehow be protected from current so excessive compared with that for which it is designed. As a practical solution to this there was

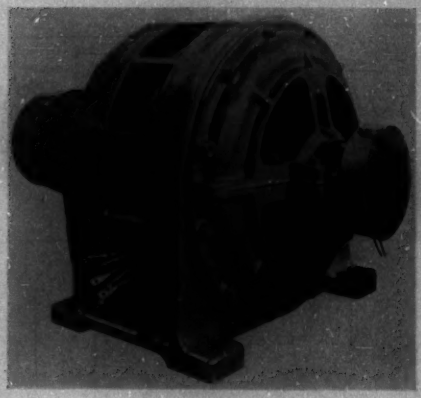


Fig. 6. The thyratron motor

introduced into the power supply a 3-phase reactor which limits the short-circuit current to 5 times normal; and the result of this change was that, while with the original arrangement arc-overs and shutdowns occurred about once a day, these failures have been entirely eliminated. It is possible and in fact probable that reversals of current which theoretically are called arc-backs still occur from time to time although they are of such limited intensity and such short duration that they are not discovered by ordinary instruments. If this theory is correct, contamination may gradually accumulate on the anode during normal operation until a momentary reversal of current takes place which removes the contamination. Future experience will show whether this interpretation is correct but at any rate arc-backs have been eliminated as a factor in practical operation. It should also be observed that while the arc-back is a failure which takes place within the tube the practical remedy has not been to change the tubes but to change the proportions of the power circuit.

Most of the failures recorded by the automatic oscillograph from which Fig. 8 was taken are indicated as failure of grid control without arc-backs. All such failures were eliminated by the use of the current limiting reactor. The difficulties encoun-

tered in earlier operation, in the form of arc-backs and grid failures, have thus been overcome. The remedy, however, was not a change in the design of the tubes but a change in the design of the power circuit. If the rules of design thus learned are observed the operation should be stable and reliable.

One evidence of the proper functioning of the commutation can be found by shifting the brushes on the distributor, just as the brushes of the d-c machine may be shifted to establish the point of best commutation. If the brushes are shifted in the direction of rotation a position will be found where the commutation begins to fail. The evidence of such incipient failures may be found by observing with an ammeter the current consumed by the motor, which becomes unsteady showing a succession of kicks tending toward higher current. The brushes may then be shifted again in the opposite direction until the current becomes steady. This method of adjustment is quite analogous to the adjustment of a d-c machine for sparkless commutation. It should be observed, however, that a brush shift against the direction of rotation does not result in commutation failure and is limited only by the operating characteristics because of the reduction of the counter electromotive force of the motor. The proper position of the brushes, therefore, gives a fair and safe margin from the point where commutation failures begin.

Fig. 7. Current limiting reactor used in connection with the thyratron motor

Two Kinds of Commutation

The discussion of the theory of commutation so far has referred to operation within the normal range of speed. It was shown that commutation takes place as a result of electromotive forces in the motor circuit. However, at starting and very low speeds there is insufficient electromotive force in the motor windings to cause commutation in accordance with the theory that has been given. This is one of the reasons for using the arrangement shown in Fig. 1, where the same tubes are used for rectification and commutation at the same time rather than the arrangement in Fig. 3, where separate tubes are used for rectification and commutation. The first arrangement provides commutation at standstill and low speeds whereas the second arrangement does not. The reason for this is that while commutation depending upon electromotive force in the motor circuit does not function at low speeds, each tube in the arrangement of Fig. 1 is associated with the power circuit as well as the motor circuit and, therefore, while the electromotive force in the motor circuit is absent, the commutation is caused by the electromotive force in the power circuit. Thus, there are 2 kinds of commutation, one caused by the electromotive forces in the motor circuit when used at full speed and the other caused by electromotive forces in the power circuit which are effective at standstill and low speeds. In the first case the commutation is initiated by the voltage of the grids and timed by the distributor. The timing of this commutation is, therefore, accurate and is controlled by the grid circuit. It may, therefore, be called grid commutation.

The other type of commutation which is effective at standstill and low speeds is not so accurately timed by the distributor. When the grid goes negative as the result of interruption of the distributor contact, this does not in itself cause any change in the power circuit. The current continues to flow as before until the electromotive force in the power circuit goes through zero and thus interrupts the current in one tube and transfers it to another tube which sometime earlier had been made conductive by the grid circuit. Thus it can be seen that it is

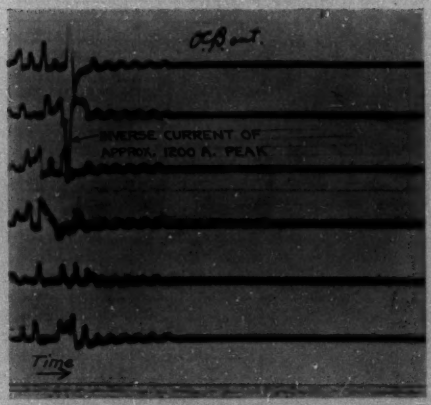


Fig. 8. Oscillogram showing control failure and arc-back

the voltage of the anode and not the voltage of the grid that determines the time when the commutation will take place. This may be called anode commutation. The anode commutation is fully effective at standstill but begins to lose its effectiveness at from $^1/_3$ to $^1/_2$ speed because of the inaccurate timing. Thus the motor starts with anode commutation which is as effective in producing starting torque as the commutator in any d-c motor. As the motor begins to gather speed and to acquire electromotive force, the grid commutation becomes effective and thus the motor continues to operate at full torque efficiency at all speeds between standstill and its highest speed. The arrangement in Fig. 1 by which each tube performs both rectification and commutation has thus the advantage that it has inherently 2 systems of commutation, both of which can function simultaneously although one is useful at low speed and the other more useful at high speed. Although the motor should function with grid commutation exclusively at high speed, there is some advantage in having the anode commutation, so to say, in reserve; because, if the grid commutation should fail momentarily, there is the anode commutation to fall back upon. This means that if some particular current transfer did not take place when properly timed by the grid, it would be forced to take place a fraction of a half cycle later by anode commutation. This makes operation as a whole more reliable and explains why only a slight disturbance is observable when the distributor brushes are adjusted so that the commutation begins to fail.

Operating Characteristics

The operating characteristics of the thyratron motor may be better compared with a steam engine than with any other electric motor. The phase shifter in the grid circuit which is used by the operator for starting the motor and adjusting the speed admits to the motor the current flow needed to produce the desired power and may appropriately be called a throttle control in analogy with the throttle on a steam engine. The resistance used for speed control of slip ring induction motors might also be called throttle control, but the throttling in the thyratron motor is accomplished by reduction of power factor instead of by wasting of energy. This has the double advantage that no provisions need to be made for dissipating wasted energy and that the wattless kilovoltamperes consumed at reduced speed by the thyratron motor are much cheaper than the corresponding kilowatts of the resistance control, and can be compensated at a comparatively low cost by the use of capacitors or synchronous condensers.

As may be seen from the diagram of Fig. 1, the motor field is excited by the direct current that results from the rectifier action of the tubes. It is also possible to operate the motor with a separately excited field but the series excitation has proved the most convenient and gives the high overload and starting torque characteristic of a series motor. In Fig. 9 is shown the speed-torque characteristics with the throttle control full open as well as with various settings for reduced power. In Figs. 10 and 11 are shown the adaptation of the thyratron motor to

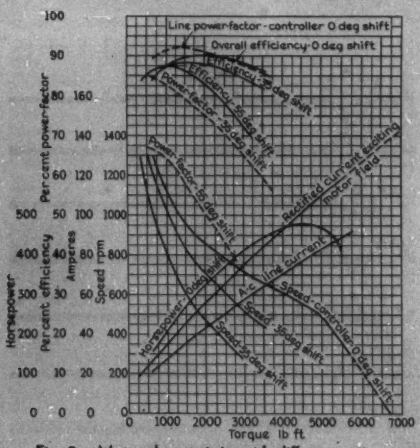


Fig. 9. Motor characteristics with different settings of the controller

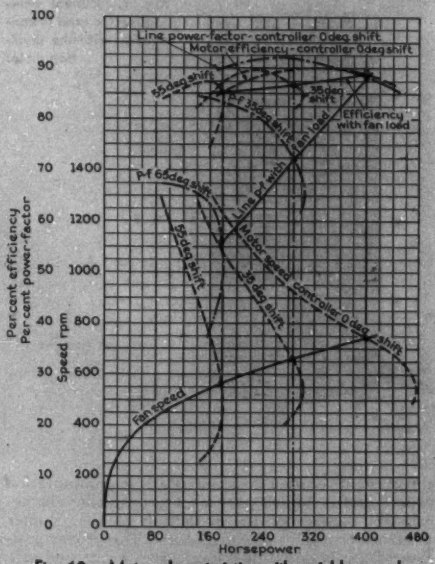


Fig. 10. Motor characteristics with variable speed control for fan load

drive a fan at variable speed. The speed-horsepower characteristics of the fan are superimposed upon the motor characteristics so that intersection points of the speed curves give the actual points of operation, and thus are constructed curves showing efficiency, power factor, kilowatts, and wattless kilovoltampere consumption of the motor at various operating speeds of the fan. Among the operating characteristics the wave shape of current drawn from the line should be mentioned. From the point of view of the power supply the thyratron motor is nothing but a 6-phase grid-controlled rectifier. Therefore the same considerations apply to the practice dealing with the wave shape of the thyratron motor as with such rectifiers.

Automatic Control

The throttle control which is a function of the grid circuit lends itself well to automatic and remote control. One feature of automatic control which has been incorporated in the commercial motor design is of particular interest because of its effect upon reliability and continuity of operation. Up to full power of the motor of 400 hp the throttle remains wide open when set in the "full on" position, but if the load is increased so that the motor draws more than full load current from the line, this current reacts upon the grid circuit in such a way as to modify the phase displacement of the grid voltage independently of the phase determined by the position of the controller. The effect of this reaction of the line current upon the grid control is to limit the current which the motor can draw from the line. This automatic current limiting control has been worked out in such a way that the motor may be started from standstill with the throttle control wide open without drawing any more overload current from the line than that for which the apparatus is adapted and less than that for which the automatic circuit breaker is adjusted. The starting of the motor may thus be made entirely automatic from a remote point if desired and the arrangement insures continuity of operation with less attention. The controller may thus remain in the operating position at either full or fractional speed, and the motor may be started by remote control of the main circuit breaker and will immediately come up to its normal operating speed.

Reliability

The reliability in the functioning of the thyratron motor which has been aimed at and attained may be characterized by saying that it has stability of commutation. If a momentary commutation failure results in further accumulative changes of the functioning of the system and results in a short circuit, the commutation is unstable. When, on the other hand, such proportions of design have been observed that stable commutation has been established it should be possible to disturb this normal operation momentarily in almost any way whatever and normal operation should resume itself immediately when the cause of the disturbances has been removed. The stability of commutation may be tested by purposely

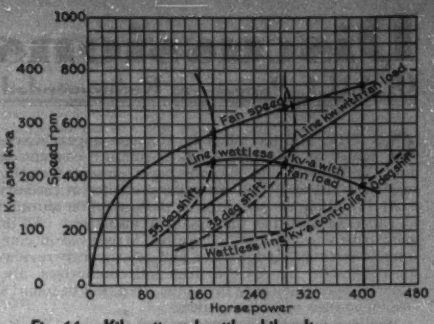


Fig. 11. Kilowatts and wattless kilovoltampere consumption with fan load

introducing such disturbances as open circuiting the power supply, interruption of the grid circuit, or misadjustments of the brushes on the distributor. Whatever disturbance is chosen as a test of stability of operation, normal operation should be resumed as soon as the circuit is reëstablished.

If any one tube is removed from the circuit the current will be carried by the adjacent tubes and operation is possible at reduced load. The current flow in any one tube may be interrupted during operation by disconnecting the grid circuit and such a measure may be used as a preliminary step to remove the tube if it should prove to be defective. It is still too early to forecast what routine of inspection and tube replacement should be put into effect for maintenance of this type of motor. It is probable that some practice will be established similar to maintenance of brushes on the commutator which also have a limited life. Ways may be thought of for taking a tube out of the circuit automatically by short circuiting or disconnecting the grid if the tube has been carrying excessive current for a prolonged period. It has not, however, been attempted to introduce such automatic devices in the first commercial design because simplicity is of greater value than automatic features in a new device which must necessarily receive some more attention by the operators.

As has already been pointed out, the thyratron equipment may be subjected to a great many disturbances without interruption of service. Fluctuations of the voltage of the power supply such as may be found in commercial systems will not cause any disturbance of operation but will only modify the speed-torque characteristic as with a d-c motor. Similarly, unbalancing of the voltage does not disturb operation; in fact one phase may be disconnected entirely and the motor will run on single-phase power supply with reduced load. The power flow through the thyratron set is irreversible and therefore a short circuit on the power system will not tend to stop the motor. If, on the other hand, it is desired to use the motor as an electric brake it is possible to so arrange the control that power will flow from the motor back into the line.

Discussions

Of A.I.E.E Papers—as Recommended for Publication by Technical Committees

ON THIS and the following 17 pages appear discussions of papers presented at the 1934 A.I.E.E. summer convention, Hot Springs, Va., June 25–29, as follows: (1) one paper presented at the session on electrical machinery (closure); (2) one paper presented at the session on power generation; (3) all papers presented at the session on automatic stations; and (4) all papers presented at the session on insulators. All discussions on the foregoing papers (except that in item No. 1) received in complete and acceptable form at Institute headquarters, and subsequently reviewed and recommended for publication by A.I.E.E. technical committees, are included. Authors' closures, where they have been submitted, will be found at the ends of the discussion on their respective papers.

Members anywhere are encouraged to submit written discussion of any paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions on papers scheduled for presentation at an A.I.E.E. meeting or convention will be closed 2 weeks after presentation. Discussions should be (1) concise; (2) restricted to the subject of the paper or papers under consideration; and (3) typewritten and submitted in triplicate to C. S. Rich, secretary, technical program committee, A.I.E.E. headquarters, 33 West 39th Street, New York, N. Y.

Insulation Resistance of Armature Windings

Author's closing discussion of a paper published in the June 1934 issue, p. 1010–21, and presented for oral discussion at the electrical machinery session of the summer convention, Hot Springs, Va., June 27, 1934. Other discussions of this paper were published in the October 1934 issue, p. 1407–11.

R. W. Wieseman: Mr. Rutan states that the formulas proposed in the paper give a minimum insulation resistance (condition 4, Table I) which is too low for synchronous converters. The resistance for condition 4 is based on a winding temperature of 75 deg C, so this value of resistance is low if the winding is measured at room temperature.

It is recognized that many operators will not allow the insulation resistances of their machines to fall to a value given for condition 4. This is the minimum value and favorable operating conditions will maintain the resistance above this minimum value. For the reasons which Mr. Rutan pointed out, coefficients for condition 3 were incorporated in Table I of the paper. It is suggested, therefore, that Mr. Rutan consider condition 3 the bench mark value of insulation resistances of machines in good condition.

Messrs. Henderson and Calvert called attention to the absence of test data in Tables II, III, and IV. These tables show a comparison of minimum insulation resistance values obtained by existing formulas and by the formulas recommended in the paper. The machine ratings listed in the tables are hypothetical and test data on these machines, therefore, are not available. Tests on many machines, however, were used to evaluate and check the coefficients of the new formulas.

In the test data submitted by Messrs. Henderson and Calvert, some machines had resistance values below that of the American Standards Association formula and the formulas recommended in the paper. The A.S.A. formula applies only when the winding is at a temperature of 75 deg C; consequently, all new machines will meet the A.S.A. values at room temperature. At 75 deg C, however, 5.9 per cent of the induction motors did not meet the A.S.A. values. These tests also bring out a very interesting point; namely, that the A.S.A. formula penalizes high voltage machines. In the formulas given in the paper this is not the case because the voltage of a machine is increased by a coefficient which places all machines regardless of voltage on the same basis. In other words, a formula based on machine dimensions is naturally more logical and more dependable than a formula which considers only the voltage and kilovolt-amperes of the machine.

Mr. Creagmile suggests that the ballast resistance of a megger should be shunted during the first few seconds of voltage application. This is a step in the right direction, especially for new machines where the absorption effect is very pronounced. Since much of the uncertainty of insulation resistance lies in the method of measuring the resistance, it is very desirable to eliminate as many variables as practicable and apply the full voltage instantly instead of allowing it to build up at a variable rate depending upon the electrostatic capacity of the winding.

The "one megohm standard" mentioned by Mr. Creagmile may apply by chance to certain groups of machines, but it cannot apply to all machines. Any "standard" of this kind is basically wrong and misleading and it should therefore be discouraged.

Mr. Hellmund points out that for many years insulation resistances were so irregular that they did not seem to be of real practical value. This is true in many cases because of the inconsistencies in the insulation resistance measurement itself. The paper emphasizes the point that consistent readings can be obtained only when the test is made under the same conditions; for example, after a 500-volt application for 1 minute. If this is done, some of the irregularities disappear.

Mr. Hellmund questions the amount of variation in the coefficients of Table I. These variations are caused by the effect of temperature, moisture, and other foreign matter in the insulation and can readily be checked by test. It is admitted that the insulation resistance of a winding is determined more by foreign matter in or around the winding than the machine dimensions. This large variation caused by impurities is taken into account by the new formulas and apparently this is just what the operators have desired for many years. Thus the paper gives for the first time expressions for the insulation resistance of an armature winding when a machine is new and when a machine has had favorable operating conditions, and also the minimum insulation resistance which indicates when a winding should be carefully inspected and reconditioned if necessary.

The author does not agree with Mr. Rylander that the formulas (accompanied by nomograms) given in the paper are complicated and that they are less accurate than the present formulas. A simple expression, which includes only the voltage of the machine and an experience factor, cannot be so accurate and dependable as an expression based on actual machine dimensions and governed by test values of insulation resistivity.

Mr. Rylander states that the suggested formulas do not eliminate any of the major variables: temperature, moisture or solvent content, and foreign matter. Table I clearly indicates the winding temperature to which the coefficients apply. The formulas cannot indicate the amount of moisture, solvent, foreign matter, or mechanical damage, etc., of the insulation. These variables are complex, but their combined effect on the winding is to lower its insulation resistance. The suggested formulas (condition 4), therefore, give a minimum value which is a red flag to stop the unfavorable action of 1, 2, or all of these variables. With reference to the lack of confidence in the coefficients of Table I and their large variation, this is simply a matter of obtaining the necessary test data. It is recognized that mica insulation compound-filled under vacuum (class B) is much more resistant to moisture and foreign material than varnished fabric (class A) insulation. Thus mica insulated machines in service have a higher resistance than varnished fabric insulated machines. Furthermore, as stated in the paper, mica insulated machines are usually important machines and they should be maintained at a relatively higher insulation resistance.

In regard to the difficulty of choosing the resistivity coefficient for mixed insulation, this again is simply a matter of obtaining

test results on this type of insulation. With reference to the lack of consistent relationship among the various "constants" in Table I, Mr. Rylander is referred to p. 6 of the paper, which explains that all constants were incorporated in the coefficient k for simplicity. The fact that different machines have different values of k for the same class of insulation, therefore, does not prove that the insulation resistivity of these machines is necessarily different or that the insulation of one type of machine is superior to that of another.

Mr. Rylander states that foreign matter may change the resistance values 10 times or 100 times or in some cases even 1,000 times. Figure 8 in the paper shows that Class A insulation resistivity can change 100,000,000 times by allowing it to absorb moisture for a long time.

Mr. Rylander's test data, Fig. 1, show the manner in which insulation resistance changes with temperature, moisture, and solvent on a particular line of induction motors. It is an odd coincidence that at 75 deg C the machines which were allowed to absorb moisture should have a resistance of exactly 1 megohm, the value proposed by some as the minimum insulation resistance for any machine.

With reference to Mr. Reed's criticism of item 11, p. 1010, it is obvious that other things besides moisture lower insulation resistance. This paragraph deals only with the effect of moisture on insulation resistance just as items 3, 4, and 5 describe only the effects of temperature, applied voltage, and time of voltage application, respectively. Mr. Reed objects to the numerous formulas, one for each type of machine, the different coefficients for each class of insulation and type of machines and the "arbitrary" nature of these coefficients, and to the special consideration given to single phase machines, etc. These factors must all be taken into consideration in determining a bench mark value of the insulation resistance of an armature winding. Conversely, the lack of appreciation of these factors is one reason why insulation resistance has been considered so erratic for many years.

Mr. Reed states that during the past 12 years more than 750,000 insulation resistance readings were taken on all kinds of electrical apparatus and that insurance is withheld if the resistance is less than 1 megohm per 1,000 volts. Incidentally, we know of a number of machines which have given reliable service with insulation resistances less than that prescribed by Mr. Reed. Insurance is based on averages so that what one gains by insurance another must lose. The paper is a step forward in this respect because it is not based on averages and "more or less" definite indications. It does not handicap one machine and benefit another, but it evaluates each machine on its own merits based on the machine dimensions and insulation characteristics.

In conclusion, it is emphasized that the formulas for insulation resistance derived in the paper are based first on the machine dimensions and second on resistivity tests which include the characteristics of the insulation. Thus these formulas are on a rational basis and they, therefore, should supersede all rule of thumb expressions such as 1 megohm per 1,000 volts. Furthermore, the paper calls attention to the fact that many of the erratic features of insulation resistance readings in the past were caused by the inconsistent methods of measuring insulation resistance. The formulas given in the paper enable one to obtain, for reference, the insulation resistance of the machine when new. In fact, the formulas can be used to check the quality of the insulation and the effectiveness of the insulation treatment. It is hoped that operating engineers will also obtain data on machines in service and thereby aid in evaluating more closely the coefficients for conditions 3 and 4, Table I.

Voltage Regulation and Load Control

Discussion and author's closure of a paper by H. C. Forbes and H. R. Searing published in the June 1934 issue, p. 903–9, and presented for oral discussion at the power generation session of the summer convention, Hot Springs, Va., June 29, 1934.

F. M. Starr: The authors have demonstrated clearly the improvement in system operation which can be obtained by making a thorough study and by the utilization of accurate and suitable instruments. It is of particular interest to note the excellent results which have been obtained in controlling load and phase angle by the methods described. Figures 6, 10, and 12 in the paper offer ample evidence of the benefits obtained.

Perhaps it should be pointed out that the problems which have been treated here are rather special ones, considering power distribution systems in general. In few cases—outside the New York area—is a secondary network fed by more than one generating source. In fact, the large majority of secondary networks in this country are fed from single bus.

In a few cases a small network may be fed by 3 or 4 feeders, each from a separate substation bus. In these cases the respective buses are usually firmly tied together with cable ties. During certain emergency operating conditions, these ties may carry considerable load, but the phase angle difference between 2 buses is scarcely ever more than 1 deg. Since networks of this type are usually small, the circulating impedance between buses and through the network is high, and as a result very little power is circulated. Moreover, the maximum phase angle difference will usually occur during the time of peak network load when even a large circulating power current will not be sufficient to give a net power reversal in any network protector.

Therefore, in general, the severe operating conditions in the New York area and the problems arising therefrom are not met in the average network distribution system. Nevertheless, the methods of control which Messrs. Searing and Forbes have developed should be of considerable general interest. The excellent results which have been obtained should stimulate study and activity along these lines by other operating engineers.

The load control scheme shown in Figure 11 and described briefly in the paper is of particular interest. I should like to ask the authors to explain in more detail exactly how the regulators and compensator function. Offhand this arrangement would appear to function in such a manner as to circulate a fairly large component of negative phase current. However, this condition may not be serious. This particular scheme is certainly a novel one and more complete operating data on the results obtained would be of considerable interest.

A. H. Sweetnam: The relative values of the load and reactive currents through the network units and in the tie lines between the generating stations is a problem of long standing in a new setting. We have long been accustomed to adding paralleling reactors to cables or transformers operating in parallel with units of different characteristics, but as a word of caution it should be kept in mind that there have probably been many instances where the desire for mathematically correct division has exceeded the economic justification. This paralleling problem at New York is considerably complicated by the nature of the circuits involved, the tapped loads, the necessity of variable load transfers, the voltage requirements at various parts of the system, etc., and the New York engineers are to be congratulated on their ingenuity and skill in arriving at a successful solution.

On a system as large as that in New York the conditions warrant such major operations as the design of new and supersensitive voltage and phase angle recording and remote indicating instruments, and the installation of voltage and load ratio transformer units in the paralleling tie lines.

In most cases, however, the network installation is only a small part of the system and the voltage or load angle relationships of the various generating stations or bus sections are determined by the requirements of the rest of the system. For example, the Boston Edison Company has the bulk of its distribution through radial substations and any interconnections between stations or with other companies as affecting bus voltages and angles are based on load requirements, feeder capacities, reserve generating capacity, relative station efficiencies, etc.

Even with the carefully controlled system at New York there will still be many cases of tripping of the network units due to reverse currents caused by certain types of regenerative loads, switching surges and unbalanced conditions when several high tension feeders are open. Also if one feeder supplies several different network areas, theoretically at least, it cannot be entirely compensated for by station control.

All of this leads to the necessity of further development at the network unit itself. There have been some changes recently in the relaying, such as by the addition of negative sequence control, but this is not the final answer.

Further study should be made of the effect on the reactive current division caused by operation of the voltage tap changers on the network transformers. These may be controlled or biased by some other method of load compensation or possibly recalibrated by time switches or remote control. This applies principally to the primary units which already have tap chang-

ing under load equipment, but some form of simple tap changer could be developed for the secondary units if found justifiable. In some cases it might even pay to include a few taps of the transformer arranged for load ratio control as well as for voltage variation.

There may be cases where reactors, separate regulators, or booster transformers could be justified in the high tension or secondary circuits, to aid in proper current control. It is thought, however, that it would be preferable to eliminate the need for all of these complications by supplying each network area from one source. The present ruggedness in design and reliability of operation for generating stations justifies the growing tendency to reduce duplication of apparatus. The various feeders supplying the area could be taken from one bus which could be sectionalized automatically in case of a bus fault, the feeders affected being transferred to an auxiliary bus. Experience shows that the remaining feeders and transformers during this transition period could well handle the temporary overload conditions. This single source idea might not always be suitable for primary network installations, but for the general secondary area it should be applicable.

Giuseppe Calabrese: The paper by Messrs. Forbes and Searing describes 2 methods for transferring power between 2 stations, shown respectively in Figs. 7 and 8 of the paper. In Fig. 7, a voltage at 120 deg with the phase voltage is injected in each phase. With the 2 station voltages equal in phase and magnitude, the power factor at which power can be exchanged is entirely determined by the impedance of the tie line, excepting for the effect of the drop between the bus and the point where the regulating transformer shunt winding is connected, a factor which is quite negligible. The series voltage necessary to transfer a predetermined amount of power can be calculated by noting that the same voltage is consumed by the drop in the tie line.

In the scheme of Fig. 11 of the paper, only 2 induction regulators are used. However, neglecting the effect of the regulator and potential transformer magnetizing currents and leakage impedances, as far as the transfer of power is concerned, the scheme of Fig. 11 is equivalent to the scheme of Fig. 7, that is, the transfer of power takes place as if a series voltage at 120 deg were injected in each phase exactly in the same manner as in Fig. 7. As this equivalence may not be apparent to all, I believe it will be of interest to prove it. Referring to Fig. 1 of this discussion, let E_a, E_b, and E_c be the line to neutral voltages at the terminals a b, and c of the regulator shunt windings. (Bold faced letter symbols indicate vector quantities; others indicate scalar quantities.) Similarly, E_a', E_b', and E_c' are the voltages from a', b', and c' to ground. If K is the regulator ratio in any particular position, from Fig. 1, showing the regulators in the boosting position, there is obtained

$$E_a' = E_a - K(E_b - E_c)$$
$$E_b' = E_b$$
$$E_c' = E_c + K(E_a - E_c)$$

Let E_0' E_1' E_2' be the sequence components of the 3 voltages E_a', E_b', E_c' and E_0, E_1, E_2 the sequence components of the 3 voltages E_a, E_b, E_c. It is obtained

$$E_0' = E_0 + K(aE_1 + a^2E_2)$$
$$E_1' = E_1 - Ka^2E_1$$
$$E_2' = E_2 - KaE_2$$

in which a and a^2 are the well-known operators indicating rotations of 120 and 240 deg, respectively. As generators generate voltages of positive sequences only, and normally there are no unbalanced loads or faults on the system,

$$E_2' = E_2 = 0$$

The expression of E_2' shows that the 2 regulators generate zero sequence voltage. As the normal operation of the Hell Gate station is with one generator on each bus section grounded, it becomes necessary to operate the Sherman Creek generators ungrounded in order to prevent the flow of zero sequence current. With Sherman Creek ungrounded and no unbalanced loads or faults on the system, E_0 becomes zero. Thus during normal operating conditions, the sequence components of the voltages at the regulator terminals are:

$$E_0 = E_2' = E_2 = 0$$
$$E_0' = KaE_1$$
$$E_1' = E_1(1 - Ka^2) \qquad (1)$$

The second of these equations shows that the regulators, in acting as source of zero sequence voltage, shift the neutral on the Sherman Creek side by the voltage KaE_1. However, as said, with the Sherman Creek generators ungrounded, this zero sequence voltage cannot force the flow of zero sequence currents excepting through parallel feeders if an equal and opposite amount of zero sequence voltage is not injected in the latter. During fault conditions, the zero sequence voltage generated by the regulators will force zero sequence current in both the parallel lines and through the fault. This point should be kept in mind in setting relays, especially if there is the possibility that regulators on parallel feeders may take different positions.

Equation 1, however, shows that as far as the positive sequence voltages are concerned, that is, the voltages that cause the exchange of power, the scheme of Fig. 1 is equivalent to injecting in each phase a voltage $-Ka^2E_1$ (at 120 deg with the phase voltage), exactly in the same manner as in the case of Fig. 7 of the paper. Thus, the same method of calculation may be used to determine the series voltage necessary to establish a predetermined exchange of power.

Regarding the automatic control of the power exchanged between 2 stations with the scheme of Fig. 11, it may be of some interest to analyze under which conditions automatic operation is possible and to show how to calculate the setting of the line drop compensator.

By automatic operation is meant operation whereby, starting with the 2 station voltages equal in phase and magnitude, any variation of load at either station will cause the regulators to transfer power in such amount and direction that the 2 station voltages are maintained equal in phase and magnitude. All the voltages acting in the circuit of the primary relay during normal conditions, that is, with no unbalanced loads or faults on the system are shown in Fig. 1.

E_{Ha}, E_{Hb}, and E_{Hc} are the Hell Gate line to ground voltages, and E_{H0}, E_{H1}, and E_{H2} their sequence components. During normal conditions, $E_{H0} = E_{H2} = 0$, that is, $E_{Ha} = E_{H1}$; $E_{Hb} = a^2E_{H1}$; $E_{Hc} = aE_{H1}$. E_{Sa}, E_{Sb}, and E_{Sc} are the corresponding Sherman Creek voltages, and E_{S0}, E_{S1}, and E_{S2} their sequence components. Normally, $E_{S2} = 0$, that is, $E_{Sa} = E_{S0} + E_{S1}$; $E_{Sb} = E_{S0} + a^2E_{S1}$; $E_{Sc} = E_{S0} + aE_{S1}$.

The relations between the voltages at a, b, c and a', b', c' have been given already.

The following analysis is made assuming the regulators in the boosting position. However, the results obtained may be extended to the bucking position by changing the sign of the factor K.

Let I_a, I_b, and I_c be the currents out at Hell Gate, and I_0, I_1, and I_2 their sequence components. Let I_a', I_b', and I_c' be the corresponding currents in at Sherman Creek, and I_0', I_1', and I_2' their sequence components.

Neglecting the magnetizing currents of the regulators and potential transformers, from Fig. 1 is obtained

$$I_a = I_a' - KI_c'$$
$$I_b = I_b' - KI_a'$$
$$I_c = I_c' + K(I_a' + I_c')$$

From which

$$I_0 = I_0'$$
$$I_1 = I_1' + K(a^2I_1' - aI_1')$$
$$I_2 = I_2' + K(aI_2' - a^2I_2')$$

During normal conditions, $I_0 = I_0' = I_2 = I_2' = 0$.

Thus:

$$I_1 = I_1'(1 - Ka) \qquad (2)$$

Let θ be the angle by which the Hell Gate voltage E_{H1} leads the Sherman Creek voltage E_{S1} and assume that both have the same magnitude, that is, $E_{H1} = E_{S1}$.

The voltage difference between Hell Gate and Sherman Creek, as shown by the insert in Fig. 1, is:

$$j\,2\sin\frac{\theta}{2}\,e^{-j\frac{\theta}{2}}\,E_{H1}$$

where $e^{-j\frac{\theta}{2}}$ is the well-known operator indicating a rotation in the negative direction of an angle $\frac{\theta}{2}$.

The series positive sequence voltage induced by the regulators is $-Ka^2E_1$

Thus the total positive sequence voltage acting on the tie is

$$j\,2\sin\frac{\theta}{2}\,e^{-j\frac{\theta}{2}}E_{H1} - Ka^2E_1$$

This voltage must balance the drop due to the currents I_1' and I_1 flowing respectively through the impedances $\mathbf{Z}$ and $\mathbf{Z}_r$, that is,

$$j\,2\sin\frac{\theta}{2}\,e^{-j\frac{\theta}{2}}E_{H1} - Ka^2E_1 = I_1'\mathbf{Z} + I_1\mathbf{Z}_r$$

Substituting for I_1 the value given by eq 2 and for E_1 the value given by

$$E_1 = E_{H1} - I_1\mathbf{Z}_r \qquad (3)$$

it is obtained that

$$I' = \frac{\left(j\,2\sin\frac{\theta}{2}\,e^{-j\frac{\theta}{2}} - Ka^2\right)E_{H1}}{\mathbf{Z} + \mathbf{Z}_r(1 + K + K^2)} \qquad (4)$$

With the 2 station voltages in phase and the voltage regulators in the neutral

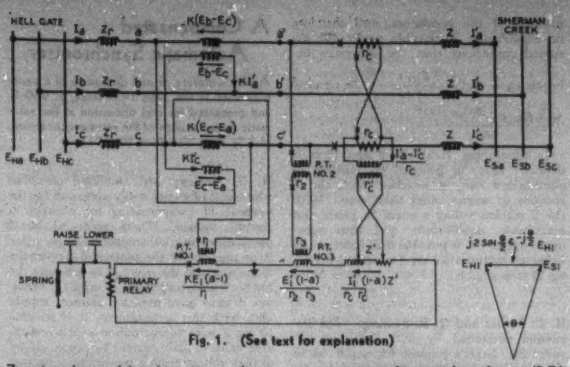


Fig. 1. (See text for explanation)

Z = impedance of line between regulators and Sherman Creek station
Z_r = impedance of line between regulators and Hell Gate station
r_1, r_2, r_3 = ratios of potential transformers (P.T.)
r_a, r_c' = ratios of current transformers
Z' = impedance of line drop compensator
All symbols indicate vectorial quantities

position, no current flows in the tie. The voltage impressed on the circuit of the primary relay is $\frac{\sqrt{3}\,E_{H1}\,e^{-j30°}}{r_3r_2}$. The pull on the relay is just enough to balance the tension of the spring. Both the raise and lower contacts remain open. Let us now add load at Sherman Creek. Sherman Creek will slow down, and current will flow through the tie causing a corresponding voltage to appear across the line drop compensator. The equilibrium between the spring tension and the primary relay pull is upset, and the latter overcomes the former, thus causing the raise contacts to close. The regulators start to boost the voltages at a', b', and c'. Additional voltages will be injected in the circuit of the primary relay through the transformers Nos. 1, 2, and 3, which, by balancing the voltage drop in the line drop compensator, are to cause the equilibrium between the spring tension and the primary relay pull to be restored (thus stopping the regulators) as soon as transfer of power in the proper amount necessary to bring the 2 station voltages in phase has been established. This is equivalent to saying that the condition of equilibrium will be restored and the regulators come to a stop when the resultant voltage acting in the circuit of the primary relay becomes equal to $\frac{\sqrt{3}\,E_{H1}\,e^{-j30°}}{r_3r_2}$. In a more general way, noting that the primary relay responds to the magnitude of the voltage impressed across it, the equilibrium is restored when the magnitude of the voltage acting in the circuit of the primary relay becomes equal to $\frac{\sqrt{3}E_{H1}}{r_3r_2}$. Thus automatic operation is possible if the line drop compensator impedance Z' is set to such a value that when transfer of power of the amount necessary to bring the 2 station voltages again in phase has been established, the magnitude of the resultant voltage acting in the circuit of the primary relay becomes $\frac{\sqrt{3}E_{H1}}{r_3r_2}$ (exactly or at least within such limits as may be set by the sensitiveness of the primary relay itself), regardless of the position of the regulators.

At any particular instant during normal operation, the line currents I_1' and aI_1' flowing in phases a' and c' at Sherman Creek cause a current $\frac{I_1'(1-a)}{r_ar_c'}$ to appear at the terminals of the line drop compensator. The current I_1' for any given angle between Hell Gate and Sherman Creek and any given position of the regulators is given by eq 4.

In the circuit of the primary relay, there act the following voltages:

The voltage due to potential transformer No. 1, $\frac{KE_1\,(a-1)}{r_1}$; or substituting eqs 3 and 4,

$$-\frac{\sqrt{3}Ke^{-j30°}}{r_1}E_{H1}\left\{\frac{Z+Z_r(1-Ka)\left(1-j2\sin\frac{\theta}{2}\,e^{-j\frac{\theta}{2}}\right)}{Z+Z_r\,(1+K+K^2)}\right\} \quad (5)$$

The voltage due to potential transformers Nos. 2 and 3, $\frac{E_1'\,(1-a)}{r_3r_2}$; or from eqs 1, 3, and 4,

$$\frac{\sqrt{3}\,e^{-j30°}}{r_3r_2}\,(1-Ka^2)E_{H1}\left\{\frac{Z+Z_r(1-Ka)\left(1-j2\sin\frac{\theta}{2}\,e^{-j\frac{\theta}{2}}\right)}{Z+Z_r(1+K+K^2)}\right\} \quad (6)$$

The voltage produced by the flow of the current $\frac{I_1'\,(1-a)}{r_ar_c'}$ through the impedance Z' of the line drop compensator, that is, from eq 4,

$$\frac{I_1'(1-a)Z'}{r_1r_3'} = \frac{\sqrt{3}e^{-j30°}}{r_ar_c'}E_{H1}\,\frac{\left(j2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}-Ka^2\right)}{Z+Z_r\,(1+K+K^2)}\,Z' \quad (7)$$

More accurately, Z' should be the parallel impedance of the line drop compensator and primary relay. In general, however, the effect of the latter may be neglected and Z' taken equal to the former.

The total voltage acting in the circuit of the primary relay is the sum of eqs 5, 6, and 7, that is,

$$\sqrt{3}\,E_{H1}\,e^{-j30°}\left[\left(\frac{1-Ka^2}{r_3r_2}-\frac{K}{r_1}\right)\left\{\frac{Z+Z_r\,(1-Ka)\left(1-j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}\right)}{Z+Z_r\,(1+K+K^2)}\right\}+\frac{\left(j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}-Ka^2\right)Z'}{r_ar_c'\,[Z+Z_r(1+K+K^2)]}\right] \quad (8)$$

From the previous analysis, it follows that the settings of the line drop compensator must be calculated by equating the difference between eq 8 and $\frac{\sqrt{3}E_{H1}\,e^{-j30°}}{r_3r_2}$ to zero or to $\frac{\sqrt{3}\,E_{H1}\,e^{-j30°}\,e^{\pm j120°}}{r_3r_2}$. Automatic operation is possible for those values of Z' thus obtained which are independent from the position of the regulators, that is, from the factor K.

By equating the difference to zero is obtained

$$\left(\frac{1-Ka^2}{r_3r_2}-\frac{K}{r_1}\right)\left\{\frac{Z+Z_r\,(1-Ka)\left(1-j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}\right)}{Z+Z_r\,(1+K+K^2)}\right\}-\frac{1}{r_3r_2}+Z'\frac{\left(j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}-Ka^2\right)}{r_ar_c'\,(Z+Z_r\,[1+K+K^2])}=0$$

From which the value of the impedance of the line drop compensator is

$$Z'=\frac{r_ar_c'}{2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}-Ka^2}\left\{Z_r\,(1-Ka)\,j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}\left(\frac{1-Ka^2}{r_3r_2}-\frac{K}{r_1}\right)+ZK\left(\frac{a^2}{r_3r_2}+\frac{1}{r_1}\right)+\frac{Z_r(1-Ka)K}{r_1}\right\} \quad (9)$$

This expression shows the value of Z' necessary to reach a position of equilibrium depends on both the position of the regulators and the angle between the 2 stations. In the particular case under consideration, it is desired that equilibrium be reached when the angle between the 2 stations becomes zero. The value of Z', in this case, as obtained from eq 9 by putting $\theta = 0$ is

$$Z'=-\frac{r_ar_c'}{a^2}\left\{Z\left(\frac{a^2}{r_3r_2}+\frac{1}{r_1}\right)+\frac{Z_r\,(1-Ka)}{r_1}\right\} \quad (10)$$

The value of Z' is thus composed of 2 parts, a constant one,

$$Z_c'=-\frac{r_ar_c'}{a^2}\left\{Z\left(\frac{a^2}{r_3r_2}+\frac{1}{r_1}\right)+\frac{Z_r}{r_1}\right\} \quad (11)$$

and a second part varying with the position of the regulators,

$$Z_s' = \frac{r_s r_s' Z_r K}{r_1 a} \qquad (12)$$

Automatic regulation is possible only if Z_s' is negligible with respect to Z_s'.

In the case of one of the feeders between Hell Gate and Sherman Creek;

$Z = 1.044 + j\,1.833$
$Z_r = j\,33$
$Z + Z_r' = 1.044 + j\,2.163 = 2.4\,e^{j64°\,35'}$
$r_1 = 120$
$r_2 = 120$
$r_3 = 5.5$
$r_2 r_3 = 660$
$r_s r_s' = 60\sqrt{3} = 104$

The maximum value of K is 0.08. Thus, $Z_s' = 1.90 - j\ .162 = 1.905e^{-j4°\ 55'}$ Z_s' can at the most be equal to

$$Z_s' = 0.0229\,e^{-j30°}$$

and is, therefore, negligible. In this particular case, automatic operation is thus possible if the line drop compensator is set at approximately 1.90 ohms resistance. The regulators once started will stop only when the angle between the 2 stations becomes zero with an approximation as determined by the sensitiveness of the primary relay. Once the latter is known, the angle at which equilibrium can be reached can be calculated with the aid of eq 8.

By equating the difference between eq 8 and

$$\frac{\sqrt{3}\,E_{M1}\,e^{-j30°}}{r_2 r_3} \text{ to } \frac{\sqrt{3}\,E_{M1}\,e^{-j30°}\,e^{+j120°}}{r_2 r_3},$$

it is obtained that

$$\left(\frac{1 - Ka^2}{r_2 r_3} - \frac{K}{r_1}\right)$$
$$\left\{\frac{Z + Z_r(1 - Ka)(1 - j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}})}{Z + Z_r(1 + K + K^2)}\right\}$$
$$- \frac{1}{r_2 r_3} + Z'\frac{(j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}} - KA^2)}{r_s r_s'[Z + Z_r(1 + K + K^2)]}$$
$$= \frac{e^{+j120°}}{r_2 r_3}$$

From which

$$Z' = \frac{r_s r_s'}{j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}} - Ka^2}\left\{Z_r(1 - Ka)\right.$$
$$j\,2\sin\frac{\theta}{2}e^{-j\frac{\theta}{2}}\left(\frac{1 - Ka^2}{r_2 r_3} - \frac{K}{r_1}\right)$$
$$+ ZK\left(\frac{a^2}{r_2 r_3} + \frac{1}{r_1}\right) + \frac{Z_r(1 - Ka)K}{r_1}$$
$$\left. + \frac{[Z + Z_r(1 + K + K^2)]a^{-1}}{r_2 r_3}\right\} \qquad (13)$$

For $\theta = 0$ this gives 2 values, Z'_1, Z'_2, for Z':

$$Z_1' = Z_s' + Z_s' - \frac{r_s r_s' a^2}{r_2 r_3}$$
$$\left\{\frac{Z + Z_r}{K} + Z_r(1 + K)\right\}$$
$$Z_2' = Z_s' + Z_s' - \frac{r_s r_s'}{r_2 r_3}$$
$$\left\{\frac{Z + Z_r}{K} + Z_r(1 + K)\right\}$$

where Z_s' and Z_s' are given by eqs 11 and 12. It is seen that both values vary widely with the factor K, that is, with the position of the regulators, and therefore no equilibrium is possible under the assumed conditions that the difference between eq 8 and $\frac{\sqrt{3}\,E_{M1}\,e^{-j30°}}{r_2 r_3}$ be equal to

$$\frac{\sqrt{3}\,E_{M1}\,e^{-j30°}e^{+j120°}}{r_2 r_3}.$$

In concluding, from eqs 9 and 13 it is deduced that, in general, no position of equilibrium can be reached with the 2 stations at angles other than zero. With the 2 station voltages equal in phase and magnitude, equilibrium, and thus automatic operation, is possible if Z' is set at the value as dictated by eq 11, provided that eq 12 is negligible.

H. C. Forbes and H. R. Searing: The discussion presented by Mr. Calabrese answers Mr. Starr's request for details as to the functioning of the regulators and compensator.

The authors agree with Mr. Sweetnam that individual regulation at the network transformer is technically a desirable solution to the problem of network voltage control. A rather complete study of regulation by this method, however, determined that for the conditions in New York City individual low tension regulators or tap changing equipment could not be justified from the economic standpoint. Development of a cheap and rugged tap changer for distribution transformers may alter this picture. Mr. Sweetnam's suggestion that the complications of network operation from numerous sources could be overcome by segregation of network supply so that a given district is served from only one source has some merit, and it is possible that generating stations built in the future will provide the necessary sectionalization so that reliable supply can be obtained from one station. It is expensive and difficult, however, to revamp an existing station to provide such segregation, and in new stations of large capacity complete isolation of bus sections may be required in order to hold the interrupting duty of the circuit breakers to reasonable values. Moreover, the cost of feeder rearrangements so that each district has a supply from only one station may be excessive.

In the authors' opinion, the decision must be made on the facts surrounding a given situation. A district located midway between 2 generating stations can probably best be served by feeders from both stations. A district immediately adjacent to a station will probably receive all of its supply from that station. Furthermore, a new station usually starts up with one or 2 units and during the transition period it is necessary to augment the supply by ties from other sources. Even with these supplementary ties the reliability of such a station in the initial stages of development may not be adequate to serve as the only source of supply to a network district and a feed to the network from adjacent stations may be considered desirable

In view of these considerations the authors think it probable that the future trend of engineering development will be such that applications will be found of the devices and methods of operation described in the paper.

A Compensated Automatic Synchronizer

Author's closure of oral discussion of a paper published in the June 1934 issue, p. 960–8, and presented for oral discussion at the automatic station session of the summer convention, Hot Springs, Va., June 28, 1934.

H. T. Seeley: Mr. Gulliksen questions whether 2 tubes are really necessary for the purpose of compensating for changes in control voltage. There seem to be 2 possibilities in the amplifier design. One is to use d-c for the plate and a-c for the filaments, and the other is to use only d-c for both plate and filament supply. Previous designs have used a-c filament supply and, with this arrangement, it is possible to get 2 point compensation with a reasonable value of plate current by proper choice of bias voltage from a potentiometer across the plate voltage source, as Mr. Gulliksen suggests. However, it appears that if the filament and plate voltages are both low at the same time, the operating point of the plate current relay will be considerably affected. Since there is no relation between low continuous voltage and low alternating voltage, the changes in operating point due to accidental, simultaneous changes in these 2 voltages probably cannot be compensated for by any method simpler than the use of a second tube.

If d-c is used for both the plate and filaments, the operating point must be lowered still further to obtain even 2 point compensation, and the plate current is so small that a sensitive relay is necessary for fast operation. The choice between this and a balanced relay with the extra tube to obtain larger operating forces is a matter of judgment.

Mr. George has pointed out the desirability of 2 settings for a synchronizing relay; a normal setting that will synchronize only under favorable conditions, and an emergency setting, selected by the mere operation of a control switch, that will increase the synchronizing angle to a much larger value than the normal. This is fairly simple with the constant angle type of relay, but the situation with respect to the proportional angle relay is not quite the same. Here the relay operating angle is determined automatically by the frequency difference, and it would be disadvantageous to change this relation. The setting that would have to be changed to give quicker synchronizing under unfavorable conditions is the frequency difference setting. As far as the proportional angle feature of the present relay is concerned, this setting can be increased to 0.375 cycle per second (as has already been done in one special case) if the breaker time does not require more than 45 deg advance at this frequency difference. Even these 2 limits can be exceeded somewhat by a sacrifice of accuracy at the smaller frequency differences, if necessary.

The means necessary for providing the 2 frequency difference settings are not yet worked out, although I am sure they can be if the demand warrants it. However, it should be pointed out that the proportional angle synchronizer can be given a high initial frequency difference setting (com-

pared with the constant angle type) without increasing the synchronizing error introduced by the relay characteristics, and, therefore, the added usefulness of the dual setting is somewhat less than in the case of the constant angle types.

Load Totalizing in the New York Area

Discussion and author's closure of a paper by F. Zogbaum published in the June 1934 issue, p. 886–9, and presented for oral discussion at the automatic station session of the summer convention, Hot Springs, Va., June 28, 1934.

R. C. Buell: Mr. Zogbaum has described a very interesting and excellent installation of telemetering equipment. I have always thought that a system operator should have available before him instantly as much information as possible in order to function properly and speedily. The thermal converter inherently has some time delay in giving its load indication; it therefore can give the operator no clear indication of swinging loads, instability, or sudden changes in load.

This paper indicates a very high degree of accuracy for this equipment. Our experience indicates that there is a departure from such accuracy with time and this, together with the effect of ambient temperature, power factor, voltage variation and the like, tends to produce a result to give an accuracy more nearly in the order of 1 per cent for a simple combination of transmitter, channel, and receiver.

In any device that depends on heating for its results, one is always interested in precautions necessary to prevent burnout. I would like to ask if protective relays to short out the thermal converters were considered, and if any experience has been obtained which indicates that such relays are not necessary.

L. O. Heath: Another item of particular interest in connection with the thermal converters used in this installation is the fact that their accuracy is not seriously impaired even at power factors as low as 50 per cent. The very low burden involved on the instrument transformers, namely, approximately 3 volt-amperes on both current and potential transformers, is another factor which generally tends toward accuracy in such metering.

M. E. Reagan: Mr. Zogbaum's paper tells of the simplification and economics that are possible with modern telemetering equipment. It shows clearly the present trend toward the centralizing of dispatching control.

Such systems are successful only because the equipment used is extremely reliable. The manufacturers have done their part in producing satisfactory apparatus. However, the system of instruments and meters must be operated over an equally reliable line. The importance of the cable requirements or specifications cannot be overemphasized. They must be maintained in a high order of electrical quality to make such a system feasible.

The next step in utilizing the possibilities of economy is to add remote control of the load to the dispatcher's board. Then he would have better service at his fingertips. He would obtain faster response to his orders especially during emergencies when delays are costly. It is also probable that he would obtain even better load equalization or distribution, which reflects directly in the economy.

E. J. Rutan: It may be of interest to present some data in connection with the initial investigations of the performance of the telemetering and totalizing system which Mr. Zogbaum describes in his paper. This system was selected as a result of comparative tests made in the test bureau laboratory. At the time, the test bureau had installed in its laboratory the 2 terminals of a 5-mile telephone cable circuit. This installation had been made in order to conduct development work on telemetering systems and on methods of transmitting phase-angle measurements, which were described in a paper by Messrs. Forbes and Searing. (ELECTRICAL ENGINEERING, June 1934, p. 903–9.)

Several telemetering systems were tried out in the laboratory and were subjected to various tests, using as a guide the proposed A.I.E.E. standards for electrical recording instruments. It was thought that telemetering systems should perform about the same as recording systems and, therefore, the test bureau has used these standards in determining performance characteristics. The tests using the telephone cable circuit also permitted obtaining data approaching operation under normal and faulty telephone circuit conditions.

After the Leeds and Northrup equipment had been decided upon, arrangements were made with the manufacturer so that one of our engineers visited their factory at the time they had assembled the equipment for trial operation. At that time we made our acceptance tests because it would not be convenient to perform these tests after the instruments had been installed in widely separated stations. The tests on the individual parts were deferred until the equipment was received but over-all tests, particularly with reference to what is known in recording instruments as friction influence, were performed at the plant. This test, which we consider a most important one, determines the amount of change in the electrical quantity at the transmitting element which is necessary before an observed change takes place in the receiving element. This might be called the sensitivity of the system. Our tests disclosed that on thermal converters developing 60 millivolts for full range indication a change of 0.2 millivolt caused the receiving device to function. This change corresponds to approximately 0.3 of 1 per cent of full scale indication and shows that the instrument is ready to follow extremely small changes. The other important characteristics have been discussed in the paper.

Since the installation of the device, the maintenance has been carried on by the test bureau. A regular program was set up based on suggestions from the manufacturer, which it was hoped could be lengthened in order to save money. Our experience with other telemetering systems has shown that it is desirable to have the maintenance period very short during initial operation. This practice permits clearing up minor defects and maintains the confidence of the operating personnel in the new device. Such a practice was justified in this case. Operation discloses that galvanometers require periodic mechanical balance on about a weekly basis. On some of the recorders in which a horizontal type of drive is used, trouble developed due to wear in the bearings and gears. These recorders are to be changed so that they will have the vertical type of drive similar to most of the others in this installation. Other troubles which resulted in failure during operation disclosed 1 defective resistance coil, 1 loose connection on the d-c side of the thermal converter, 2 loose wiring connections on the measuring side of the thermal converters and, in addition, on 5 occasions faulty indications were caused by workmen vibrating the panels while working nearby. This caused the galvanometers to get out of balance. On the telephone circuits on 3 occasions fuses blew disconnecting the lines.

From the nature of these troubles it is quite obvious that they were or can be readily cleared up and it is expected that the system will operate with little future trouble. The program of maintenance initially involved a weekly inspection which includes cleaning, oiling, and balancing. This continued for 3 months, after which the inspection was put on a 2 weeks' basis. Beginning July 1, 1934, we expected to place the maintenance on a 3 weeks' basis, finally working up to a monthly inspection. It should also be noted that these recorders are cared for daily as far as ink and chart maintenance is concerned.

F. Zogbaum: In preparing this paper the author had in mind a brief description of the system involved so that those interested could get a general picture of one of the most modern load totalizing systems. However, it seems desirable to amplify the paper as follows.

The slight time delay inherent in the thermal converter is not considered to have any serious effect upon load dispatching where the load is large and concentrated and where load swings are of a somewhat milder nature than would be experienced on some high tension interconnected transmission lines. The thermal converters and their associated receivers will indicate 90 per cent of a full scale change in the metered power in 12 seconds and 100 per cent well within 1 minute.

As far as departure from original accuracy is concerned it is pointed out that both the transmitter and receiver are provided with wide range adjustments by which a high degree of accuracy may be maintained; also, the lack of moving parts in the thermal converter transmitter further minimizes the possibility of error. Normal fluctuations in ambient temperature have no appreciable effect upon the thermal converter or the potentiometer type receivers and any change in telephone channel resistence due to temperature will have no effect on the accuracy due to the null method used.

Power factors as low as 50 per cent and voltage variation do not seriously impair thermal converter accuracy under ordinary operating conditions.

In regard to the performance of the thermal converters under short circuit conditions, no special precautions, such as lock out relays, are used for protection. Laboratory tests have shown that the thermal converter will withstand 20 times normal current for 2 seconds, thereby providing a safe margin for most faults encountered.

Electronic Regulator for A-C Generators

Discussion and author's closure of a paper by F. H. Gulliksen published in the June 1934 issue, p. 877–81, and presented for oral discussion at the automatic station session of the summer convention, Hot Springs, Va., June 28, 1934.

G. W. Garman: This paper describes a very interesting application of electron tubes. The data given shows that excellent results have been obtained.

Electron tube devices are relatively new and require a certain amount of knowledge and experience before confidence can be instilled into those who are to use them. Furthermore, the present cost of electronic tube devices has limited their application where they are competitive with the equipments generally in use at the present time.

We have been actively engaged in the development of electron tube regulators for more than 8 years. During this period particular emphasis has been placed on the needs of a central station type regulator. While the general form of attack has been remarkably similar to the regulator described by Mr. Gulliksen, the design of the particular elements is very different.

As may be noted in Fig. 1 of this discussion, the voltage determining means is composed of 3 copper oxide rectifiers and a thyrite bridge. To eliminate the disadvantage of single-phase regulation, the voltages of all 3 phases are rectified and then added together to obtain a single continuous voltage that is a function of all 3 alternating voltages. This continuous voltage is then impressed on the thyrite bridge.

The excitation circuit consists of a 3-phase grid-controlled thyratron type rectifier. Usually the only reliable power source is either that of the generator being regulated or that of the bus supplying power to the synchronous condenser. With a single-phase short circuit, the single-phase rectifier would be inadequate.

Control of the thyratron output or field excitation is obtained by superimposing a controlled continuous voltage upon a fixed alternating voltage. The fixed alternating voltage lags the anode voltage by 90 or 120 deg depending upon the type of rectifier system used. By varying the superimposed continuous voltage the field excitation can be smoothly varied from zero to the maximum value. This superimposed voltage is obtained from the thyrite difference voltage after it has been amplified by means of the 2 pliotrons operating in parallel.

It has been found and can be proved mathematically that with no inherent inertia in the voltage regulator hunting will occur

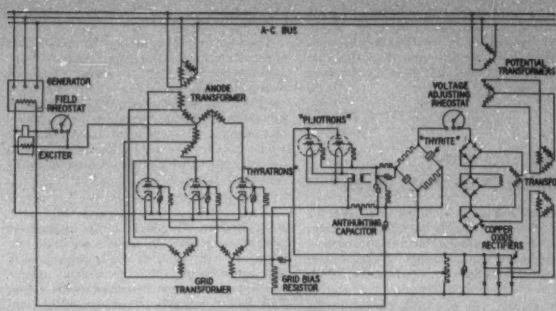


Fig. 1. Circuit of electronic tube regulator

due to the inertia in the field circuit of the exciter. It can be shown that to prevent this hunting it is necessary to introduce into the circuit a voltage that is proportional to the rate of change of the synchronous machine field or exciter armature voltage. The voltage drop across the resistor in a series resistor and capacitor circuit when connected across the exciter armature furnishes the required voltage. The other resistors and capacitors in the grid circuit of the pliotrons form a damping and quick response circuit that has been found necessary under certain conditions.

To avoid using exciters with special field windings, it is only necessary to add an additional capacitor in the antihunting circuit. The exciter can then be self-excited in the normal manner with the advantage that the regulator can be placed into or taken out of service with the same ease as the mechanical type of voltage regulator.

In reviewing those factors which add to the reliability of the regulator, copper oxide rectifiers are used with a conservative rating to convert the alternating voltage into a continuous voltage. The 2 pliotrons in the regulator are operated in parallel and lightly loaded to give long life. A failure of one of these tubes will cause only a fraction of a per cent change in the regulated voltage. Because a 3-phase type of rectifier is used, a failure of one of the thyratrons will cause only a fraction of a per cent change in the regulated voltage. Furthermore, the voltage rating of the anode transformer is such that normal excitation can still be obtained even though the primary supply voltage is reduced to half, or less, of normal.

The variation in the regulated voltage of the synchronous machine, from no load to full load, is the same as for the mechanical type voltage regulators; namely, less than ± 1 per cent. This voltage variation can of course, be reduced by the use of tubes with a higher amplification factor or by means of another pair of amplifier tubes. It is thought that this additional refinement is not required in the majority of cases.

Regulators of this type have been in practically continuous operation for over 3 years. Operation has been satisfactory and tube replacements have been a minimum.

With this service record on a developed and successful device, the question arises: why has this type not been commercially exploited to a greater degree? The answer lies in the high degree of accuracy and perfection in the mechanical types of regulators and their relatively lower costs at the present time.

The electronic tube type regulator goes further than mere voltage regulation. It furnishes and controls the exciter field current. There is no reason why synchronous machine field current cannot be supplied directly provided the requirements do not exceed the tube capacity. The future of this type of control will, therefore, depend upon obtaining large sized tubes at a cost competitive with existing methods of excitation.

A limited number of direct excitation type electronic voltage regulators have been made. The largest installed regulator supplies and controls the excitation of a 15,000-kva synchronous condenser. The full load excitation is 560 amp at 135 volts. This regulator exciter has been in service for approximately 8 months.

H. T. Seeley: I think Mr. Gulliksen is to be complimented on obtaining fast and accurate regulation of circuit voltage by a booster, because the regulation of a booster is inherently more difficult than that of a generator of equal rating. For example, a sudden change of 5 per cent in source voltage would require an immediate change of about 50 per cent of full excitation on a booster with a rating of plus or minus 10 per cent of circuit voltage.

In reading Mr. Gulliksen's paper, I was unable to reconcile the mention on p. 877 of a regulator which "does not need any dry cell battery" with the description which followed this statement, and possibly others were similarly confused. I now understand, from the presentation, that the regulator without dry cell battery uses a glow tube as a voltage standard and is not the same regulator described in detail in the paper.

We have made factory installations of regulators using glow tubes as voltage standards and have found them quite satisfactory where ordinary accuracy is required. One of these is described in the paper by C. B. Foos, "A Vacuum Tube Controlled Rectifier," published in the April 1934 issue of ELECTRICAL ENGINEERING.

Our experience with the relative speeds of response of a tube regulator on pick-up and dropping load is the same as that mentioned by Mr. Gulliksen in his reference to Figs. 3 and 4. The reason for the difference in response may be made clear by the following considerations. The speed of build-up may be increased to any reasonable value required merely by increasing the source voltage available for the tubes, but when a large sudden decrease in excitation is required, we can only put a negative charge on the grids of both thyratrons, and this cannot stop their conduction, so the rate of build-down is determined entirely by the time constant of the field circuit. These conditions may be improved only by adding series resistance on the field circuit to reduce its time constant and a compromise is necessary in this regard because excessive losses in this circuit may be objectionable.

C. W. LaPierre: In the author's Fig. 7 covering the lamp bridge detector no special provision is made to take care of the second harmonic output of the bridge. This second harmonic arises from the 120-cycle pulsation in filament resistance corresponding to each half wave of 60-cycle current. It is always present whether the bridge is in balance or not and its magnitude is a function of the thermal time constant of the lamp filament. For some types of filament construction the second harmonic is so large that it tends to obscure the small fundamental frequency voltages which indicate unbalance in the bridge.

For some time we have been experimenting with a lamp bridge designed to give a result several times as precise as that covered in the present paper. We have found that a precision of better than a few tenths of one per cent could not be consistently obtained over a long period with ordinary commercial lamps. With special care in the lamp construction, a precision of a few hundredths of a per cent is feasible. It would be of interest to have data on the actual balance voltage over a period of time of the bridge in the present paper.

As to the lamps, I would like to know whether ordinary commercial lamps are used and also their rating.

Phillip Sporn: Electronic voltage regulators have been in service on the American Gas and Electric Company's system for a little more than 4 years, and considerable valuable operating experience has been gained during this time.

The first of these regulators was installed in March 1930, controlling a 15,000-kva synchronous condenser at our Howard substation near Mt. Vernon, Ohio. It consisted of a 3-phase thyratron rectifier supplying excitation to the field of the condenser exciter. At the time of installation this equipment was frankly termed experimental, and 2 different schemes of controlling the thyratron output, one entirely by vacuum tubes and one partly mechanical, were provided. This regulator has now had approximately 35,000 hours of actual service and has proved to be as reliable as the mechanical types of regulators. Because of the type of circuit employed in the vacuum tube scheme of control, it was found to be less satisfactory than the mechanical scheme, and as a result it is planned in the near future to replace both types of control with a newer type entirely electrical which has proved its worth in actual operation. Practically the only point of wear experienced has been at the thyratron tubes. These have given an average life of approximately 15,000 hours, and one tube functioned 17,800 hours before failure.

Two regulators using the newer type of vacuum tube control mentioned above for the thyratron output were installed in April 1931. One of these was used with a 25,000-kw and the other with a 20,000-kw generator, both at our Glenlyn, Virginia, plant. Like the earlier regulator, these supply excitation for the fields of the main exciters. These regulators have not been in service as continuously as the earlier one, having been used only approximately 18,000 hours each. The control scheme appears to be entirely satisfactory, and the only source of trouble has been failure of thyratron tubes, the average life of a tube being approximately 13,000 hours.

As a step further in advance, a fourth electronic regulator was installed in September 1933, on a 15,000-kva condenser at Scranton, Pa., this time supplying the excitation for the condenser field itself directly from the thyratron tubes. Since placing in service, this regulator has been in use almost continuously. A few troubles have developed, none of which appear to be fundamental; we are coöperating closely with the manufacturer in this and we believe they will be successfully eliminated. However, it is still too early to say definitely that all troubles have been overcome, and the service hours have been insufficient to furnish data on tube life. We are hoping to be able to present before the Institute in the not too distant future further and more technical details on all these tube applications.

F. H. Gulliksen: With reference to Mr. Seeley's discussion, I wish to mention that the new type of voltage regulator which does not need a dry cell battery uses a diode as the voltage indicating element. The principle of operation of this new regulator is somewhat similar to the type *AT-1* regulator described in the present paper.

Mr. LaPierre asks about the characteristic of the lamps employed in the monitor bridge. These lamps are standard 25-watt 125-volt type *S-11* mazda lamps. Data on the actual balance voltage of the bridge over a period of time are unfortunately not available; but the balance point for the monitor remains with $\pm 1/10$ of one per cent during a period of at least 2 or 3 days.

Flashover Voltages of Insulators and Gaps

An A.I.E.E. committee report, June 1934 issue, p. 882–6.

Selection and Performance of Suspension Insulators

Philip Sporn, E. L. Peterson, and V. A. Mulford, June 1934 issue, p. 936–42.

High Voltage Insulators

W. A. Smith and J. T. Lusignan, Jr., June 1934 issue, p. 969–73.

The Suspension Insulator

K. A. Hawley, June 1934 issue, p. 895–8.

Radio Influence Insulator Characteristics

G. I. Gilchrest, June 1934 issue, p. 899–902.

Recent Developments in Suspension Insulators

G. M. Barrow, June 1934 issue, p. 867–70.

A New Porcelain Post Insulator

G. W. Lapp, June 1934 issue, p. 922–5.

Discussions of a group of papers presented for oral discussion at the session on Insulators of the summer convention, Hot Springs, Va., June 28, 1934.

Sidney Withington: Emphasis may appropriately be given to a number of points mentioned in the various interesting and timely papers presented on the subject of porcelain suspension insulator design and operation.

There has been a tendency to differentiate somewhat sharply between "mechanical and electrical strength" and "ultimate mechanical strength" in discussing suspension insulator characteristics. It should be borne in mind that the so-called "electrical" failure of an insulator under stress is very likely to result in rupturing the insulator under service conditions because of the power arc which follows the failure, especially in railway distribution circuits which are rigidly grounded and involve considerable power capacity. It seems logical, therefore, to consider that the ultimate mechanical stress of an insulator is not of vital importance, but that the mechanical and electrical

strength is the principal criterion. It is, of course, of vital importance to avoid dropping the conductors in the event of an insulator failure, and this can best be accomplished by emphasizing a high mechanical and electrical strength rather than a high ultimate mechanical strength.

For a number of years some importance has been attached to the requirement that insulators contemplated for a given service be subjected to the standard temperature cycle test under mechanical stress, in order to insure that the wedging action of the pin will not be a factor in the ultimate failure of the insulators in service. This was proposed in the report of the electrical section of the American Railway Association, Sept. 26, 1932, p. 40, and some railroads have adopted this as a requirement.

The time factor for insulators under stress is of primary importance. It is apparent that the long-time tensile strength is definitely less than that which would be recorded by the test stipulated in the A.I.E.E. standard test specification. A factor recognizing this reduced value should be applied in designating the rating of the insulator. This was suggested in the report mentioned in the previous paragraph.

It is desirable that the time-stress tests be carried on outdoors or with other means for varying the temperature over a reasonably wide range if full value of this form of test is to be obtained. The mere "alternate freezings and thawings each year" mentioned by Mr. Hawley, such as occur frequently during the winter season, cannot be said to constitute a temperature cycle. For this reason 2 years of such test cannot be said, without qualification, to be sufficient to demonstrate the ultimate life of the insulator. It has been the experience of a number of insulator users that insulators of a given design have performed satisfactorily for 4 or 5 years and have subsequently shown definite signs of distress.

In the assembling of suspension insulators with a resilient compound, such as hot asphalt, it is necessary to take care that the composition or quantity of the compound used is not such as to cause an explosion within the cap in the event of puncture of the insulator. Certain types of insulators have shown a tendency toward troubles of this kind, which on occasions have caused a complete rupture of the cap under obviously high mechanical pressure, which of course has resulted in the parting of the insulator and dropping the line conductor.

The vulnerability of insulators to damage by stones and other materials may be of particular importance in selecting the insulator design for a given service, especially along railroad right of ways where the stone ballast provides effective ammunition for use by mischievous trespassers in some localities. In such cases, it may be found desirable to adopt a rugged mechanical design, even at some sacrifice of electrical refinements.

The continual change in insulator design details by manufacturers may be embarrassing to the users of insulators. Rather important details have been modified without advice to the purchaser or any change of designation. Some of these changes, as has been pointed out in one of the papers under discussion, have more or less seriously affected the reliability of the design for specific service. In spite of the apparent confusion which frequent changes in detail may involve in catalogue data, etc., modification of even relatively small details should be frankly noted by the supply company for the advice and guidance of the consumers.

The statement that porcelain is less susceptible to vibration than hardware is especially interesting. On the New Haven Railroad electrification a number of instances have been experienced from time to time which have seemed to indicate that vibration has caused insulator porcelain failures. Measures adopted for reducing the vibration of the insulators in such locations have produced valuable results at these locations. Possibly the type or kind of vibration may be an important factor.

It is of importance, as has been mentioned, that each individual insulator assembly be subjected before shipment to a routine tensile strength test, as required in the A.I.E.E. test specification. Instances have occurred where a failure due to an undetected flaw in the hardware has dropped a conductor as soon as stress has been applied in the field. This type of failure is very serious, as it is likely to cause personal injury to members of the construction force engaged in the installation.

In connection with developing data on the application of suspension insulators to individual service, the compilation of standard recommended practice under varying conditions of circuit characteristics, temperature variation, moisture, salt, air pollution, etc., should be of value as a guide to the designers of transmission lines. Some data of this nature, especially in connection with railway problems, were proposed in the American Railway Engineering Association proceedings for 1926, p. 147.

It is suggested that when the A.I.E.E. standard insulator specifications are next revised they be modified to include thermal tests under mechanical stress, as indicated above, and also include a recognition of the ratio between the mechanical and electrical strength as applied on a short-time basis in a testing machine, and that over a relatively long period of time; the long-time values would more nearly approach conditions actually experienced in service, and upon these ultimate strength designations and factors of safety should logically be based.

R. W. Sorensen: The insulators and the service rendered by them, described in the papers by Messrs. Hawley, Smith, and Lusignan, and Sporn, Peterson, and Mulford, show a remarkable insulator evolution since the time of the contemporary discovery in 1917 by the late Prof. Harris J. Ryan and myself, when on 2 separate and distinct testing programs we found that certain insulators not in use on transmission circuits had a failure rate equal to others of the same vintage and manufacture which were in use on power lines and were thus subject to voltage stresses. All developments from the time of this turning point in the explanation of the cause of insulator failures have shown that the mechanical, rather than the electrical, problems predominate and are the problems which, as yet, remain to a large extent unsolved in the great program of obtaining insulators uniform as to performance, and having a life equal to or greater than the life of other apparatus materials and devices used in power transmission.

The papers under discussion show the ability and ingenuity of engineers in overcoming the difficulties involved in the production of high grade insulators and in devising methods of testing and inspection of insulators which insure, for the most part, the meeting of prescribed standards. Nevertheless, our present standards rules, governing the grading of insulators, seem somewhat deficient in providing a way to determine the life of insulators under long-time mechanical and electrical loads. For this reason, it appears to me desirable and, in fact, almost absolutely necessary that more data from long-time mechanical loading tests, similar to the data presented by Messrs. Sporn, Peterson, and Mulford, be made available. As a contribution toward this goal, I am planning to present at the Pacific Coast convention results of some insulator studies which include long-time loading tests.

Briefly, as an indication of what these tests show with respect to this problem, I would like to call your attention to the relative ability to stand long-time load tests of 8 of the several lots of insulators which I have tested. On the basis of a life expressed in terms of pound-day-load to cause failure, the relative values shown by these 8 groups are as follows:

5.0..6.0..8.8..12.7..13.3..13.4..14.0..17.1

With the best lot showing a value more than 3 times that of the poorest lot, it is quite obvious that much can be learned regarding insulator selection from long-time tests, and that much aid can be given in making a proper selection when we have learned enough about such tests to include them in our insulator specifications.

H. F. Brown: The symposium on insulators presented at the summer convention is of particular interest, including as it does 5 papers from 4 of the leading manufacturers' representatives, one from well-known "consumer" representatives, and a paper from the power and transmission committee relative to the standardization of flashover data for insulators.

The paper by Messrs. Sporn, Peterson, and Mulford is of particular interest to other consumers in that it presents a critical analysis of the performance of insulators of various manufacture over many years. It is apparent to nearly all insulator consumers that while most manufacturers have "standardized" on the outward appearance and dimensions of both suspension and pin insulators, the internal construction still varies greatly among the various leading manufacturers; and often, as Mr. Sporn points out in this paper, the internal construction varies from time to time in the same type of insulator by the same manufacturer, thus rendering long-time tests more or less meaningless as to performance of present day designs.

I believe with the authors of this paper "that the present A.I.E.E. standard tests for suspension insulators are not in themselves sufficient to furnish a basis for detecting all insulators of inferior design and manufacture, or for comparing competitive makes of insulators." Although it is probably true that "modern suspension insu-

lators of proper design and manufacture, properly selected and correctly applied, can be expected to give satisfactory performance over a long period of time. . . . ." it is, nevertheless, a difficult problem for the consumer to determine just what the "proper design and manufacture" is, when the manufacturers themselves are apparently not in agreement on many of the important details covering these points. For example, Mr. Hawley in his paper covering the improvements made in suspension insulator design during the past few years, gives comparative data on pin or bolt design, with 1, 2, and 3 steps, arriving at the conclusion that the 1-stepped bolt, especially the single-stepped bolt with curved shape, is not as efficacious as the 2-stepped bolt. Mr. Barrow in his paper demonstrates just as conclusively that the single-stepped bolt, with curved shape, behaves much better than the multi-stepped pin on repeated changes in temperature and load. Mr. Gilchrest points out the efficiency of metallic coatings applied to the glaze for improving the "radio influence" characteristics of insulators, while Mr. Lapp in turn shows how these effects may be reduced by changes in the shape of the top of the insulator, without resorting to special coatings applied to the glaze. In each of these details the manufacturer no doubt has a sales argument, which is left to the consumer to evaluate, if he can.

Not all of the large consumers of insulators have on their staff engineers who are specialists on insulator design, and they in turn must lean heavily on the engineering staff of the various insulator manufacturers for the salient features of design, and on some standard specifications such as those of the A.I.E.E. for guidance in determining their selection of proper design for a particular installation or application. There may be a few isolated instances where insulators already installed may be expected to perform, as Mr. Sporn indicates, "satisfactorily for 50 years"; but experience has proved that there are more instances where both pin and suspension designs which have satisfactorily passed all A.I.E.E. tests, including thermal cycle tests and long (2 year)-time load tests, have so failed in service, and with an increasing percentage of failures each year, so that they have had to be replaced completely within 5 or 6 years of their installation. Very possibly some of these insulators were overrated, but the tests applied were not able to demonstrate that fact.

In connection with thermal tests of suspension insulators, these are now specified to be made between the limits (approximately) of freezing and boiling water. Since the cement in most suspension insulators is set under steam, at high temperatures which are probably never again experienced in service, it would seem that there is something to be said in favor of changing the temperature limits of the A.I.E.E. thermal cycle tests to, say, minus 20 deg F and plus 150 deg F, as more nearly representing actual service conditions.

It is well known that the leading insulator manufacturers have not only pooled their important patents covering details of the so-called "standard" designs, but have as a natural result entered into price agreements as well, so that the purchaser has little to guide him in his choice other than "reciprocity buying," unless there are definite data as to a better product which can be demonstrated by tests other than long time performance. It would seem that the manufacturers should not only be in agreement upon the essentials of internal as well as external design, but there should also be some agreement among them as to manufacturing and assembling methods. For example, in his paper detailing the manufacturing methods of suspension insulators, Mr. Smith specifically mentions a time interval between cementing on the cap and the cementing in of the pin. Some manufacturers perform both of these cementing operations at the same time. If there is any more merit in one method than the other, it would seem desirable to standardize on that method, rather than leave it to the consumer to determine which method may give a better performance of the product. Numerous other differences in manufacturing will occur to those familiar with insulator manufacturing and assembling. While many of these details might be considered "trade secrets," it would doubtless advance the art materially if some of these differences could be eliminated by agreement among the manufacturing engineers.

Most of the so-called "standard" insulator designs, particularly of suspension insulators, have been developed specifically for the great network of cross-country transmission lines which have grown so rapidly within the past 2 decades. Their successful performance in such service is not necessarily an indication of equal economic performance on the catenary and distribution systems of electrified steam railroads, although they have, of necessity, been so applied. It is my opinion that there is a large field for improvement in design of both suspension and pin insulators for this service. Less fragile porcelain shapes, the grading of units in strings, having in mind the steeper potential gradients resulting from grounded circuits, and greater mechanical strengths have economic possibilities if they can be successfully combined.

Theoretically, there should be no reasons why the insulator should not last for as long a time as any other part of the transmission line, because, with the exception of the exposed surfaces of the metal cap and pin, it is an assembly of inert materials. The manufacturers have made great strides in the past 20 years, and have contributed much to the success of power transmission at very high voltages. With the extensive laboratories and facilities for research at their disposal today, progress during the next few years should be, and probably will be, just as rapid.

C. Francis Harding: After reading all 7 papers of this symposium it is evident that the recent developments in design, manufacture, and usage of all types of porcelain insulators have been most satisfactorily outlined. It is unfortunate that the corresponding characteristics of glass insulators which have been attracting considerable attention and warranting increasing usage during the last few years, were not represented in a paper in order to complete adequately this symposium.

Another important consideration which might well have been included in this series is a more detailed analysis of the effects of humidity upon flashover of both glass and porcelain insulators, particularly under impulse tests. An early paper by Littleton and Shaver before this Institute indicated the rather surprising effects of humidity upon such flashover values which were obtained in the laboratories of the Corning Glass Company and confirmed in the high voltage laboratory of Purdue University. This paper might have been included in the bibliography to advantage. It is believed that tests under surge conditions of all types of insulators exposed to variable and particularly high humidity or rain should be reported in the near future. Test values so obtained are known to be very different from corresponding 60-cycle values and of course represent the conditions under which failures frequently occur in service.

Another cause of mechanical failure which has been given inadequate attention is the probable lowering of the ultimate strength of insulator materials under repeated vibration, a condition to which the insulators of the larger lines are continuously subjected. As it is well known that some of the materials used in the assembly of insulators, particularly portland cement and possibly the hardware and insulating material itself, are considerably reduced in ultimate strength after subjection to several hundreds of thousands of mechanical vibrations, it is hoped that laboratory tests closely simulating line vibration conditions may be developed to determine the extent of strength reduction caused by such vibrations in service.

W. A. Kates: In the first paragraph of Mr. Barrow's paper, he notes that the details of his unit's cap and pin are so shaped as to resolve mechanical load into compressive stresses in the porcelain, and he contrasts this fact with the tensile and shear stresses in older designs. On p. 869, however, he notes in several instances that the pin pulls down or nests into the cement in adjusting its position under load. Figure 4 illustrates this also. I believe that further discussion of the means of eliminating tensile stress would be in order. The comparison of the insulator with keystone, arch, and buttresses is hardly permissible. Load supported by the keystone of an arch is supported with an accompanying yield of the arch. The arch is not attached to a superimposed structure. Were it so attached, tension would occur at the upper surface of the arch or at the upper ends of the buttresses. In the diagram, Fig. 1b, if the load is resolved into forces acting outward toward the cap, a zone of tension will obtain at the upper end of the pin hole. This conclusion is inevitable regardless of whether one considers the force exerted outward in a bursting manner or in axial shear. A corresponding zone of tension obtains at the lower edge of the cap by similar reasoning. The existence of these zones can be demonstrated by photoelastic studies. The design is, therefore, an attempt to minimize the effect of these tensile stresses rather than one which resolves the load entirely into compressive components. Tensile stresses still occur.

A considerable part of the paper is devoted to a discussion of the elimination of wedging. Even after considering this dis-

cussion, I would like to inquire the difference between the phenomena shown by the changing slope of the curves of Fig. 4 and the process of wedging.

In Table I I note that for the compression type insulator the time-load strength for one week is only 11.5 per cent greater than that for 2 years. Does the author believe that one week time-load test can be substituted for a 2-year test if proper allowance is made?

Referring to the same table, do the time load tests all include equal cyclic variations? In the text the author states "time load tests through several seasons of normal weather and temperature changes is an indication of the ability of the compression type to take care of thermal stresses."

In the last paragraph it is stated: "the time-load test is inherently a natural basis for measuring service performance, as the degree to which load and temperature variations could be accelerated without insulator failure constitutes a measure of comparative merit." If this is correct, why was a 48-hour cycle test over a 140 deg temperature range believed to be an indication of design characteristics more satisfactory than the A.I.E.E. immersion test of 20-min cycles over a temperature range of 166 deg F?

In the testing of a large number of glass suspension insulators, we have found that electrical failure is merely an indication of initial mechanical failure. This can be readily determined by visual inspection of the transparent shell. I would like to ask the author if his experience has shown that the same is true of porcelain. Is the electrical failure merely an indication of a mechanical crack? If not, how has this been determined?

The Institute Standards, paragraph 41-301, mentions 3-sec axial pull of 40 per cent of the rated ultimate strength. It has been our experience with glass insulators that this time is entirely too short to indicate a satisfactorily uniform product and we have, therefore, substituted a 5-min test of the same per cent of rating. Would the author suggest the use of a combined mechanical-electrical test as a factory production test, and if so, how long a time of application does he recommend?

Commenting now on Mr. Hawley's paper, on p. 898 is a summary of a number of time-load tests, and these tests are cited as demonstrations of design improvement. In some of these tests the number of units was 3, in others it was 6, in others 12. A consideration of the mathematical theory of uniformity of quality in a manufactured product indicates that these numbers are rather small from which to draw conclusions pertaining to an object which must be manufactured with uniformity and in large quantities. These values may be on the peak of the quality curve, or on one slope, and formation of conclusions from 3 figures is hazardous. It has been the experience of the speaker and his associates that lots of 12 are none too large for obtaining data for generalization, and 20 to 30 are preferable if cost permits.

I would like to ask Mr. Hawley concerning the electrical failure of porcelain. As mentioned in the discussion of Mr. Barrow's paper, we have found that with glass electrical failure is merely an indication of initial mechanical failure. I would like to ask the author if his experience has shown that the same is true of porcelain. Is the electrical failure merely an indication of mechanical crack? Or is it another type of failure and if the latter, how has this been determined?

I would also like to ask Mr. Hawley whether his experience indicates that the combined mechanical-electrical test outlined in the Institute Standards, paragraph 41-301, is indicative, or if longer time of test is preferable.

Commenting on both papers in general, I note that both titles imply broad consideration of the improvement of "the suspension insulator." Perusal of the papers indicates a consideration of only the 10 in. cap and pin design as composed of hardware and a porcelain shell, assembled with portland cement. As this implication is so patent and so broad it seems only fair to note here that a substantial portion of the suspension insulators purchased in 1934 are not of the cemented type. Other types are available, have demonstrated their advantages, and are finding an increasingly broad usage.

Both papers discuss designs which have been subjected to quite extensive tests. Presumably each has been designed for carrying a specified service load over a long period of time. Unit loadings over the cap surfaces are much less than in the pin hole and therefore the pin holes and pin designs have been given largest consideration. Mr. Barrow's design is that including a single load bearing surface on the pin. Mr. Hawley adheres to the multiple stepped construction and notes the inadvisability of large masses of cement in the pin hole. A third one of the larger insulator manufacturers lists in his catalogue 4 different kinds of pins including the multiple stepped, spring supported, and flanged types, and one combination of 2 of these. This variety and the emphasis and mathematical proof supporting each one of the variety excite especially careful consideration of any one type making broad and exclusive claims to correctness while utilizing the same cement, porcelain, and metal. A true test of efficiency of design is not a discussion of the theories but can best be measured by the results. Loads of 25,000 or even 100,000 lb can be supported by single unit composite structures of vitrified shells and metal parts if these are made large enough. I think it would be interesting if, in presenting papers such as these, the results obtained in described tests were not only given in pounds per insulator but in pounds per square inch of load bearing surface, pounds per cubic inch of volume, or some similar figure. Figures such as these would enable those not so intimate with insulator design to form an opinion of the merit of a particular unit in terms calculable for any insulator regardless of size or shape. Thus the engineering design of an insulator having a 4-in. diameter could be compared with that of an insulator having a 6-in. head even though their ultimate strengths differ greatly.

C. L. Dawes and Reuben Reiter: This discussion does not apply to any particular paper but is submitted at the request of the insulator committee. For more than a year research involving power-frequency measurements on suspension insulators has been conducted at the Harvard Engineering School. Practically no investigation of this character has as yet been conducted on power line insulators. By means of our high voltage bridge we are able to measure with some precision the power loss, the power factor, and the capacitance of suspension insulator disks at power frequencies. These quantities are measured as functions of 2 parameters, voltage and mechanical stress. With specially designed mechanical apparatus it is possible to apply tension to over 20,000 lb and yet make electrical measurements. We find, however, that it is not safe to stress standard disks to much over 12,000 lb.

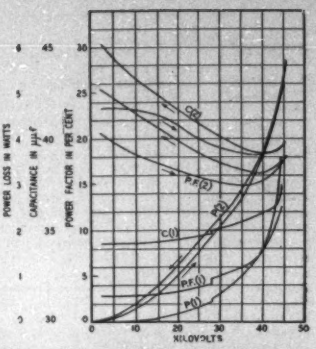


Fig. 1. Variation of power loss, capacitance, and power factor with voltage at 60 cycles

Curves (1) for first trial test; curves (2) after several tests. Tension 400 lb; temperature 21 deg C; relative humidity 75 per cent

In contrast to impregnated-paper cables and similar dielectrics, insulators are composed for the most part of vitreous and other inorganic materials which are usually associated with electrical stability. It was with some surprise, therefore, that we found wide variations in the electrical properties of such insulators with change in voltage, even with little mechanical stress. Moreover, our investigations show that the factors which affect the electrical characteristics are so numerous and difficult to control that they prevent exact duplication of the characteristics in a single specimen even in successive test runs. For example, we find that the characteristics are affected by humidity and by the time of application of the voltage.

In Fig. 1 power loss, power factor, and capacitance are plotted as functions of voltage with a constant value of stress of only 400 lb. In test (2) the voltage was carried to its maximum value and then was gradually reduced to zero. The tests designated by (1) were the initial tests made on the insulator. Those marked (2) were made after 7 cyclic applications of voltage over a period of 2 weeks. It will be noted that the power factor of the porcelain insulator varies widely with voltage and also that it reaches high values. For example, the power factor goes as high as from 15 to 20 per cent, whereas at ordi-

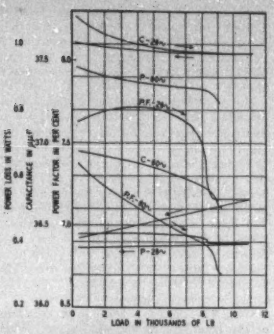


Fig. 2. Variation of power loss, capacitance, and power factor with mechanical load

Tests made at 30 kv and with frequencies of 26 and 60 cycles; temperature 19 deg C; relative humidity 50 per cent

nary temperatures the power factor of impregnated-paper cables is of the order of 0.5 per cent or less. Also, these values of power factor are very much higher than those for porcelain bushings in good condition. The slight abrupt increase in the electrical quantities in (1) occurring at 28 kv is due to the power being interrupted for 15 minutes. The increase in power factor and capacitance with voltage is undoubtedly due in part to corona formation on the hardware, particularly at the edges of the cap.

The characteristics designated by (2), taken after 7 cyclic applications of voltage, are quite different from those designated as (1). The power loss has more than doubled. The capacitance has increased substantially, and now decreases with increase in voltage except near the highest values of voltage. The initial value of power factor is 20 per cent and it decreases with increase in voltage until at 40 kv it begins to increase. The increase at 40 kv in both the capacitance and the power factor are undoubtedly due to corona formation at the edges of the cap. As the voltage is decreased the power loss, the power factor, and the capacitance are all substantially greater than with increasing values of voltage.

In Fig. 2 the effects of mechanical stress are shown. The voltage was held constant at 30 kv and tests were made at 26 and 60 cycles. With 26 cycles a cycle of stress is shown, the stress being increased to 11,000 lb and then decreased to zero. The electrical quantities are all less for the return portion of the cycle. The sudden and large decrease in power factor at 9,000 lb is undoubtedly due to some readjustment of the pin, the cement, and the compound used for sealing. In Fig. 2 the origin is not shown, so that the proportionate variations are not as large as they may appear at first sight. The 60-cycle power loss is considerably greater than the 26-cycle power loss, but the power factor and the capacitance are greater for 26 cycles.

These results are submitted to indicate the direction which our research is taking, and also to show in a preliminary way the effects of voltage and mechanical stress on the electrical characteristics. At the moment it is not possible to analyze and evaluate the different effects shown in these figures, although investigations now being made will undoubtedly make this possible. For example, a graphite guard ring around the porcelain, which interrupts surface leakage, has a marked effect on the characteristics.

In the near future it is planned to publish our results more comprehensively together with theories to explain the characteristics. We also find considerable difference between the characteristics of porcelain and glass insulators. These power frequency characteristics may have little or no bearing on the usefulness of such insulators in service, but the more that we know about a piece of apparatus the better we understand it, and we are in a better position to analyze its operation.

W. A. Hillebrand: The group of papers presented at this session is evidence that the design of a cap-and-pin insulator is an engineering problem and as such may be solved in more than one way. The final test is that of service, but sufficient time has not yet elapsed to demonstrate conclusively the superiority of any one design under average conditions of use.

The constituent materials are portland cement or "type metal" alloy, porcelain, steel, and malleable iron. The elastic properties, temperature coefficients of expansion, and ultimate strengths of these materials differ widely from one another and will vary with composition and method of manufacture. The most critical element is the porcelain, whose mechanical integrity must be maintained, and the entire assembly must be designed for this. The most important requirement is that the properties of the respective materials shall be compatible with the design adopted, otherwise the apparently contradictory results reported by different investigators are to be expected.

Cement and porcelain are used principally in compression and shear, but within the insulator head it is impossible to impose a compression load without setting up shearing stresses in the areas bounding that to which the load is applied, and it is the writer's belief that ultimate failure of the material generally occurs along the shear surfaces. Therefore, criticism of a design that deliberately utilizes cement and porcelain in shear is not necessarily sound. Furthermore, a bursting stress in the interior of a tube, like the insulator head, is accompanied by tension stresses in the tube wall if the slightest movement occurs. This movement is prevented by the use of a heavy-walled cap, whose contraction in cold weather may shear off the flange of lightly loaded insulators in suspension position. This has been observed to a limited extent in suspension insulators, and to a much greater degree in the larger station pillars.

It is not the writer's purpose to condemn any particular design but to call attention to the fact that, as always, a compromise must be made. The most effective use of material that will meet test requirements and produce maximum life is yet to be determined and the designer should still be left a free rein in the solution of his problem.

The longest lived insulators have been those designed for low ultimates and, particularly, for low thermal stresses. Emphasis on long time, high load tests results in thicker metal parts with probably increased thermal stresses. Whether or not these have been pushed to the danger limit we do not know, but it is probable that this feature can be stressed to the point where insulator life will be shortened as a result of the "doughnutting" previously referred to.

The relation of the elastic modulus to the ultimate strength of typical porcelain is such that the ultimate strength is reached with a yield of the order of 0.1 per cent. The wall thickness of the cap-and-pin insulator is 1 in. or less so that the material may be ruptured with a total deformation of not over 0.001 in. This is the order of dimension within which the designer must work. Instruments for measuring deflections under load or temperature change should read to at least 0.0001 in. and preferably to one-tenth of that value. Equipment of this type is difficult to construct and involves elaborate compensation for deflection of supporting members. However, measurements of this refinement are essential for a real understanding of how the component parts of a given assembly behave.

Because of the smallness of deflection that occurs up to failure, the configuration of parts becomes of vital importance. The effectiveness of a given design may be materially altered by a change in the shape of cap, pin, or porcelain. Therefore, whenever such a change is made, the unit should be given a new catalogue or identification number. Otherwise, important and carefully compiled life records such as those submitted by Messrs. Sporn, Peterson, and Mulford lose much of their value because of the impossibility of distinguishing in later years among insulators that are really different.

Professor Dawes has referred to tests of dielectric loss and power factor of suspension insulators. He eliminates surface losses by means of guard rings, but, unfortunately, one of the most important elements is the cement, which is a poor insulator or a semiconductor. Is it possible to separately determine the losses in cement and porcelain? In any event, as a contribution to our knowledge of the subject, his results will be of great interest and may possess a significance that as yet we cannot assign.

One of the most important properties of glass, including insulator glaze, is the adsorption of water vapor in a surface layer of the order of 250 molecules thick. This subject and that of the surface resistance of glass have been most exhaustively studied by the Bell Telephone Laboratories, and in the *Bell Laboratories Record* for October 1933, Mr. Yager gives much significant data. This layer will change in thickness with atmospheric humidity, usually with a time lag of many hours. With it surface resistance changes over wide limits. It is probably responsible for the tenacious retention of space charges which we know may persist for minutes. Because of its effect upon resistance and space charge, it also is probably an important factor in determining the degree of radio influence. Its influence upon dry flashover has been brought prominently to the attention of

engineers in recent years. The following test will serve to illustrate how markedly a porcelain insulator, as a gap, differs from other gaps because of its surface properties. Five successive flashovers were taken at 1-min intervals on a sphere gap, needle gap, and insulator, respectively, all having approximately the same flashover voltage. The differences between maximum and minimum values for each of the 3 were:

Sphere gap	0.3 per cent
Needle gap	3.0 per cent
Insulator	15.0 per cent

In 5 successive flashovers 1 min apart of a suspension disk, I have seen each arc take a separate path at widely separated points around the circumference. In each case the arc cleaned up its path, leaving it of higher resistance to breakdown.

The reason for dwelling upon the peculiar properties of glass surfaces is that they are extremely important in some cases in determining insulator performance, and yet their influence is too often overlooked.

The insulator subcommittee and the several authors are to be congratulated upon the symposium presented. Although apparently a simple structure, the distribution of stresses within the suspension insulator is extremely complex. Add to this the very small displacements that occur up to failure and it is possible to understand how painfully slow and difficult it is to learn intimately and accurately what is taking place. The papers presented contribute to our knowledge and are a step toward the ultimate goal of learning what maximum and working loads may safely be developed in roughly 10 lb of porcelain, malleable iron, steel, and cement.

High Voltage Insulators

Discussion and author's closure of a paper by W. A. Smith and J. T. Lusignan, Jr., published in the June 1934 issue, p. 895–8, and presented for oral discussion at the insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

W. A. Hillebrand: This paper is welcome because the authors call attention to many factors of vital importance in the production of a successful insulator that have not hitherto been stressed and which often tend to be overlooked.

K. A. Hawley: We heartily concur in the manufacturing goal set in this paper. We regret, however, that there is within it practically no information about insulator developments in design or supporting data.

Our experience in making short wave impulse tests does not indicate that the voltages obtained are proportional to the leakage distances. The factors are considerably more complex than this. Our experience indicates that it depends partly upon tight string distance and partly only upon leakage distance.

Electric needles starting from electrodes separated solely by porcelain travel outward because of the high flux concentration at their point until corrugations introduce air gaps between their ends, then for a ways these needles will jump clear of the porcelain surface.

W. A. Smith: Regarding Mr. Hawley's criticism of our use of the leakage distance relationship in comparing breakdown voltages at short time lags, obviously we do not mean that every increase in leakage distance will increase the flashover voltage. However, such factors as increased diameters and additional petticoats of normal shapes will raise the impulse flashover voltages at short time lags more than the increase in striking distance and much more in proportion to the increase in leakage distance. Extremely deep petticoats help little in increasing the breakdown voltage, but an examination of insulators and bushings of the usual designs show discharge marks well into the petticoats and corrugations after applied waves which have caused breakdowns within a few microseconds, indicating that the leakage distances rather than the striking distances have been the important factor.

Mr. Hawley expresses regret that in our paper there is "practically no information about insulator developments in design or supporting data." This paper was not intended as a detailed discussion but as a general outline of certain phases of insulator manufacturing. Details of design and relative data belong to a separate paper and may be presented at some later date.

The Suspension Insulator

Discussion and author's closure of a paper by K. A. Hawley published in the June 1934 issue, p. 895–8, and presented for oral discussion at the insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

W. A. Hillebrand: The papers by Messrs. Barrow and Hawley and the comments that follow will illustrate the extent to which conflicting results may be obtained by different workers in the same field. With much of Mr. Hawley's thesis we agree, but wish to take exception to some of his statements which otherwise might be accepted as of general application.

Through the application of methods that are quite similar, competitive designers have been able to obtain short and long term strengths that, for a given amount of material, are much the same. On the other hand, competitive designs do not in all respects produce similar results.

Under certain conditions glazing over the sand will increase the strength of an insulator, but we have been able to obtain values just as high with sand not glazed over but with a successful combination of glaze and carefully selected sand having grains of proper size for the glaze used. Glazing over the sand is objectionable in that it makes it practically impossible to produce resiliency in the joint by coating the sanded surface, a practice that seems to have been fully justified by its application to millions of insulators during the past 17 years.

Again, some designs will show an increase in strength with age whereas others will not. In Table II of the paper the increase between 18 and 28 days is altogether in the combined electrical and mechanical strength, but not in the ultimate, indicating an apparent ability of the older cement to better distribute stresses, although the average at which it let go seems not to have altered.

On p. 897 the statement is made that insulators have failed because of the use of a relatively large amount of cement in the pin hole. Is this assumed to be because of cement expansion or because of localization of mechanical stresses? In all my experience, with the one exception of a lot of 60-kv pin type insulators in which the pins had been cemented in the field by filling much of the center shell with a very dry cement, I have not found an instance of insulator failure which could be definitely attributed to cement expansion. Does the author's experience conform to this?

On p. 896 failure is referred to as occurring at the boundary of the sand layer. Was this also the end of the glaze coat? In common with others, we find the strength of porcelain appreciably affected by the glaze.

Among improvements referred to is that of the straight pin hole. There has never been any difficulty in manufacturing straight pin holes in so far as the manipulation of the clay is concerned. The taper has been set by practical limitations in the manufacture of blocks and molds.

On the effect of pin eccentricity in lowering mechanical strength, many of our organization are in agreement. Nevertheless, a lot of insulators in which the pins were purposely assembled with their axes at the maximum possible angle with that of the pin hole showed remarkably little variation in the mechanical strength at electrical failure. This leads to the conclusion that the effect of eccentricity is largely determined by design, manufacturing tolerances, and whether or not caps and pin are coaxial, regardless of how the porcelain may be assembled with respect to either.

Again, the statement is made that cement and porcelain have the same modulus of elasticity. This must be true only for the particular materials referred to by Mr. Hawley. In our experience the values for the 2 are not the same.

K. A. Hawley: Mr. Withington has called our attention to the need of rating suspension insulators by their combined mechanical and electrical strengths. Our A.I.E.E. Standards No. 41 are written to cover this "M and E" strength. A complete understanding of it involves several separated paragraphs that may well be combined and interpreted. At present they are somewhat confusing. The present strength ratings in the catalogues are based solely on the mechanical and electrical value.

We have found that the long time ratings are but little below those obtained by quick tests. The margin is not so great as with most other structural materials. We therefore do not understand Mr. Withington's statement that they are much less. Testing for 2 years in an outdoor frame where there have been an unusual number of freezing-thawing cycles and at practically the strength rating of the insulator appears to us to be fully equal to use over a longer period at a much less load. This appears

to us to be the only somewhat accelerated test that we can run that surely uses most of nature's tricks. We are very doubtful of the true value of highly accelerated loaded thermal shocks. Nature has not done those things upon insulators that have broken in service.

In our own experience we hesitate to say that vibration is a major contributing factor in insulator aging. There is no laboratory so well equipped as the transmission line or catenary system for such tests. When there is trouble, coöperation between the manufacturer and user should be had for complete analysis.

Strength tests on every insulator going through the factory are imperative. Routing in production is so arranged that none can escape such tests. While defectives are scarcely ever found, we realize that so long as we are human this is one thing that must not be overlooked.

Some data will be found in the Frey-Hawley paper which is referred to in the current one upon the effect of natural contamination upon insulator surfaces. Mr. Lloyd, in a contemporaneous paper on insulator flashover values, also had similar informatiou. Mr. Withington may find them of interest.

We agree with Mr. Brown that standard tests will not surely eliminate types that may give poor service. It is necessary first to choose those types that have been satisfactory, and then apply tests as Messrs. Sporn, Peterson, and Mulford have done. Where the user has not acquired this experience it is necessary to call upon the maker for references.

Suggestion has been made that scarcely enough insulators were placed in the frames for the conclusions that we have drawn. Those of us who have lived with these tests feel decidedly otherwise after seeing the very satisfactory results.

Mr. Kates has asked if the application of electricity while testing is but an indicator for mechanical failure. We consider it so.

We find that there is little need for a test only slightly slower than that specified in the Standards. We see no need for a combined routine load and electrical test in our manufacture. It is fully as effective to separate them and considerably safer.

The work of Messrs. Dawes and Reiter is very interesting to us. We will make no more comments until their work is published in full and they are able to draw more complete conclusions. Such researches are of real value.

In answer to Mr. Hillebrand's comments, we thoroughly agree that we have not seen failures due to cement expansion where proper and easily available cement has been used. Our experience shows trouble from cement masses caused by contraction, absorption, and freezing, all of which are easily controlled in several ways when the problem has once been understood.

Pin eccentricity in itself does not appear to be a hazard. If, however, it bears against the procelain, there may be trouble. The star washer keeps the pin where it should be and stops any possible trouble.

A slight glaze coating over the sand keeps the sand in place while firing and adds to the strength of the assembly. Factory control easily prevents overfilling between the sand grains to the extent that resilient coatings would be a hazard.

Flashover Voltages of Insulators and Gaps

Discussion of an A.I.E.E. committee report published in the June 1934 issue, p. 882–6, and presented for oral discussion at the insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

C. M. Foust: The progress made within recent months in the securing of accurate impulse flashover voltages of insulators and gaps on the 1 x 5- and $1^1/_2$ x 40-μsec waves is very gratifying. The close agreement among laboratories is unusually encouraging when it is kept in mind that detailed methods of arriving at voltage values and wave shapes were quite varied among the several laboratories.

I would like to call attention to this wide range of measurement methods which includes the following:

1. Measurement of voltage amplitude across the test specimen by direct sphere gap comparison.
2. Measurement of voltage amplitude across the test specimen by preliminary calibration of surge generator output voltage, as indicated by sphere gap against surge generator excitation voltage.
3. Measurement of surge generator discharge circuit constants and calculation of voltage wave shape across the test specimen.
4. Recording of voltage wave shape across the test specimen by oscillograph.
5. Measurement of voltage amplitude and wave shape across the test specimen by oscillograph using voltage divider ratio and oscillograph deflection sensitivity.
6. Measurement of voltage amplitude and wave shape across test specimen by calibration of oscillograph deflection directly against the sphere gap.

All the laboratories which submitted data used either one or some combination of more than one of these methods of measurement and check.

The close agreement among the data submitted by the several groups makes for confidence in the results obtained by each group in spite of the differing methods.

K. A. Hawley: The publication of average flashover data has led to commercial difficulties. Insulator purchasers, not realizing that there are wide variations in flashover values which are caused by things not yet entirely understood, have insisted on writing in their specifications as minimum values the average data given. It is by no means always possible to demonstrate to the visiting inspector these average values, as all who have worked in the laboratories know full well. The help of the Institute's membership to understand that published data are average rather than minima will be greatly appreciated by the manufacturer.

K. B. McEachron: It is significant that a milestone has been reached in connection with the agreement of flashover voltages of insulators and gaps as presented in the committee report. It has taken a relatively long time for the various laboratories to arrive at these agreed upon values, but this is the natural result to be expected from the type of problem involved. Although the 60-cycle test data would seem a logical basis on which first to secure agreement, the paper shows that the impulse values are in better shape today than the 60-cycle values. This is probably due to the very great interest which has developed in the past few years concerning impulse values for insulators and gaps. Agreement will no doubt be reached in the not too distant future for the 60-cycle flashover values, as the laboratories are now busily engaged in securing the necessary data.

Of the various factors which affect the flashover of gaps and insulators, considerable work is still required concerning the effects of air density and humidity. The laboratories are to be congratulated for their work in the past, and we look forward confidently to the extension of the data now available in order that the industry may not be hampered by the lack of knowledge on these flashover values.

J. E. Clem: In connection with the committee report on the flashover of insulators and gaps, it might be interesting to review the work of the laboratory group which is actually carrying on this work.

A few years ago when impulse values came into use, there were great discrepancies among the flashover values emanating from different sources. The differences were in some cases as high as 40 per cent, and it was quite obvious that the industry could not get along with such a situation.

The work was begun by the General Electric and Westinghouse laboratories, joined shortly after by the Ohio Brass Company. Some time later the Locke Company began direct participation, and lately the Allis-Chalmers Company entered the group.

First the impulse flashover values of insulators and gaps were studied, and little progress was made for a long time. As the work progressed, however, minor errors were eliminated and the values steadily came closer. The values for the long wave (1.5 x 40-μsec) were within the tolerance limits set up by the group some time ago, but because those for the short wave (0.5 x 5- or 11 x 5-μsec) were not, it was decided not to make public any values until full agreement was reached. As soon as all the laboratories agreed to use the 1 x 5-μsec wave based on a uniform definition, the main source of differences was eliminated and an agreement soon was reached.

The values agreed upon were given in a report submitted this spring to the joint National Electrical Manufacturers Association-Edison Electric Institute coördination committee. This report covered impulse values only. No agreement has been reached in regard to 60-cycle flashover values.

R. W. Sorensen: It is very interesting to note the progress that has been made by the several outstanding industrial laboratories interested in this program in reaching an agreement as to what are the proper surge voltage flashover values for gaps and insulators. The values as given naturally deal entirely with insulator strings made up wholly of sound units. I have found interest in making some studies of flashover values at power frequency voltages on insulator strings in which some of the units are defective. I think it would be very interesting if some of those laboratories which have surge generators would conduct for us similar tests for surge voltages.

Selection and Performance of Suspension Insulators

Discussion and author's closure of a paper by Philip Sporn, E. L. Peterson, and V. A. Mulford published in the June 1934 issue, p. 936–42, and presented for oral discussion at the insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

K. A. Hawley: An effort at correlating laboratory acceptance tests and field experiences as given by the authors is of real value to all concerned. The form of acceptance tests used by these authors may involve a little longer time than is usual in insulator investigations and purchases. It will, however, be very well indeed to consider the points raised by them in future revisions of the insulator standard specifications. We regret that the authors have apparently not made full use of the manufacturers' advice in examining insulators which have broken. It is largely by examination of defective material that the manufacturer can continue to make improvements.

W. A. Hillebrand: To serve as a basis for purchasing, the authors have established the following test schedule:

1. Time loading test; 6,000 lb for 72 hours.
2. Thermal test of insulators that pass test No. 1; 10 thermal cycles, each consisting of a 10-min immersion in boiling water followed by a 10-min immersion in ice water. During this test half of the insulators are subjected to a load of 3,000 lb.
3. Porosity test; 6 hours in a solution of fuchsine in alcohol at 10,000 lb per sq in. pressure.
4. Electrical and mechanical test; given all units passing tests 1 and 2. Start at 6,000 lb and increase by 500 lb every 30 sec to electrical failure, and continue to complete mechanical failure.

The designer is faced with the double duty of meeting a test specification and at the same time building into the insulator the longest life that he is able to. In their mechanical requirements the authors apparently have not handicapped the design with respect to life. The schedule seems reasonable and it is hoped that it will meet with general adoption, because it is obviously in the interest of economy to have to design an insulator of given rating for but one specification. The following modifications are suggested, for the obvious reason that the maximum loading occurs at reduced temperatures:

The 72-hr loading of paragraph 1 should be at a temperature of 32 deg F.

For the insulators subjected to both the mechanical loading and thermal cycles of paragraph 2, it is suggested that the loading be 1,500 lb during immersion in hot water and 4,500 lb during immersion in cold.

The emphasis on life is welcome and the statement that the useful life of a lot of insulators may have been reached when 15 per cent have failed is a frank recognition of the hazard inherent in the material.

According to Table II of the paper, insulators manufactured through 1927 showed more or less porosity. The actual record must have been largely determined by the method of making tests and of interpreting results, because in our plant any porcelain which would show a penetration of from $^1/_{16}$ to $^1/_8$ in. would allow the dye to go completely through the test piece. In addition to pore space, the dye will penetrate fissures formed in breaking up the test specimens. If the test pieces are not wiped and dried completely after immersion and before breaking to detect penetration, the wet dye will flow around the edges of the freshly broken surfaces. Also, in any porcelain it is possible to find pore spaces which have not been completely filled in the firing, but these are not necessarily a detriment if isolated and of such small proportions that mechanical and electrical strengths are not impaired. Laps are something quite different.

In 1925 committee D-9 of the American Society for Testing Materials started to develop a quantitative test to replace the qualitative dye test. Their work resulted in a method which is based upon the extraction of the air in the samples by placing them in a vacuum over mercury. This test, D-116-30, now replaces the dye test for porosity and is recommended to the insulator subcommittee for consideration.

The results of any test should be based upon the performance of acceptable ware. Electrical porcelain must insulate throughout the full length of its life, but overemphasis on porosity will result in a product that is glassy, overvitrified, and weak mechanically and electrically.

W. A. Kates: On p. 936 of their paper the authors state that the present A.I.E.E. standard tests for suspension insulators are not sufficient to form a basis for detecting insulators of inferior design and manufacture. With this I heartily agree. The irregularities of the oil puncture tests, for example, were pointed out by Drs. Littleton and Shaver of the Corning Glass Works in the September 10, 1927, *Electrical World*, and again in the April 14, 1928, issue of the same journal, some 2 years before adoption of the present standards. It may be easily demonstrated in a short time by anyone with the aid of a testing transformer, oil, insulators, and a few drops of water. Vagaries due to humidity were also pointed out in a companion paper in 1928. Also, it can be readily demonstrated with transparent glass that cracked shells, having visible cracks undetectable by power loss measurements, will satisfactorily withstand either 60-cycle or continuous voltage for 5 minutes, and high frequency tests prolonged for 5 minutes, or to thermal failure of the material in question. An oil puncture test, too, fails to detect such cracks. In Mr. Lapp's paper, paragraph 1, he notes most failures of porcelain insulators are caused by lack of internal soundness, corroborating our experience. Have the authors had similar experience in their tests of porcelain or any indication that service failures are the ultimate result of such initial conditions?

These 2 aforementioned facts excite valid question of the suitability of service records as criterions of design because these service records, consciously or not, assume all insulators to be in perfect condition when installed. Such may or may not have been the case. The failures in service may have been due either to design or manufacture, although to the operating engineer the results of the failure are the same.

The authors note on p. 939 the use of test sticks for field testing. Presumably the data of Table IV and Fig. 2 were obtained from the results of testing with these sticks. Are failures so detected the only ones summarized, and if so, are failures due to other causes such as arcing or mechanical damage believed inconsequential?

There is one factor which is pertinent to this paper but which I do not find stated. That factor is the basis for the implication that inequalities in performance denote corresponding inequalities of merit. Were the units compared all of the same mechanical ultimate rating? Were these ratings assigned by the manufacturer? Were all units intended for the same mechanical loadings in service?

In the second paragraph it is stated that although vast improvements in product have been made, "it does not follow that a uniformity of the product has been reached that will assure satisfactory operating reliability." In 1930 the National Electric Light Association insulator research subcommittee in its preliminary report recommends the expenditure of $15,000 to initiate research of far reaching effect on the suspension type porcelain insulator. The concluding remarks of the authors' paper is that a life expectancy of 50 years is not beyond realization. I would like to ask the authors if this is their present expectancy of suspension insulator life.

Philip Sporn: With regard to Mr. Kates's question on the use of test sticks, the data in Table IV and Fig. 2 were obtained from tests with insulator test sticks, and failures due to arcing or mechanical damage are not summarized. The latter are certainly not inconsequential but the authors do not believe that such failures should be included as they have no bearing on the depreciation of insulators as a whole nor on their life expectancy.

Mr. Kates inquires as to whether the insulators compared were all of the same mechanical strength rating, whether the ratings were assigned by the manufacturer, and if all the units were intended for the same mechanical loadings in service. It is true that some of the insulators tested were of a higher mechanical strength rating than others but most were in the same strength classification. As stated in the paper, the tests were originally designed for insulators to be used on the 132-kv system. The authors do not believe that the loadings are excessive for even the lightest of the units that were under consideration, and in all cases were under the strength ratings as given by the manufacturers. As a matter of record, the higher rated strength units did not always test out the best and in one case the lower strength units of one manufacturer tested better than the higher strength units produced by the same manufacturer.

With regard to the concluding question of Mr. Kates, the authors believe that a 50-year life may be possible with some of the units being manufactured today although they admit that available data are limited.

The authors are pleased to note that some members agree with them that present A.I.E.E. standard tests for suspension insulators could be broadened to advantage to include additional tests which would be of considerable assistance in detecting insulators of inferior design and manufacture.

Radio Influence Insulator Characteristics

Discussion and author's closure of a paper by G. I. Gilchrest published in the June 1934 issue, p. 899–902, and presented for oral discussion at the insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

W. A. Hillebrand: The paper describes an interesting and important method of rendering a porcelain surface conducting and at the same time eliminating the undesirable fringe effect at the edge of the coating. Since the copper oxide used in the glaze can be reduced to metallic copper by the application of an acid of sufficient strength, it is important to know if the glaze will meet the conventional specification that it must be unaffected by acids in the concentrations found in the atmosphere of industrial communities.

All of the radio influence tests were evidently made upon clean and dry insulators in which the voltage distribution is entirely determined by the capacitances of the several insulator shells. When wet, or partially wet, and dirty, surface resistance controls the distribution of voltage, and in an erratic manner. Under these conditions the radio influence characteristics would unquestionably be quite different. This is particularly true of suspension insulators, which, in a gathering fog, may have an appreciable radio influence at voltages as low as 25 per cent of those reported in the table on p. 902.

In coastal and other regions hygroscopic salts such as magnesium chloride from sea water, for instance, which may be present in the atmosphere, will collect on insulator surfaces and modify their behavior to an important degree. Above 60 per cent relative humidity these salts may absorb enough water from the air to reduce the surface resistance to less than 1 per cent of its value when clean. Leakage current is correspondingly increased and the fall of potential caused by this current in passing from tie wire to insulator surface may cause breakdown of the air at this point and corresponding radio influence at a much lower voltage than when the insulator is dry and clean. In one section of the country, the influence level, based upon field measurements, seems to be several times as high when the insulators are dirty as it is after they have been washed by winter rains. This is a condition which apparently no coating as yet proposed can remedy.

The statement that for field application an asphalt emulsion offers the best solution is questioned on the ground of probable carbonization and destruction of this coating by leakage currents in wet weather. A conducting paint that, from several years' experience, seems to be but little affected by weather should give a longer life.

The voltages for minimum radio influence of similar insulators as reported respectively by Mr. Gilchrest and by Mr. Lapp seem to be inconsistent and to further emphasize the necessity for a standard test arrangement for determining the point of breakdown at which the influence becomes apparent.

K. A. Hawley: The de cription given by Mr. Gilchrest of the circuit for determining radio frequency influence has, we believe, been recognized by certain of the joint committees on acoustical relations. The data given by Mr. Gilchrest upon the circuit with varying constants is of real value and may become the basis for standardizing such tests. The results obtained by placing copper coatings upon the tops of pin type insulators appear to be satisfactory providing the coating is permanent. The results obtained are much like those which have been obtained by our company by the use of proper gaps on the insulators and which have been described in ELECTRICAL ENGINEERING.

G. I. Gilchrest: Mr. Hillebrand refers in his discussion to the possible effect of acids found in the atmosphere of industrial communities. Insulators having the copper oxide glaze treatment have been in service under various industrial conditions during the past 3 years. Also, accelerated life tests have been made during our research investigation of the permanency of the coating.

The surface tends to remain copper oxide excepting under acids sufficiently strong to reduce the copper oxide to copper. The developed copper surface must be tinned in order to protect it from the atmosphere, which would normally return the copper to copper oxide. We find the conductivity of the copper oxide glaze is practically the same after 2 or 3 years in the atmosphere of industrial communities as the regular porcelain glaze.

Mr. Hillebrand questions the performance of insulators treated with copper oxide glaze under fog conditions. Many tests have been made with the copper oxide glaze insulators subjected to salt sprays, dust sprays, atomized water sprays, etc., under laboratory conditions. The performance of the insulators treated with copper oxide glaze is substantially the same as the performance of standard insulators with respect to wet and dry flashovers. The copper oxide surface performs the same as the standard glaze surface. The copper oxide glaze treatment is not proposed to eliminate the effect of fog conditions but will definitely improve the performance of the pin type insulator under conditions of dirt and moisture accumulation on the surface, up to the point where static streamers begin to discharge over the insulator surface. Where fog conditions are sufficiently severe to warrant additional leakage surface, special shape of sheds, etc., the copper oxide glaze may also be applied to advantage.

Mr. Hillebrand indicates in his discussion that he believes that a conducting paint should give a longer life than an asphalt emulsion. Doubtless Mr. Hillebrand's assumption is correct. However, in our experimentation, we have found that the metallic painting is not satisfactory because it leaves a metallic edge from which discharges take place. These discharges offset to quite an extent the advantages of the metallic glaze which eliminates the discharges from tie and line wire to porcelain. As explained in the article, the copper oxide glaze treatment entirely eliminates the discharge from the conducting surface because of the grading affect that exists between the metallic surface and the undeveloped copper oxide surface. The asphalt emulsion eliminates the static discharge from line and tie wire to the porcelain and does not give a metallic edge that must be present with metallic painting.

Recent Developments in Suspension Insulators

Discussion and author's closure of a paper by G. M. Barrow published in the June 1934 issue, p. 867–70, and presented for oral discussion at the insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

W. A. Hillebrand: Mr. Barrow's paper is a plea for the one-step bolt or button head pin, the relative merits of which time alone can answer. With his insistence upon the importance of resilience and recovery in the center pin I heartily agree. With the statement that static time loading is the most important test of an insulator I cannot concur. Carried to its ultimate conclusion, it will probably result in too heavy caps and doughnutting. The test is of value only in its relation to the performance of the insulator in other ways, particularly when subjected to extremes of temperature.

The statement that the greatest hazard is where the porcelain envelopes the metal is also open to question, because cap contraction on the practically unloaded insulator in suspension position may, in some instances, be of greater importance. On p. 868 Mr. Barrow states: "It is of interest to note that in experimental assemblies where much slippage of the cap occurred, the bell of the cap was ruptured by splitting; the porcelain was not impaired." May I ask of what material these experimental caps were made? Also, is it probable that caps made of other materials and within practicable manufacturing limits would have acted similarly?

A. E. Davison: The author is to be congratulated upon having made available to engineers representing consumer organizations data regarding the fatigue limits of materials and equipment in which the writer is interested. He also is to be congratulated upon having modernized the testing of equipment associated with transmission line conductors wherein fatigue and failure resulting from vibration are making themselves more and more evident to those responsible for the maintenance of transmission lines having higher mechanical tensions.

Mr. Barrow says: "The results of these (vibration) tests indicate that the porcelain is less susceptible to vibration than the connecting hardware. They also confirm research findings that the fatigue strength of the porcelain is at least 80 per cent of the static strength in comparison to approximately 60 per cent and less for metal."

Data of this nature are desired by consumer engineers and it is hoped that representatives of other supply organizations will either confirm Mr. Barrow's statement regarding conductor materials or supply authoritative data regarding "endurance limits" of the materials and of the fabricated

equipment which they themselves advocate.

Time-load tests are briefly referred to by the author. No reference is made by the author to either "creep" or permanent stretch.

K. A. Hawley: Many of the things pointed out by Mr. Barrow are confirmed in my 1931 paper and by the one in the current issue. The tension and shear type design with its multiple ridges inside of the cap has fully been commented on in the first paper for these upper ridges carry most of the load delivering it well above the keystone of the arch. This insulator, therefore, must not be confused with the multiple stepped insulators described in my current paper.

The objections that we see to the single step bolt need not be repeated for they are also fully covered. A comparison of this design as disclosed in patent 1,822,485 filed in 1924 will be of real interest for in that was fully contemplated the effect of curved steps upon the insulator bolt.

G. M. Barrow: The discussions on the insulator symposium are interesting as they indicate a careful analysis of the subject from several different points of view. A number of references are made relating generally to the present A.I.E.E. standard test specification and specifically to several items of my paper on which I wish to comment. My paper naturally was restricted to insulators of our own design and manufacture. Figure 1*a* of the paper illustrates a tension and shear design, several million of which are in use and giving very good service. Figure 1*b* illustrates a later type of insulator which has been in production for 5 years and is commonly known in the trade as the compression type design. The remarkable improvement in sustained time-load performance of this latter design is given in Table I.

The analogy to the keystone arch and buttress principles of construction for this compression type design has some basis on facts. To illustrate, by cutting slots in the bell of the cap this buttress support is so weakened that the porcelain is permitted to yield sufficiently to cause rupture at a load of approximately 8,000 lb. The normal breaking load is 15,000 lb. Again, by reenforcing the bell of the cap by shrinking a metal ring on to it, and minimizing yield in the porcelain, the breaking load is increased to approximately 20,000 lb. Tensile and shear stresses cannot be eliminated entirely but they are reduced to such a degree that the total load carried for a long period of time is greatly increased.

Such reenforcing of the cap adds considerable weight and is not justified economically. It may also produce shear stresses that would cause the "doughnutting" Mr. Hillebrand mentions. The cap on the compression type design is of the approximate thickness of the former shear type. The caps that split without impairing the porcelain were made of malleable iron. Measurements of cap yield under insulator load have been made on both malleable iron and forged steel caps, and the results demonstrate that the caps approach the elastic limit at high loads when slipping occurs. Experience with the shear type design and these data indicate that the cap on the compression type design need not introduce any new hazard. Having equalized the other factors, the design of the pin with respect to the stress distribution and behavior under load and temperature changes remains the important factor in the assembly.

I believe Mr. Hillebrand's comment on the importance I attach to static time loading, that "carried to its ultimate conclusion it will probably result in too heavy caps and doughnutting," points out one of the features which would limit such a conclusion and which would force the use of a less heavy cap to obtain the optimum on time-load. This point illustrates the balance of the several factors in the assembly relating to stress from static loading and thermal changes that is required to get the most out of it and maintain the mechanical integrity of the porcelain.

The time-load test with or without thermal changes undoubtedly offers a good criterion of comparison, as may be seen from Mr. Sorensen's paper on such tests in the August issue of ELECTRICAL ENGINEERING, p. 1221–4. A design that does not show a satisfactory performance on a test such as his cannot be expected to show to better advantage when also subjected to combined load and thermal changes. Conversely, a design that shows the best performance on static load test without thermal changes may not necessarily show the best performance under combined load and thermal stresses.

Many of these new developments originated since the A.I.E.E. Standards No. 41 on insulators were issued and last revised, and no doubt some recognition and adoption of them will be taken in the next revision. After the time-load performance over a period of 2 years or longer is determined, it might be checked by a test of 1 or 2 weeks if proper differential in load is made. A time-load test of such short duration may disclose a comparatively poor design but I doubt that it would be sufficient to determine the best one. The time-load test through several seasons of normal weather and temperature changes may, I believe, be taken as an indication that the compression type design will take care of thermal changes, considered on the basis that the shear type design did not under similar load and thermal changes. The A.I.E.E. 20-minute immersion cycle thermal test over a range of 166 deg F is largely in the nature of a heat shock test on the assembly and gives practically no information on the ability of a design to withstand a 48-hour cycle time-load thermal test over a range of 140 deg F, with a lower temperature limit. It would not be expected, however, that a design that does not meet the A.I.E.E. 20-minute test would pass the 48-hour time-load test. Electrical failure on time-load test of otherwise dielectrically sound porcelain I consider to be the confirmation of a mechanical fracture. The 3-second axial pull at 40 per cent of rated strength (A.I.E.E. Standards 41-301) is considered a check only on the workmanship of assembly and not as a test on the soundness of the dielectric or the ability of the design to withstand stress. Mr. Kates mentions the use of a 5-minute test on glass insulators instead of the 3-second test as a better indication of satisfactory uniform product. This indicates questionable workmanship or susceptibility to injury in assembly and weakness in combined mechanical-electrical strength. This latter is a design characteristic, the check on which should not be combined with factory routine proof tests.

A New Porcelain Post Insulator

Discussion and author's closure of a paper by G. W. Lapp published in the June 1934 issue, p. 922–5, and presented for oral discussion at the Insulator session of the summer convention, Hot Springs, Va., June 28, 1934.

W. A. Hillebrand: Mr. Lapp has developed an insulator which, under most conditions, will have much less radio influence at rated voltage than will the conventional pin type designs. The emphasis on low electrostatic capacity is believed to be sound and in many situations the employment of an insulator utilizing this principle may be the only practicable solution.

However, the reliability of the conventional single and multipart designs has been established through 40 years of service and they should not be discarded until the new insulator, in sufficient quantity, has demonstrated its ability to meet the objections which experience and reason will raise.

The insulator is not new, having been in use as a station post or pillar for over 20 years. In limited quantities it has been used for outdoor service, but became discredited due to the tendency for the head to crack off from the heat of a power arcover. Although insulators of this type inherently develop great strength as a cantilever, their resistance to mechanical shock is low because of rigidity and complete lack of resilience. Its ability to withstand the shock of an automobile colliding with the pole is yet to be determined.

Accordingly, the great danger with this insulator is that of dropping the conductor in case the insulator is broken, although this is to some extent minimized by the fact that the conductor is carried above and not below the cross arm. This danger is aggravated by the fact that the particular usefulness of this insulator is on lines running along highways and through cities, towns, and villages.

Another source of breakage is in the contraction of the metal base upon the porcelain in cold weather. Such insulators have not been free from internal sweating in the past and condensation on the inner wall increases the danger of puncture by lightning. The insulator has a low wet flashover voltage. When a dirty unit of this type is wetted by a fog or drizzle the head will tend to dry more rapidly under the leakage losses, with complete voltage unbalance and probable radio interference at this time.

A few scattered comments on statements made by the author follow. The statement is made that failures of pin type insulators have been due to lack of internal soundness. We have generally attributed them to poor design, poor assembly, or to a combination of the 2. It is inferred that the shells of multipart insulators will carry

cracks, once started, into the body of the porcelain. Judging from observation of many insulators that have cracked in service, aging cracks start in the inner part of the porcelain and work outward, rarely progressing in the opposite direction, unless caused by a blow. The shells that are so severely criticized are valuable for many reasons. They furnish wet and dry flashover resistance, leakage resistance, and act in a valuable way as radiating fins that conduct heat to and from the center of the insulator, tending to equalize temperatures throughout. The annular flanges on the new post type insulator do not add strength to it as a cantilever in the direction where strength is most needed.

J. C. Rah: Referring to this paper, it is interesting to note that the post type of insulator is coming into prominence again after having been practically abandoned for many years. I believe that an insulator of this type has greater possibilities in its field than any other type, as it can be adapted more easily for various purposes. Because of the flexibility of its design, which makes it easier to treat theoretically and to produce commercially, such an insulator may approach more closely to the electrical and mechanical characteristics of an ideal insulator. That an insulator of this type can be more universally used is shown by the example of bushings designed in a somewhat similar manner in which proper arrangement of capacities can be obtained more readily than with any other type using few and large petticoats.

However, I would like to mention one point that the author makes on p. 925, at the end of the second paragraph, under the subtitle, "Electrical Characteristics," in which he says: "The internal air path is a region of negligible dielectric stress." From my experience I have found that one of the most important reasons why such a post type insulator has been practically abandoned during the past few years is that the dielectric stress in this internal region is of real importance. In a closed up air space inside of an insulator, ozone is generated under electric stress and eventually nitric acid is produced which, in one way or another, will cut down the useful life of the insulator assembly. In corroboration of this statement, there was a short notice in one of the issues of the *Electrical World* about 8 years ago, which reported a case of nitric acid damage to an air break switch that was mounted on post insulators of a type similar to that described in this paper.

May I suggest that, in order to get all the benefits from the advantages of this type of insulator, it would be advisable to fill up the internal space with an insulating material of a higher dielectric constant than air, and as near to the dielectric constant of porcelain as possible.

This insulator is an excellent example of how radio interference may be reduced in its effect by design only, without any additional remedial procedures.

R. W. Sorensen: The insulator described by Mr. Lapp in his paper has many desirable features, but its design suggests to me some undesirable ones; not the least of which is the difficulty of greatly reduced flashover voltage in foggy and rainy weather because of the closeness of the petticoats. That is, is there not a probability of a heavy flow of water down over the petticoats when they are so close together, such as to produce a fairly continuous stream which would be conducive to a low arcover voltage? I would therefore, like to have Mr. Lapp discuss this particular phase of his insulator.

K. A. Hawley: Mr. Lapp has endeavored to overcome radio interference trouble in pin type insulators by working in the opposite direction from other investigators such as Mr. G. I. Gilchrest in his current paper and by ourselves with capped insulators.

In decreasing the electrostatic flux he has tried to eliminate the cause of the trouble, while in shorting out air gaps we have stopped the trouble in a different way. Mr. Lapp has established a factor, L/CP, which gives the measure of flux concentration of the tie wire. This factor no doubt has some merit in comparing insulators such as shown in his article. However, it leads to absolutely wrong conclusions when comparing the coated top or insert type insulators

In determining the radio interference point they have used a radio set loosely coupled with the insulator under test, separating the antenna from the conductor by about 4 ft. Tests made in our laboratory indicate that separation even by this short distance will raise measurably the radio interference point. It would have been much better to have used a circuit like that described by Mr. Gilchrest.

The Lapp post type insulator with special recessed head appears very fragile and probably will be easily broken by hunters or by stone throwing.

G. W. Lapp: Dr. Sorensen inquired if there is a radio effect due to cascading water drops between corrugations of the porcelain post insulator. This is a pertinent question. Under some conditions there is a certain characteristic little banging sound from this cause distinct from the frying sound of ordinary corona or static. This sound is minimized in service by the fact that the sparklets between falling drops are shunted by the short wet surfaces between corrugations. Such wetting of the recessed surfaces is encouraged by the ready access of drifting fog or spattering of rain up under these relatively short petticoats. In several years actual experience with this type of closely spaced corrugations, interference of this character has not been reported.

Mr. Hillebrand, Mr. Hawley, and others discuss a number of points:

1. Sensitivity of receiver for laboratory tests may be neglected since radio effects on a dry insulator start at a critically sharp voltage value which is the minimum for initial effect and is identified as the point of initial corona.

2. Mechanical reliability has been established by shooting tests and by blows with hammers and falling weights. The corrugations do run around and although they add nothing to cantilever strength, they prevent a crushing blow from cracking the body of the insulator. Cantilever strength can be designed to specification. The problem of pinch-off at the base is taken care of by providing adequate distance and easy radius of curvature between the lip of the base and the first corrugation. There is not present an opportunity for concentration of impingement and shear comparable to the head of an ordinary switch type having a large radially rigid shell adjacent to a metallic lip.

3. In the statement that lack of "internal soundness" has caused most insulator failures, it is meant to include assembly of the insulator parts as well as the inherent quality of the parts themselves.

4. Low wet flashover does not seem to mean flashover in service. In fact this type of corrugated leakage path provides improved freedom from flashover under extreme conditions of dirt and moisture to such a degree that it brings into question the established criterion of wet flashover as an all important factor. Increased length of leakage path having characteristics of relatively uniform width and uniform wetness and dirtiness enables this insulator to discourage flashovers through the usual switching and impulse surges. The observation in the oral discussion of J. T. Lusignan that impulse flashover seems to be a function of leakage distance is confirmed to a degree by experience with this insulator as conditioned in actual service.

Mr. Rah brings up my statement that "The internal air path is a region of negligible dielectric stress," and mentions the formation of acid-forming ozone in the hollow space. This subject has been given careful consideration; not so much from the point of view of avoidance of puncture, but more especially to avoid that small degree of conductivity that might cause radio disturbance. The hole at the bottom is effectively plugged by a combination metal-core rubber-capped plug forced into the hole, followed by asphalt coating, and cement-backed at the time the metal base is cemented on. Before plugging the hole the air is scavenged out with a blast of carbon dioxide, thus eliminating moisture, nitrogen, and oxygen, all of which would be necessary to form nitric acid. This inert gas is confined under considerable pressure. The rubber plug is of very stable quality not in contact with oxygen, light, or active dielectric field. Since moisture is absent or of very low content in the inside atmosphere of the fire-clean porcelain hole it is expected that not even high resistance condensation will deposit on the inner wall. If the dew point is below freezing moisture conductivity will be absent or negligible. To give full assurance against puncture and indicate performance, impulse flashover tests were applied to a 66-kv porcelain post insulator. Tests were made dry, wet, and lastly wetted outside and inside with tap water of low resistance. Many impulse shots showed no puncture, no decrease in flashover voltage wet, and no tendency for the spark to follow the outside leakage surface of the insulator even when the hole was thoroughly wetted. The only case of blow-up we know about on switches was due to deterioration of poorly applied plugs in the top of tubular posts. It should be understood that these posts have solid porcelain closed tops.

The statement that the upper end of the hole is a region of negligible dielectric stress is indicated by the fact that the concentration of stress under the tie wire is not sufficient to cause corona at duty voltage, and the diffused gradient inside the hole is of course much less than the gradient at contact outside. There is no visible corona at the top of the hole at flashover voltage as shown by looking through an open hole in the base in the dark.

If the hole were filled with material of higher dielectric constant as Mr. Rah suggests, it would increase the capacitance of the insulator and also create a problem of volume expansion and contraction which happily does not exist.

News

Of Institute and Related Activities

The Institute Budget for 1934–35

EARLY in the present year Mr. E. B. Meyer, then chairman of the finance committee of the Institute, furnished to the membership in the columns of ELECTRICAL ENGINEERING (March 1934, p. 375–81) a presentation of facts and figures relating to the annual budget. While it has always been the practice to include in the annual report of the board of directors to the membership a detailed statement of financial operations for the corresponding fiscal year, it was felt that the exigency of the times warranted a more thorough explanation of some of the problems as they have been presented to the board of directors, together with a brief outline of the steps toward solution, as taken by the finance committee.

Almost concurrently, President J. Allen Johnson, then vice president of the Institute, delivered an address on the subject "An Insight Into the Workings of the Institute" before a meeting of the North Eastern District held in Worcester, Mass., May 16–18, 1934. Essentially the full text of this address was printed in the July 1934 issue of ELECTRICAL ENGINEERING, p. 1039–46.

An opportunity has thus been afforded to the membership to become better informed regarding the organization and activities of the Institute and the nature and relative importance of the various items that make up the annual budget. With the purpose of showing the extent of study and consideration given to the subject, the article on the budget included particularly an explanation of the expenditures for those activities considered by the board of directors and the finance committee to be of major interest to the greatest number of members. For comparison purposes, and also to show the curtailments effected during the period to bring expenditures within the limitations of expected income, the article contained a statement of expenditures for the appropriation year ending September 30, 1931, and also a statement of the anticipated expenses for the year ending September 30, 1934.

The finance committee feels that the membership will now be equally interested to receive a report of the actual income and expenditures for the appropriation year which ended September 30, 1934, together with a statement of the estimates for the present year, with comments on the expense budget to indicate any material departure from the policies already explained by Mr. Meyer and in effect during the past year. Figures for the last appropriation year and estimates for the present year are given in Table I.

Publications

ELECTRICAL ENGINEERING. The unified publication plan which has been in effect since January 1934 has enabled the Institute to supply its members and enrolled Students with virtually twice the amount of technical material formerly published and at a greatly reduced unit cost. The budget provides for the publication of the same amount of technical papers and discussions as was contemplated in the adoption of the 1933–34 budget and also takes into consideration a moderate increase in printers' charges which becomes effective in January 1935.

TRANSACTIONS. Upon publication of the December 1934 issue of ELECTRICAL ENGINEERING, approximately 1,900 pages of technical material will become available for publication of the 1934 annual volume of TRANSACTIONS, to be distributed to members and others who have already authorized the subscription charge for this volume. The budget covers not only the expense involved for the completion and distribution of the book, but also provides an allowance for printing the text pages of the January to September issues of ELECTRICAL ENGINEERING which will be included in the succeeding volume.

YEAR BOOK. In the effort to allocate as much as possible of the expected income to those activities which are of the greatest interest and benefit to the membership, it was decided to omit any appropriation for the publication of another edition of the Institute YEAR BOOK in 1935; the necessary appropriation is included, however, to maintain the current records. A good supply of copies of the 1934 YEAR BOOK remains on hand, for distribution to members upon request.

Institute Meetings

The appropriation for meetings to be held during 1934–35 has been estimated to conform with the expenses of the past year for the 3 annual national conventions, and also to include an allowance for meetings in Districts Nos. 5 and 7, provided for in the 1935 meetings schedule.

Institute Sections

Practically all of the Sections of the Institute accepted the invitation of the board of directors to make voluntary reductions of 20 per cent in the maximum amounts of their appropriations for the year ending September 30, 1934, as determined under the by-laws. It has been the desire at all times to support Institute Sections as liberally as circumstances would permit, and although there have been no evidences that the work of Sections on the whole has been seriously handicapped by the reduced appropriations (to the contrary, some Sections have voluntarily refunded an additional portion of their appropriations, and others show unexpended balances), the board of directors is inviting the Sections this year to accept voluntary reductions of 10 per cent, rather than 20 per cent, of the maximum annual appropriations, and thus contribute to the effort to allocate equitably the anticipated income to the various activities planned for the year.

Institute Branches

To allow for an increase in the expenses of Branch meetings, as indicated by expenses reported for last year, the appropriation for this purpose has been slightly increased. The appropriation for traveling expenses incidental to the District conferences on Student activities has been maintained at the same amount as last year, an increase in the number of such conferences being anticipated. In addition to the allowance for representation by the counselor and the incoming Student chairman of each Branch within the District (alternates not authorized) an allowance has now been made for the traveling expenses of the District secretary to the annual District conference. The appropriation again provides for a combined conference in Districts 8 and 9, and makes the usual allowance for traveling expenses for the conference of counselor-delegates to the 1935 summer convention.

Administration

The appropriation of the administrative department absorbs the full salary of the national secretary and the office manager, and 41 per cent of the total of salaries paid to 20 other members of headquarters' staff (the smallest staff per 1,000 members of any of the Founder Societies). At the recommendation of the finance committee, the board of directors voted to restore a portion of the headquarters' staff salary reduction effected in June 1932, to the extent of 5 per cent of the salaries now being paid.

Other items in this appropriation are provided for to the same extent as last year: expenditures for postage, printing, telephone service, telegrams, insurance, cartage of mail, express shipments, engrossing diplomas, check tax, bank collection charges, miscellaneous office supplies, and headquarters' expenses.

Traveling Expenses—General

Under this classification are shown the traveling expense allowances for the meetings of the board of directors and executive committee, the annual meeting of the national nominating committee, the visits of the vice presidents to the Branches and Sections within their Districts, and the annual meetings of the geographical District executive committees. For the latter

meeting the appropriation provides for the allowance for traveling expenses for the vice president, the District secretary, either the chairman or the secretary of each Section within a District, and (in accordance with recent approval by the board of directors) the chairman of the District committee on Student activities.

Other Activities

The remainder of the budget comprises those items for which further explanations, beyond the statement of the appropriation or activity, the amount expended last year, and the estimate for the present year, probably are unnecessary. Mention should be made, however, that the appropriation for American Engineering Council has been increased by $3,000 (appropriation for calendar year 1934 being $6,000) with the expectation that the other member societies will proportionately increase the amount of financial support for the year beginning January 1, 1935. Similarly, the board of directors authorized an additional allowance of $1,000 in the appropriation of Engineering Societies Employment Service for the particular purpose of sharing, with the other Founder Societies, the estimated salary and clerical expenses for a representative of the employment service in Washington. The proposed increases in these appropriations are, therefore, conditional upon approval by the other societies of their respective shares of the total appropriations estimated.

It is the intention of the finance committee to report more in detail regarding the various aspects of these and other appropriations in the columns of future issues of Electrical Engineering.

In formulating the expense budget for the present year, the board of directors and finance committee have endeavored to give the various phases of Institute life the degree of emphasis which each deserves. The estimate of income to be received during the year, of which the major portion is derived from membership dues, is predicated upon a continuance by each member of his active interest in the general and financial welfare of the Institute, as evidenced in the results of budget operations for the appropriation year which ended September 30, 1934. In this connection it would seem most appropriate to quote the closing remarks of J. Allen Johnson on the occasion of his address at Worcester:

> ".....the Institute seems to reveal that its aims and activities are rooted in a spirit of mutual helpfulness to each other and disinterested service to humanity. Its officers, its headquarters staff, and those who work on its committees all share in that spirit. The principal obligation of membership, it seems, is to cultivate that spirit, the possession of which, after all is said and done, yields the most lasting satisfactions of the professional life."

Table I—Institute Expenses and Income for Year Ending September 30, 1934, and Budget for Year Ending September 30, 1935

	Actual Expenses and Income Year Ending 9/30/34	Budget for Year Ending 9/30/35
Expenses		
Publications		
Text matter	$70,379.76	$68,650.00
Advertising section	10,671.64	10,625.00
Year Book	6,008.26	2,450.00
Institute meetings	9,399.09	10,900.00
Institute Sections		
Appropriations	16,443.77	18,132.00
Trav. exp. convention delegates	2,962.35	3,100.00
Other expenses	4,691.64	5,000.00
Institute Branches		
Meetings expenses	967.15	1,000.00
Trav. exp. District conferences on Student activities	2,797.16	4,550.00
Other expenses	1,363.17	1,525.00
Administration		
Headquarters salaries	29,714.18	31,250.00
General (postage, printing supplies, etc.)	11,058.32	11,500.00
Membership committee	6,055.78	6,850.00
Traveling exp. general		
Board of directors	2,369.90	3,250.00
Geographical Dists.	1,355.42	1,800.00
Nat. nominating com.	1,207.90	1,250.00
United Engg. Trustees		
Building assessment	2,966.40	3,000.00
Engineering Societies Library	7,345.38	8,566.00
Engineering Societies Employment Service	2,954.79	*3,700.00
American Engg. Council	7,625.00	*9,000.00
Standards committee	4,655.00	6,200.00
Other committees and miscellaneous expenses	11,705.92	10,302.00
	$214,697.98	
Excess of income over disbursements	19,831.22	
Total	$234,529.20	$222,600.00
Income		
Dues	$168,398.60	$155,750.00
Students' fees	8,604.50	8,500.00
Entrance fees	3,654.00	3,500.00
Transfer fees	875.00	800.00
Advertising	22,842.85	20,000.00
Elec. Engg.—non-member subscriptions	11,278.37	11,000.00
Trans. subscriptions	4,015.82	4,500.00
Miscellaneous sales	5,681.83	5,000.00
Revenue from badges	1,184.40	1,250.00
Interest on securities	7,993.83	8,000.00
Excess of estimated expenses over est. income		*4,300.00
Total	$234,529.20	$222,600.00

* As explained in notes, appropriation increases totaling $4,000.00 were authorized by board of directors conditional upon corresponding increases in the financial support of joint activities by the other Founder Societies concerned.

The Institute's 1935 Winter Convention

The annual A.I.E.E. winter convention will be held in the Engineering Societies Building, 33 West 39th St., New York, N. Y., January 22–25, 1935. The scheme inaugurated last winter of starting the convention on a Tuesday and limiting it to 4 days' duration will be followed again this winter. Tentative plans for the program which are developing rapidly indicate that the first 3 days will be taken up with a number of technical sessions of unusual interest, important committee meetings, and social events, while the fourth day will be devoted exclusively to inspection trips. Details as soon as they become available will be announced in subsequent issues of Electrical Engineering.

A tentative technical program consisting of 12 sessions has been planned to meet the diversified interests of the membership. Some of the sessions are general in scope so as to be of interest to a large number of members while others are more highly technical to meet the needs of specialists. Two symposiums on electronics will treat some of the general developments and applications in this rapidly expanding field of the electrical industry. Another symposium on noise will tell what is being done in the way of measurement and standardization to bring about more quiet operation of electrical equipment. In addition to these 3 symposiums there will be 9 other sessions on subjects as follows: illumination, general overhead line problems, power cables, communication, electric welding, electrical machinery (3 sessions), and education.

Some of the papers for these sessions have already been published, beginning with those for the illumination session which appeared in the August 1934 issue of Electrical Engineering. Other papers have been or will be published in issues subsequent to the August issue on up to and including the January issue. This should make possible a careful advance study of the papers which are to be presented.

General Committee Appointed

The 1935 winter Convention committee is constituted as follows: *Chairman*, C. R. Jones (A'16, M'30), T. F. Barton (A'12, F'30), C. R. Beardsley (A'08, F'30) C. O. Bickelhaupt (M'22, F'28), R. N. Conwell (A'15, F'31), A. F. Dixon (A'14, F'26), H. S. Osborne (A'10, F'21), D. M. Simmons (A'22, F'28), W. R. Smith (M'18, F'30), George Sutherland (A'20, F'27), and R. H. Tapscott (A'18, F'29). The following have been appointed as chairmen of subcommittees: C. S. Purnell (A'29), *dinner-dance;* S. A. Smith, Jr. (A'24, M'31), *inspection trips;* and George Sutherland (A'20, F'27), *smoker*. Other committee chairmen and the complete committees are now being appointed.

General Power Applications Committee Appointed

A complete list of the Institute's officers and committees for 1934–35 was contained in the September 1934 issue of Electrical Engineering, p. 1332–5, with the exception that the members of the technical committee on general power applications were not included, as the committee at that time had not been appointed. Announcement of the membership of this remaining committee was recently made, and is presented below.

The listing of this committee is arranged in the same style as the listing in the September issue, so that all who so desire may make the previous list complete by cutting out and pasting the following one on it.

Power Applications, General

Mark R. Woodward, Chm., Babcock & Wilcox Co., 20 North Wacker Drive, Chicago, Ill.

E. A. Armstrong	H. A. Maxfield
L. M. Dawes	F. J. Meyer
C. W. Drake	John Morse
J. F. Fairman	D. M. Petty
J. F. Gaskill	H. W. Rogers
A. E. Knowlton	L. M. Shadgett

A.I.E.E. Directors Meet at Institute Headquarters

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute headquarters, New York, N. Y., October 19, 1934.

Present: *President*—J. Allen Johnson, Buffalo, N. Y. *Past-Presidents*—J. B. Whitehead, Baltimore, Md.; and H. P. Charlesworth, New York, N. Y. *Vice Presidents*—F. M. Craft, Atlanta, Ga.; A. H. Hull, Toronto Ont.; F. J. Meyer, Oklahoma City, Okla.; G. G. Post, Milwaukee, Wis.; R. W. Sorensen, Pasadena, Calif.; R. H. Tapscott, New York, N. Y.; W. H. Timbie, Cambridge, Mass.; and A. M. Wilson, Cincinnati, Ohio. *Directors*—L. W. Chubb, East Pittsburgh, Pa.; F. M. Farmer, New York, N. Y.; N. E. Funk, Philadelphia, Pa.; H. B. Gear, Chicago, Ill.; P. B. Juhnke, Chicago, Ill.; G. A. Kositzky, Cleveland, Ohio; Everett S. Lee, Schenectady, N. Y.; A. H. Lovell, Ann Arbor, Mich.; A. C. Stevens, Schenectady, N. Y.; and H. R. Woodrow, Brooklyn, N. Y. *National Treasurer*—W. I. Slichter, New York, N. Y. *National Secretary*—H. H. Henline, New York, N. Y.

Action of the executive committee on September 24, 1934, on applications for admission to membership, transfer, and Student enrollment, as follows, was reported and confirmed: One applicant transferred to the grade of Fellow; 4 applicants elected and 16 transferred to the grade of Member; 46 elected to the grade of Associate; 16 Students enrolled.

Reports were presented and approved of meetings of the board of examiners held September 19 and October 17, 1934. Upon recommendation of the board of examiners, the following actions were taken: 2 applicants were transferred to the grade of Member; 13 applicants were elected to the grade of Member and 31 to the grade of Associate as of November 1, 1934; 296 Students were enrolled.

Approval was given to recommendations of the standards committee, as follows: (1) That the "Test Code for Transformers," developed by the committee on electrical machinery and now in revised form, be submitted to the American Standards Association for consideration by the sectional committee on transformers; and (2) that the Institute withdraw from sponsorship of the sectional committee on radio, leaving the committee under the single sponsorship of the Institute of Radio Engineers.

Five members of the board of directors were selected to serve as members of the national nominating committee, as follows: H. P. Charlesworth, Everett S. Lee, A. C. Stevens, J. B. Whitehead, and H. R. Woodrow.

The finance committee reported monthly disbursements amounting to $14,248.97 for September and $20,625.67 for October. Report approved.

A budget for the appropriation year beginning October 1, 1934, submitted by the finance committee, was adopted.

Institute representatives and alternates were appointed as follows: G. L. Knight reappointed to the board of trustees, United Engineering Trustees, Inc., for the 3-year term beginning in January 1935; E. L. Moreland appointed a representative on the standards council of the American Standards Association for the 3-year term beginning January 1, 1935, and H. S. Osborne and E. B. Paxton reappointed alternates for the year 1935.

The Mershon tennis trophy having been permanently won at the 1934 summer convention, the board accepted, with an expression of appreciation, an offer of Past-President Ralph D. Mershon to donate a permanent tennis trophy to remain in the possession of the Institute, the name of the winner of the tennis tournament each year to be engraved thereon.

The Board authorized the coöperation of the Institute with American Engineering Council and other engineering societies in the proposed census of engineers to be taken by the bureau of labor statistics, Department of Labor.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

Future AIEE Meetings

Winter Convention,
New York, N. Y., Jan. 22–25, 1935

South West District Meeting,
Oklahoma City, Okla., Apr. 24–26, 1935

Summer Convention,
Ithaca, N. Y., June 24–28, 1935

Pacific Coast Convention,
Los Angeles vicinity, Fall 1935

Great Lakes District Meeting,
Indianapolis—Lafayette Section territory (Date to be determined)

November 15 Last Date for Suggesting Nominations

The national nominating committee of the A.I.E.E. will meet between November 15 and December 15, 1934, for the purpose of nominating Institute national officers to be voted upon in the spring of 1935. The articles from the constitution and by-laws regarding the procedure of the national nominating committee and the method of submitting suggestions to it were contained in ELECTRICAL ENGINEERING for October 1934, p. 1425; this article also called attention to the fact that members are invited to suggest nominations up to November 15, 1934. For those members who may not have seen the previous article, this invitation is repeated here. To be available for the consideration of the committee all such suggestions must be received by the secretary of the committee at Institute headquarters, New York, N. Y., not later than November 15, 1934.

INDEPENDENT NOMINATIONS

The nominations as made by the national nominating committee are required by the by-laws to be published in the January issue of ELECTRICAL ENGINEERING or otherwise mailed to the Institute's membership during the month of January. Attention of the membership is hereby called to the fact that additional nominations may be made independent of those of the national nominating committee as late as February 15. The following provisions quoted from the constitution and by-laws govern such independent nominations:

Constitution

Sec. 31. Independent nominations may be made by a petition of 25 or more members sent to the national secretary when and as provided in the by-laws; such petitions for the nomination of vice presidents shall be signed only by members within the district concerned.

By-laws

Sec. 23. Petitions proposing the names of candidates as independent nominations for the various offices to be filled at the ensuing election, in accordance with Article VI, section 31 of the constitution must be received by the secretary of the national nominating committee not later than February 15 of each year, to be placed before that committee for the inclusion in the ballot of such candidates as are eligible.

On the ballot prepared by the national nominating

Membership—

Mr. Institute Member:

The membership committee has set for itself the bogey of obtaining more applications each month than in the corresponding month of the preceding year. Your helpfulness in sending in the names of persons who, you feel, should be invited to join the Institute is making the attainment of this bogey possible. If you have not yet sent in a name to the chairman of your Section membership committee, will you not do so promptly?

Very truly yours,

Everett S. Lee

Chairman National Membership Committee

committee in accordance with Article VI of the constitution and sent by the national secretary to all qualified voters during the first week in March of each year, the names of the candidates shall be grouped alphabetically under the name of the office for which each is a candidate.

Suggestions for Research Projects

With the object of stimulating interest in research work, the committee on research of the Institute has collected from electrical engineers in the industry suggestions for research projects suitable for advanced or graduate students and others in the engineering schools who are desirous of undertaking some kind of research work in the electrical engineering field.

A first list of over 100 such research suggestions in 12 branches of electrical engineering has been assembled. A widely varying range of experimental facilities is involved, from the simplest equipment found in any electrical laboratory to highly special facilities which would be available only in a very comprehensively equipped laboratory.

Copies of this list in mimeographed form may be obtained by any member of the teaching staff of an engineering school by merely addressing a request for a copy (or copies) to the committee on research at Institute headquarters, 33 W. 39th Street, New York, N. Y.

"Science Series" Reprints May Be Made Available

The special "science series for engineers" which has been appearing in the pages of ELECTRICAL ENGINEERING during the past year, is now nearing completion. This series consists of a number of articles, each on one of the important fields of present-day science, and each prepared by an authority in the particular field discussed.

If there is sufficient demand, all the articles in this science series will be combined in a substantially-bound booklet some 80 pages in length, and issued by the Institute.

Such a booklet should be of particular value to the practicing engineer, the recent graduate, the engineering student, and the teacher, as it will afford an authoritative digest of important current developments in the fields of science closely related to electrical engineering.

Anyone interested in obtaining this booklet combining reprints of all the articles in the science series should send an order at once to the A.I.E.E. editorial department. For convenience, an order blank appears in the advertising section of this issue.

M. M. O'Shaughnessy, Hetch Hetchy Builder, Dead. Michael Maurice O'Shaughnessy, dynamic head of the engineering department of the city of San Francisco, Calif., since 1912, died October 12, 1934, in that city, at the age of 70. Although the work that brought him the greatest prominence was the 20-year development of San Francisco's Hetch Hetchy water supply and power project, which he developed from its inception, Mr. O'Shaughnessy directed all San Francisco's municipal engineering work which, in addition to tunnel, street, and sewer developments, included the completion of an extensive municipal railway system. Born in Limerick, Ireland, in 1864, and graduated with honors from the Royal University, Dublin, in 1884, Mr O'Shaughnessy came to the United States in 1885 and spent the next 27 years first in railroad work and then in hydraulic engineering, water supply development, and dam construction in various parts of California and in the Hawaiian Islands. Mr. O'Shaughnessy had been a member of the American Society of Civil Engineers since 1902; in 1920 was president of its San Francisco Section.

Monument to Edison Erected in Japan

IN memory of the late Thomas A. Edison, a beautiful monument was erected in Japan by engineers and followers of the great inventor in that country in the outer-gardens of "Iwashimizu-Hachiman-Gu," one of the famous old shrines located at Yawata near Kyoto City. It was dedicated to the public on May 23, 1934, by Count Keigo Kiyoura, president of the Edison Monument Erection Society, organized jointly by 10 leading scientific societies of Japan.

The site was selected by the executive committee of the Society due to the fact that there Mr. Edison found the most suitable material of bamboo for use in his first experiments with carbon incandescent lamps.

This monument measures 3 m in height, 11 x 11 m at its base, and the stone on the top measures 1.5 x 1.5 x 1.5 m.

There is a tablet placed on the steps in front of the monument, carrying an inscription in Japanese, the translation of which is roughly as follows:

Thomas Alva Edison, the great American, was a man of unparalleled talent and originality and indefatigable energy. He made many valuable inventions, which gained him a world-wide fame and which contributed much to the progress of science and to the welfare of mankind. Of these, his incandescent lamp is the most notable. However, before its invention, he carried on experiments with various kinds of carbonized fibers in order to find a suitable material for the filament, and found that bamboo was ideal. In 1880, he sent a party to Japan with the object of securing suitable bamboos. Fortunately, through the good offices of Mr. Masanao Makimura, Governor of Kyoto Prefecture, good material was found in the grove of Iwashimizu-Hachiman-Gu. With this material, Edison was at last able to gain practical results. Who can deny the grace of the Hachiman gods in his undertaking? There are no cities in the world where electric lamps are not lighted, nay, even out-of-the-way hamlets enjoy this great boon of civilization. Thus, his services have certainly been stupendous! Edison said that invention was the result of ninety-nine per cent of perspiration and one per cent of inspiration. Indeed he was a self-made man and a man of strenuous effort, and this great invention was the outcome of his painstaking labor. Wonderful services can be rendered only by such an extraordinary man as Edison. His name abundantly deserves to be handed down to posterity. Consequently, with the support of those interested, we have erected a monument in memory of Thomas Alva Edison at Otokoyama, historically related to his success, for the purpose of immortalizing his brilliant exploit and proclaiming to the world the divine virtues of Hachiman Daijin.

The photograph reproduced in the accompanying illustration was taken at the unveiling ceremony and shows Dr. Eiji Aoyagi, professor of electrical engineering, Kyoto Imperial University, who served as chief of the executive committee, delivering his address. At the left are 4 priests of the Iwashimizu Hachiman Shrine.

On the white disk in the face of the rectangular stone at the top of the steps is carved a bas-relief of the profile of Edison, not clearly visible in the photograph reproduced herewith. The inscription quoted above is carved in the face of the lighter stone located part way down the steps.

What Place the Engineer in the Changing Economic Scene?

RECOGNIZING the obligation of the engineer to make his especial contribution to the complex problems of human relationships, social and economic, the Institute's New York Section scheduled 2 prominent speakers to appear before a general meeting of the Section in the Engineering Societies Building, New York, October 10, 1934.

Speaking under the title of "Is the Economic Scene Changing?" Dr. Virgil Jordan, president, National Industrial Conference Board, presented some of the fundamental considerations of the present economic state, the conditions which produced it, the manner in which its significance may be interpreted, and pointed out the relation of the engineer to modern trends; Col. W. T. Chevalier, vice president, McGraw-Hill Publishing Company, directed the attention of the engineer to other aspects of the situation, and indicated the lines along which opportunities lie ahead for the engineering profession.

Doctor Jordan has been active in the field of economics since his graduation from college in 1912. Between 1920 and 1929 he was chief economist and editor of the publications of the National Industrial Conference Board. Between 1929 and 1932 he was economist for the McGraw-Hill publications, and in the latter year returned to the National Industrial Conference Board as its president. In 1928 he was the organizer and chairman of the Conference of Statisticians in Industry, and in 1931 was the conductor of an investigation of American consumer expenditures.

Colonel Chevalier, following many years' experience in the construction field, became a consultant on technical advertising and promotion in 1921, and in the following year became associate editor of *Engineering News-Record*. He became business manager of this publication in 1923, and since 1927 has been publishing director of civil engineering and construction publications of the McGraw-Hill Publishing Company. During the period 1917–19, he was successively captain, major, and lieutenant colonel of engineers with 11th U.S. Engineers on field service in France, mainly on field fortification, road and railway construction and maintenance; he is at present colonel, Engineers Reserve Corps.

In view of the significance of social and economic trends, and their influence on the future conditions under which the engineer may be called upon to work, abstracts of these 2 addresses are presented herewith.

Dr. Jordan's Address

To understand accurately the position and prospects of the engineer today I think that it is first necessary not only to secure a firm grasp of the economic actualities of the present situation, which in itself is difficult and rare enough, but also to explore some aspects of the social and political psychology of the situation which may be unfamiliar.

The situation today is the result of exceptionally powerful psychological and perhaps biological forces that are at work acting upon the economic realities which underlie the whole picture. And both these psychological and biological forces, and the economic realities themselves, are largely obscured today and remain unseen to most of us.

The economic scene which we are now considering is in my view unchanged fundamentally. It has always been unchanged in its essential elements. What is changing is primarily men's conception of the economic scene and their attitude toward it. And it is this change in conception and attitude which is the source and origin of the problem that confronts us all and confronts you especially as engineers.

We are living in an age of what I call economic illusion, or you might call it social self-deception, or political hypnotism. The engineer has, partly unconsciously and partly deliberately, been the cause, or an important factor, in the development of that economic illusion. He has now become one of the foremost victims of it. And finally, if we are all to be saved from the disaster to which any such widespread social illusion leads, the burden of salvation will rest largely upon the engineer.

Now the essence of this economic illusion which is the center of my discussion, is the idea of automatic, universal, effortless, and unlimited abundance of passive prosperity and permanent security, provided by a self-operating industry under the compulsion of an all-powerful and all-wise state, a state which has become the new god, the basis of a modern religion, the great protecting and flourishing mother, the great beneficiary of everyone, which creates all things and makes all things perfect and permanent and secure. This is the essential idea in all of its manifestations that permeates the political and social atmosphere today, not in this country alone but in most of the western nations. In its deepest sense this illusion, or this conception, may be called a psychosis of that great human mass, great mass of humanity that was thrown suddenly into existence during the short span of the past 150 years when the population of the Western world trebled as a result of the sudden development of the power age.

Perhaps this single statistical fact is the germ or key to the whole situation. From 1800 up to the present time, in that 130 years, the population of Europe increased from 180,000,000 to 540,000,000, becoming 3 times as great. Now that sudden hurling of this great mass of humanity in the short space of 130 years, into existence, in a biological sense at least is the basis of this tremendous psychosis that has swept and has come to its crucial development in the present time in all of the Western countries. The mob or the masses—what I like to call that terrible abortion—of the industrial revolution, born of the sudden mating of science and nature, abruptly projected into a world which it did not create, which it took no part in creating, and which it does not understand, that mass, that mob is unconsciously searching today for escape from its responsibilities and the struggle of existence imposed by its relentless realities of life, trying in many ways to return to the womb of passive effortless gestation from which it sprang.

Mass Indolence Is a New Phenomenon

Individuals of course have always, for the most part, been essentially lazy. Perhaps a basic, the most primitive economic principle of all, is that of trying to get the greatest possible satisfaction with the least effort. Only relatively few individuals in any period of history have been in a real sense centers of creative energy. But the phenomenon of organized mass indolence or mass laziness, is a new phenomenon in human history, organized in the sense that it is not only physically organized, but that it has developed a whole philosophy, a whole structure of theory as a rationalization of its indolence. It is the first time that indolence has been erected into an economic and political principle upon which a system of social organization is sought to be based.

Now all of us in some measure today, whether we are conscious of it or not, are subject to this acute psychosis that the industrial revolution has slowly developed in all of the Western world. We live willingly or unwillingly, consciously or unconsciously, in a sort of dream state of wish fantasy, fearing effort and risk, troubled by nightmares and paranoias of persecution and oppression by wicked and powerful individuals and groups, suspecting, envying, even hating, and seeking to destroy the distinctive creative individual or institution, fleeing the strenuous life of personal effort and enterprise, preferring the secure life to the strenuous life; searching incessantly for security, unwilling to awake from a dream world and grapple with realities, surrendering easily to the embrace of the vision of passive plenty and permanent protection.

That is perhaps a fundamental description of the basic state of mind of most people in the Western nations today, a brief summary of their psychological trend. I say it affects all groups, and I want to be perfectly explicit in that respect by making it clear that I recognize above all that it affects the business group particularly. It is not merely a phenomenon of the employee group, but has become today a characteristic trend of mind of the employer or enterpriser group in this country particularly. Business men's whole behavior today is conditioned by this search for security and this expectation of passive, profitable operation. You see that reflected of course in the tenacity with which business men cling to the idea of protecting profits by various devices of price fixing; you see its most magnificent embodiment in all of the beautiful dreams of N.R.A., but you see it also even in the scientific group, and to a large extent among the engineering group, in the decline of pure research activities, in the general assumption that it is desirable to restrict inventive advance, in the general acceptance of the conception of the men as of the machine which pervades the minds not only of business men but to an increasing extent of a great many men in the scientific field as well.

This Illusion Causes a Regressive Trend

Now this whole trend toward the establishment of a passive consumption and static security system, which we see manifested everywhere today, is fundamentally a regressive trend. It is regressive biologically and also in the economic and political senses, a relapse or a return to an earlier form of life, of a less highly developed and highly creative form of life. Biologically the symptoms of it are obvious enough to the eye. It reflects itself of course in the great phenomenon of declining birth rate in all of the Western nations, in the fear of children, the fear of the new generation, and the fear of death; the relatively diminishing proportion of young people in the population and the increasing proportion of older people. These are the first symptoms of the disappearance of race vitality and of biological degeneration.

Along with that of course comes the disappearance of personal individuality, or rather the tendency to regard manifestations of individual action as anti-social, as dangerous, disruptive, and in consequence the increasing emphasis upon the importance and necessity of organized regimentation and standardization—all of them reflecting the trend toward a termite organization of life, socially and politically, which we have manifested in more or less perfect form or a highly advanced form in Russia, Italy, and Germany today.

This Age of Plenty

Now I want to emphasize particularly the economic expressions, manifestations, and implications of this age of economic illusion. The first, of course, is the widespread acceptance of the idea of the automatic productivity of industry, the feeling that modern machine industry has become in a very real sense of dehumanized process in which the human factor is no longer an important element; that it has reached the stage of an automatic affair, so that the rôle of management in modern industry is constantly minimized day by day, and even to the point of being ignored altogether in many manifestations of governmental policy toward industry.

We all believe in one way or another that we are living today in an age of plenty, in a surplus economy, which has occurred by some species of magic which we don't fully understand but which we associate with the activities of the engineer and the scientist, and that that age of plenty or this surplus economy has an inherent tendency toward excessive production, toward over investment in productive facilities, toward the creation of excess productive capacity; and that our problem is essentially one of control of this abundance, this avalanche of abundance that threatens us all. As a direct consequence of that general idea which is universally accepted so far as I can see, we have put all our emphasis in our thinking today upon problems of consumption. We believe without question that our economic and political difficulties are all manifestations of under-consumption, of the inability to consume, and that our essential task politically, socially, is to devise means for increasing consumption through the redistribution of purchasing power or income in money terms.

The "New Deal"

Now all of those ideas are directly embodied in the whole New Deal program as we call it, that is, in all of the legislative and administrative policies of the present administration, with the concepts that we increase our prosperity by increasing the amount of money in circulation, increasing the prices of commodities; that we increase prosperity by stimulating spending, and buying and consumption of products; that we must do that by a vast program of public expenditure in the form particularly of expenditure and credit creation for non-productive works, non-productive public facilities; and that we can increase our prosperity by bringing about certain very marked forms of redistribution of money purchasing power, such as extracting it from people who live in cities and paying it to people who live on farms, by increasing wages, money wages, by shortening working hours, by developing plans for old-age payments, payments to the aged who are increasing constantly in proportion to the population, and whose function is purely a passive one of consumption.

Doctor Jordan

Along with those ideas goes of course the general acceptance of the idea of restricting profits in order to divert purchasing power from those groups in the population who can't immediately or directly spend all of their income, but must invest it in various ways, thereby building up excessive productive capacity and preventing adequate consumption of goods produced. Those ideas also carry the policy of high taxation of higher income brackets and of corporate surpluses for the same purpose, diverting purchasing power immediately and directly into consumer channels. They carry also the implication which is directly embodied in many of the codes, of restrictive production and of control of investments, expressed in the Security Market Act and the Stock Exchange Regulation Act. They carry the idea of price fixing as price fixing under governmental control in order that the government or governmental agency may properly apportion the flow of consumer purchasing power as between wages and payments upon capital investments. They carry the implication also of the guarantee of profits, and finally there blossoms in the idea which is now very seriously considered, of adapting the European conception of cartels to the organization of American industry.

So that by thorough-going group organization under governmental control there may be complete regulation of the flow of purchasing power by industry as between wage earners, employees, or as they are commonly thought of, mere consumers, and recipients of payments upon capital investments.

Result—A Lowered Standard of Living

Now all of this process, all of this legislative structure which embodies these general philosophies, the philosophy of passive consumption which is the basis of the economic illusion under which we live, inevitably must lead to a lower standard of living. The standard of living, of course, is a simple and direct function of effective production, in which the essential factors, apart from natural resources, are human effort, intelligence, organization, technical knowledge, saving, and risk taking. Today all of these factors are supplanted by the general process of political prestidigitation and governmental magic, monetary magic, fiscal magic, and regulatory sleight of hand—all of them designed, through the redistribution or the redirection of the flow of purchasing power to raise the general level of prosperity. This is called planning today, a word that covers the confusion and vagueness and fogginess of thought that underlies the whole process; and it consists mainly or practically altogether in devices for redistribution of income. That is what it comes down to essentially, not to increased production, which is the basis of the standard of living, but to appropriate, redistribute, and stimulate consumption of foods and goods produced.

Reduced Production Prolongs the Depression

As I said it is universally assumed that the problem of production today has been completely solved, that the standard of living as a function of productive, effective production, is infinitive, but that the problem of distribution and consumption is unsolved, that it remains for effective governmental action to solve, and that it must be solved by the state alone through deliberate action.

Now of course from my point of view our essential problem is that of effective production. The fact that we do not produce and cannot produce effectively is the reason we have had a depression and is the reason we are not recovering from this depression. Production is hampered in this and every other country by an enormous structure, an elaborate network of artificial restrictions and false concepts, popular concepts as well as political and governmental concepts. In this country we are suffering today from what may be said is a universal sabotage of production by labor and also

by management and by the agencies and institutions that control the flow of capital for industry, a sabotage that reflects itself in widespread inefficiency of labor in many forms in almost every industry, a deliberate, conscious, direct withholding of productive effort in almost every field of labor today by a fear of capital investment and a complete unwillingness of risk taking in every field.

Those factors that tend to sabotage and hold back effective productive effort in every field are the basic reasons why we are as we are, why our standard of living is what it is, why it is so difficult, so slow to raise it.

Trend to State Capitalism

Now that situation and that psychological background are moving us steadily and rapidly in this country toward the establishment of a comprehensive system of state capitalism under central, bureaucratic dictatorship. That is the natural, inevitable response in political terms to a psychological and economic situation such as confronts us here and now. This network, this structure of governmental control, of artificial restrictions placed piecemeal, developing spontaneously in response to these psychological conditions in every field of industry, invite constantly an extension of such controls. They carry with them the inevitable process of expanding regulation, because such regulation exercised in one element or with respect to one part of the economic picture, creates unbalanced conditions and disturbances in the economic balance which necessitate further injection of state power, of governmental control in other parts of the picture. There is no escape from that.

State planning or state regulation cripples inevitably the natural forces of productive effort and moves relentlessly toward socialism. There is no break in that process; there has been no break in that process in any Western country. It has moved steadily from the first rudimentary and elementary injection of state power or state interference in the natural processes of production, to complete socialization and complete dictatorship in the end. That of course carries with it inevitably the implication of the end of personal liberty and individual action in every field, and implies a radical and complete change in our whole political institutions; because both in its origins and in its development, private capitalistic enterprise as distinguished from governmentalistic enterprise is the same thing as free democratic or republican institutions. They originated together and they have grown up together, and they will come to an end together. One cannot survive the other. In all of the Western nations that progressive parallel destruction of democratic and republican institutions and the destruction of private, capitalistic enterprise, have proceeded very far. Even in Great Britain which stands out in the world today as perhaps the most, the noblest old figure among the nations as the embodiment of the principles of private capitalistic enterprise and democratic institutions, beneath the surface has undergone a transformation and is separated only by very short steps from the more advanced stages of capitalism which we see in Germany and Italy and Russia, and to a large extent in the United States. Today in the United States between 40 and 50 per cent of the total national income in monetary terms passes through the hands of governmental agencies and is taken out of the channel of free disposition by private enterprise.

Engineer Has Both Aided and Been the Victim of This Illusion

Now the engineer, to come back to the subject with which we are concerned, has aided this process in many ways. He has aided it by his scientific, technical achievements, and by his labor-saving devices as they are called, which have created or provided the basis for this widespread illusion of automatic productive power. He has provided the basis for this universal idea that labor, effort, and risk taking are becoming more and more superfluous in our economic system. Scientists and engineers themselves, aside from the general effect of their technical contributions, have helped to foster this illusion of abundance by constant paper demonstrations of the enormous productive capacity of modern industry under certain theoretical organization of its forces of production. These paper demonstrations always ignore the human obstacles and the human inertia which underlies the whole organization of production, which is the fundamental reason for our inability to utilize our productive forces to the full extent theoretically possible, and these paper demonstrations ignore also that basic law of diminishing returns, and the more basic law perhaps of the degradation or dissipation of capital, which is in economics quite comparable to the principle of entropy in physics.

Now while the engineer has in all of these ways undoubtedly been a most important factor in stimulating and developing this era of economic illusion in which we live, the tragic fact is that they themselves have become the most pathetic victims of this illusion, because it has found its expression in public policies and in social principles which inherently regard the engineer and his kind as enemies of progress and prosperity. The engineers are regarded with aversion in the public mind as agents who are constantly contributing, unwillingly, perhaps, just by force of nature, of their temperament and their training, to this unbalance of production and consumption which is the heart of our economic problem.

Responsibility of the Engineer

Now where does it leave us; where does it leave the engineer from the point of view of the future, this whole picture that I have been describing in such a sketchy way, because I couldn't hope to cover the whole field of problems involved? It seems to me quite clear that in the end the solution of the problem, or at least the task of release from the dilemma in which we find ourselves, comes back in the last analysis to the engineer. In the end only he can offset or compensate for this vast destruction of productivity which the intervention of the politician and of the planner and of the mob must inevitably lead to. That is what is taking place today under our eyes, a tremendous destruction of productive power the world over, progressive because nothing accumulates so rapidly on a geometric scale as paralysis of productive power in thickly populated and highly organized society. The task of providing and maintaining even the degree of abundance and security which has existed up to 1929, a very formidable task as I view it looking ahead, the task of maintaining that degree of abundance and security will rest primarily upon the engineer.

In an age of economic illusion such as we live in, the engineer is more indispensable than ever if he himself is unflinchingly alive to the realities of the economic problem that confronts us. Among the figures that move in this economic scene, only he can save this great mass of humanity from self-destruction. And he must not expect to be thanked for it. That mob that rules destiny today in all of the Western world will take his service for granted, it will not show any gratitude for it because they have no understanding of its essential significance at all. But while he is performing that task, he should not neglect his responsibility as, let me call it a propagandist, in inculcating the discipline or gospel of realistic thought about these problems. The rarest thing in the world today is that unflinching realistic approach to these basic economic and social problems, because if he acts effectively as such a propagandist he may, I hope, in time spread a little of that realism into the political sphere. The burden of creative accomplishment as you know full well, and as all of those who have studied the course of history with a realistic eye know, that burden of creative accomplishment always rests on a very few in every society, a few who must carry the rest on their backs, usually without appreciation, without understanding, and now, in the face of outright antagonism.

Other groups in the community, if there are any who can be brought to understand that situation, must aid those creative few who are carrying the mass, and they must be mobilized and I think that they are to a certain extent being mobilized today in the United States to aid in protecting these creative forces from destruction.

Support of the Present Administration

It seems to me, coming down to the situation which confronts us these very days through which we are living in this country, that from the point of view that I have been describing to you, the President of the United States needs, to the fullest extent, the sympathy and support of every American who has any deep understanding of the dangers that confront us in this country, whether we approve or not of the things that have been done during the past year and a half. The essential danger that faces us now at the end of 1934, and that will face us more critically before 3 or 4 or 6 months have elapsed, in my opinion, is that the President may become the helpless victim of forces which he has set in motion or which have been set in motion in this country during the past year and a half, and instead of being able to serve effectively as a leader of those forces as he has up to the present, there is a real danger in the next few months that he may become their helpless victim and be swept away by them.

And to avoid that, whatever one's political sympathies or general philosophy may be, as Americans we have to realize that the crisis to which this era of economic illusion strongly stimulated by governmental policies has brought us, may lead to chaos and complete destruction of our whole economic and political system in this country.

So that in that situation the engineering mind which has not been brought to play effectively in a political sense up to the present, may be called upon I believe to play an important part, both directly in its contribution to the solution of some of the practical and immediate problems that confront us, and as a protagonist or propagandist or as a vehicle of expression to the public mind of some of the more realistic points of view toward these problems that we urgently need to grasp today if we are to avoid some of the dangers that lie ahead.

Colonel Chevalier's Address

In order that we may be clear to start with, I want to say what you are going to find out very quickly, that I am not an economist and have no economic pretensions. I am going to try to make a picture for you of this scene that Dr. Jordan has presented to you as a philosopher and an economist, as it looks to the eye of an engineer. To indicate the solution of all of these problems, even, from the standpoint of the engineer only, is a task far beyond my poor powers, but perhaps if we can reconcile some of these views as each of us sees them from his own eyes, it may be a fruitful visit.

Dr. Jordan has well emphasized the fact that it is fundamental in the engineer's philosophy that production is the fundamental factor in our civilization and in our material progress. And if the engineer were to define his function in a phrase he would have to say that his major purpose is to increase the productivity of his fellow men so far as the physical world and physical agencies are concerned. Therefore, if some of these philosophies of restriction upon production should prevail, the engineer is in a bad state indeed, for he has lost the reason for his existence. Now I should like to take, as a text perhaps, a clipping from an issue of the *New Yorker*. It appeared about the time of the airmail controversy. And writing under the head of a "Reporter at Large," Morris Markey had this to say:

"I don't know much about the disputes down in Washington. I have gathered vaguely that a gentleman named McCracken had to get a rested and that a lot of papers were destroyed which shouldn't have been. All of that seems pretty remote when you are standing out there on the field watching a man like Thaddok pull one off the ground and strike off for the mountains to Chicago. I don't think Thaddok or Texas or this fellow Mike knew anything about manipulation of contracts or that he cared anything about such affairs. (Now this is the significant part.) It made me feel a little sore to think that they and all those roster of mechanics and hangar men and such, all the engineers who burnt their eyes out over drawing boards to make better airplanes, and all the men who have watched hundred hour full throttle tests on new engines, to think that such a decent and competent crowd should take it on the chin now and be discredited by inference at least because a little crowd of slickers 2 or 3 years ago made monkeys out of a little crowd of politicians. But this is no doubt a bootless sort of complaint. Honest and deft hired men have suffered before, I seem to recall, because of the sad fact that their bosses smelled money and lost their honor in the race for it."

Making the System Safe for the Producer

Now I know how easy it is to over-simplify a problem and therefore I run the risk of over-simplification when I say that from the standpoint of one engineer at least the only problem that confronts us in this whole economic muddle is that of making the system safe for the producer.

Colonel Chevalier

Now I recognize 3 kinds of producers. There are the men that work with their hands, and the men that work with their heads, taking into account the scientist, the engineer, and the manager; and the men that work with their thrift, those that deny themselves the current satisfaction of the wealth they have created in order to make possible the creation of those agencies that are going to multiply our productive capacity in the future, that provides the tools with which the engineer has to work.

Now with all this productivity that has been created through the improvement in our technology, our producing plan, and in our management, I have the feeling, which I cannot prove, that it would be relatively easy to create an abundance for all of us if we could confine it to the producers, the 3 classes that I have mentioned. The reason that we are not able to confine it to the producers is because somewhere in the circuit we manage to cut in on the distribution of the wealth we create a vast horde of parasites who by speculative manipulation and the operation of credit and financial agencies, are enabled to reap a profit on a vast scale where they did not sow. And everyone who by such manipulation puts himself in a position to command wealth without creating it, is taking it away from someone who has created it.

Now you say, well, but speculation is the life of progress. Yes, creative speculation is the life of progress. But predatory speculation is its death. It to me is the greatest enemy of the engineer in the economic order, and regardless of what I may think about some of the funny things that have been done in Washington during the last year, I am thoroughly in sympathy with everything that can be done to curb excessive predatory speculation whether it be done through a securities act or control of the exchanges, or by some closer supervision of the use of credit.

Now we talk a great deal about the prosperity of a few years ago. Dr. Jordan has talked to you tonight about all of the troubles that we have and may have if we don't watch out. In my opinion these troubles were born from 1923 to 1929, and not in the last year or the last 2 or 3 years. We heard a lot about the prosperity of a few years ago. Well, who had the prosperity? I recently found for example that if you compared 1923 to 1929, the nonfinancial corporations during that period showed an increase in profits of only 14.1 per cent. Those were the productive activities of the country, and that was their increase in reward. During the same period from 1923 to 1929, the financial corporations showed an increase in profits of 177.3 per cent.

Prices and Production Can't Be Fixed

Now I am not worried about the future of the engineer. I don't think a lot of these things that Dr. Jordan has told us about are going to happen. I hope they don't. Every engineer that I know has had to scratch his head harder than ever, first of all to get a job, and secondly, to make good on it when he had it. Every manufacturer that I know has had to devote more energy and more technical skill in order to survive than he had to exercise 10 years ago to make a profit.

Now I agree with the foolishness of a lot of things that some of our industrialists in their despair of a year ago have tried to do. I sat down in Washington last fall and worked with a great many of them trying to resolve some of their difficulties and to get them through the N.R.A., and worked with them sympathetically. And the 2 things that everyone wanted were the chance to fix the prices and the chance to stop anyone else from going in business. Well now, that looks good from a close-up, but when you get away and look at it from a distance the whole thing loses scale somehow, it is out of proportion. I don't know anything about some of the higher aspects of economic philosophy, but I do know this, that if we are going to keep this so-called capitalistic system the 2 things we can't do are fix prices and stop the entrance of new capital into production. The industrialists today who try to do those 2 things are doing more to upset the capitalistic system than all of the soap box orators from here to the Nevsky Prospekt in my opinion, because a principal prop of the capitalistic system is a free competition to enable you constantly to reduce the cost of production so that more people can be brought into

the market. Only in that way can we justify the withdrawal of wealth from current consumption in order to provide the new productive capacity. And furthermore, if we freeze the methods and process by keeping new enterprise out of a field, we are doing the surest thing possible to stop this increase in our productivity that is the life of the system and constantly gives employment to the capital that distinguishes it.

Heritage of the Capitalistic System

So many people have said, "You see we have gone along for 150 years here and we have done awfully well. You know the best thing to do is to let it ride; don't disturb anything. We have got along fine and we have prospered in comparison with the rest of the world. Look at what we have done in 150 years in this country under this system we are operating under."

Well, all right, as an engineer I look at it and what do I see? I see 150 years ago when we took over the establishment, a set-up. Here was 3,000 miles by 1,000 miles of the earth's surface filled up with natural wealth beyond the wildest dreams of a Coresus, and a little handful of white people on the Eastern shore with just a few red savages to be driven off the reservation, and it belonged to that little group of white people. They inherited the earth and everything above it and underneath it. And for 150 years we have been living on our capital. We have been living on our patrimony, and we have been able to make the old speculative thing work because every time we cleaned out one bunch of suckers there was a new place for them to go and dig up some more for the wise ones to take away from them on the next turnover.

Now that is not funny; that is a fact. That is what we have been doing for 150 years in this country. Now the engineer has been both the beneficiary and the victim of that process because that psychology of easy money through speculation was present.

When I say that we have got to make the system safe for the producer, I mean that we have got to make finance work to serve creative industry rather than simply to serve finance and speculation. That is the salvation of the capitalistic system in which I believe, and in spite of all its faults I love it still. The capitalistic system has a lot of friends, but I remember the definition of a friend. A friend is a man that knows all your faults and still likes you. Well, I am a friend of the capitalistic system in that respect and I want to see it survive, and it is not going to be made to survive by just damning the government and everything that it does to deal with an emergency.

The Job of the Economist

Now Dr. Jordan says that it is the engineer's job to help the community to get out of the mess that the community says the engineer put them in. I don't agree with him. I say that that is the economist's job. The trouble is that they can't get in a huddle long enough to agree on anything. When I say it is up to the economist I mean this, that if we have developed a great productivity, and no one doubts that, and if the people would like to live on a little higher standard than they have, and get the benefit of some of this productivity, you call it redistribution of income or anything you please, I don't care; I say we should be able to reconcile those 2 conditions and not have one crowd over here starve because they can't get rid of their surplus and the other crowd starve because they can't get it.

My theory is that that business of effecting that change of wealth is a function of our financial system. If that isn't what a financial system does, then it is a mess, because it doesn't do anything else; it doesn't produce any wealth. Look at these corporations that got the 177 per cent increase in profits in 7 years, just what wealth did they add to this world of ours? They rendered a service, yes, the same as a cash register, the same as a bookkeeper. I am not belittling that service. But when somehow or other there is such a proportion of the wealth we create that trickles out in that process somewhere and sticks and doesn't get from producer to producer, then I think there is something wrong. And I say to solve that problem is the job of the economist.

The Job of the Engineer

Well, what is the engineer going to do about it? Well, the first thing I think he ought to do is keep everlastingly prodding the economist. Now you go down the street and get these fellows that know all about money and finance and banking and credit, and you get together with them and come back and show me how we are going to effect this change of value and services that is going to make use of the enormous productivity that has come about during the last hundred years.

That is the first thing we can do. The second thing we can do, that we are going to have to do, is to continue building. I am now getting away from the personal problem into the problem of the profession. We are going to have a job to do in the next decade to make up for what we have lost in the last 2 or 3 years. There is a perfectly enormous arrearage of productive effort that we have got to put to work.

Now if you think the job is finished in this country, ride across the continent on a train and see a lot of these overgrown mining camps that we call cities and towns today. I am not reproaching them. What they have done in the last 50 years, some of them, has been remarkable, but it isn't a circumstance to what they are going to do in another 50 or 100 years, what needs to be done to make them real cities, typical of American civilization.

Now I don't know my facts, but when Doctor Jordan was talking about the fact that pure science had gone on a holiday or something of the sort, I couldn't challenge that statement, but I didn't think so. I thought we had built up quite a lot of scientific research in the last few years that has yet to be applied to practical purposes, due to the breakdown of the machinery that I am talking about.

Now, then, we have not only got to rebuild a whole lot, but we are going to have to replace a lot of old tools that have become obsolescent. So the engineer is going to have a big job there in my opinion. Then we are going to have to develop refinement of technique and method to a degree we never dreamed of before. I remember in my own short lifetime when I first started in the construction industry that construction equipment was about on a par with agricultural machinery, crude, rough castings, just stick a shaft through a casting and you had a bearing. Today we build construction machinery like automobiles, roller bearings, special steels, forced lubrication—one power shovel costs 12 or 15 thousand dollars. So we have developed constantly as we have been drawing down that supply of our natural resources. And as we have gone through that process we have been compelled to make better and better and better use of them. And that has led to refinement in engineering practice and in my opinion we are going to have to do more of that in the future than we have done in the last 30 or 40 or 50 years, because we are going to have to make what we have got go farther.

Developing the Social Consciousness

And finally we are going to have to develop this consciousness that Dr. Jordan was talking about, that we are something more than hired men. The greatest thing that is wrong with the engineering profession is our psychology.

In order to broaden our interests, one of the first things is getting a better grasp of the purpose of what we are doing, the economic and social objectives of our work. In Richard Harding Davis' famous yarn "Soldiers of Fortune," I remember one place when Clay was working on the mines and Alice Langham's father was his employer, and he said to her, "Miss Langham, all you see is a lot of rock to be blasted out and carried down here and dumped in a ship to be carried away and help make your father rich; that is all you see in my job. But I see a mountain of ore there, and in that ore there are facilities and services and utilities innumerable that I am going to take out and send to men who will fashion them into instruments to help men live better, go farther with their lives." And he used the expression that I always have remembered. He said, "I prefer to bind a laurel to my plow than to go through life calling myself hard names because I am a plowman."

Now we have got to bind a laurel to our plow. I don't mean that that is going to make us richer in the pay envelope at the end of the month, although it may. If more of us will have that vision of our work, and more of us will translate the productivity of the modern science into service and commodities and goods for the producers of wealth instead of into speculative profits for the few who by hook or crook put themselves in a position to control it and manipulate it; then we will be doing a good job for the profession and we will probably profit ourselves in the process.

Interests of Business Men

Now in closing, just to get the record straight, I don't want anything that I have said here to create the impression in your mind that I am ranting against the people

who save their money and provide capital and make honest investment in the productive agencies of our economy—not at all. They are the very people whose interests I would like to see better protected. I am not at all finding fault with the business men. You know one of the most pathetic things in the world today is the average industrialist, the producer, the man whose energy has built a plant, whose driving power has brought together an organization and inspired it, and gone out and sold a product, who has made a real contribution to our economy and employment of capital and labor and in service to his community, those real industrialists of which we have so many in this country—somehow or another they allow the forces of finance and speculation to convince them that their interests are in common and every time someone attacks the citadel of waste and depression, or rather depredation and speculation and manipulation, it is very easy to rally a bunch of these good old sturdy producers to come and do their stuff in order to prevent the harness being put on, or a yoke or something of the sort, because they think their interests are the same; they are not the same. Some day they will see that their interests as producers are diametrically opposite to the interests of those who seek to acquire without creation. And we will never have a Utopia, but all that I hope is that out of the next generation we may learn to put a premium on creation of wealth rather than acquisition of wealth, because that is the essence of all that I have been trying to say to you tonight of an engineer's vision of what we are going through and what we hope will come out of it.

A.S.M.E. Elects Officers. Officers of The American Society of Mechanical Engineers to serve for the year 1935 were recently elected. The newly elected president of the A.S.M.E. is Ralph E. Flanders, president, Jones and Lamson Machine Company, member of the Industrial Advisory Board of the N.R.A., and of the Business Advisory and Planning Council. He is a national authority on machine design and construction, representing the A.S.M.E. on the sectional committee on standardization and unification of screw threads since 1921, and serving as chairman since 1930. He was president of the National Machine Tool Builders Association in 1924, is a director of the Social Science Research Council, and is a lecturer at the Tuck School of Business Administration at Dartmouth College. He is known to members of the A.I.E.E as chairman of American Engineering Council's committee on the relation of consumption, production, and distribution; progress reports of this committee were published in ELECTRICAL ENGINEERING during 1932 and 1933. Newly elected vice presidents of A.S.M.E. are James H. Herron, president, James H. Herron Company, Cleveland, Ohio; Eugene W. O'Brien editor, *Southern Power Journal*, Atlanta, Ga.; and Harry R. Westcott, president Westcott and Mapes, Inc., New Haven, Conn. Newly elected managers are B. M. Brigman (M'28) dean, Speed Scientific School, University of Louisville, Ky.; J. W. Haney, professor of mechanical engineering, University of Nebraska; and Alfred Iddles, vice president, United Engineers and Constructors, Inc., Philadelphia, Pa.

Assembling the First of the Boulder Dam Generators

THE first of the 4 Boulder Dam generators each rated at 82,500 kva, is shown here in the Schenectady, N. Y., works of the General Electric Company. Another of these generators is under construction in the same works, and the 2 others are being built at the East Pittsburgh, Pa., works of the Westinghouse Electric and Manufacturing Company. The sections of the stator frames are shown here being bolted together. Before delivery at Boulder Dam scheduled for November of this year the stator will be taken apart for shipment by rail, 40 freight cars being required to transport it. Brief information on these generators has been given in ELECTRICAL ENGINEERING for November 1933, p. 796–7, and for March 1934, p. 499.

Naval Architects and Marine Engineers to Meet. The Society of Naval Architects and Marine Engineers will hold its 42d annual meeting in the Engineering Societies Building, 29 West 39th Street, New York, N. Y., Thursday and Friday, November 15 and 16, 1934. A technical session is scheduled for each morning and each afternoon of the 2-day meeting; 3 papers per session. At the Friday morning session David Arnott, chief surveyor for the American Bureau of Shipping, New York, will present a comprehensive paper on "Some Examples of Arc Welded Ship Construction."

Exposition of Power and Mechanical Engineering. The 11th National Exposition of Power and Mechanical Engineering will take place at Grand Central Palace, New York, N. Y., during the week of Dec. 3–8, 1934. This exposition, which is held every second year, is being held concurrently with the annual meeting of The American Society of Mechanical Engineers Exhibits now under construction are coordinated to emphasize the saving of power costs. This keynote reflects the need of modernization and replacement of old and obsolete equipment. The exposition is said to offer a setting in which the evaluation of materials and machines to be used for rehabilitation and new construction is aided by the possibility of comparing a wide range of competitive items at the same place and time.

Former Chairman of Pittsfield Section Dies. William Porter White, manager of the customer division of the central station department of the General Electric Company, died Sept. 22, 1934. He was born at Beaufort, S. C., Sept. 18, 1885. Following his graduation from Clemson College in 1906 he entered the testing department of the General Electric Company at Pittsfield, Mass., and later transferred to the transformer department. In 1927 he was selected as manager of the holding company division of the central station department, and in 1933 he became manager of the customer division. Mr. White was a member of the Institute for a time, having been elected an Associate in 1919, and was at one time chairman of the Pittsfield Section.

Former President of Franklin Institute Dies. Dr. Walton Clark, formerly vice president of the United Gas Improvement Company and formerly president of the

Franklin Institute of Pennsylvania, died at his home in Chestnut Hill, Pa., on July 30, 1934, after a long illness. He was born in Utica, N. Y., in 1856, and entered the gas industry at the age of 17. He held positions with various properties, until he entered the United Gas Improvement Company in 1888. He became vice president in 1903, and retired 11 years ago, becoming consulting engineer. Dr. Clark was elected president of the Franklin Institute in 1907 and held office for 17 years. He was a past-president of the American Gas Light Association and of the American Gas Institute. Until recently he was a member of the Institute, having been elected Associate in 1908 and Member in 1911, resigning in April 1934.

Engineering Foundation

Engineering Foundation Pays Tribute to Founder Swasey

To PAY fitting tribute to Ambrose Swasey of Cleveland, Ohio, upon the 20th anniversary of his creation of The Engineering Foundation, and in celebration of his approaching (December) 88th birthday, some 67 engineers, industrial leaders, educators, and scientists assembled for dinner at the Union League Club, New York, N. Y., Thursday evening, October 18, 1934, with Mr. Swasey present as the guest of honor.

In opening the ceremonies, H. P. Charlesworth, chairman of The Engineering Foundation, and past-president of the Institute, paid high tribute to Founder Swasey and spoke appreciatively also of the tireless, long-time services of Director Alfred D. Flinn. The 4 speakers scheduled for the program included Dr. Frank B. Jewett, former vice chairman of The Foundation, and past-president of the Institute; Dr. Michael I. Pupin, second chairman of The Foundation, and past-president of the Institute; Dr. Karl Taylor Compton, president, Massachusetts Institute of Technology, Boston; and Harold V. Coes, president, United Engineering Trustees, Inc., and past-president of The American Society of Mechanical Engineers. Circumstances, however, prevented the attendance of Doctor Pupin and Mr. Coes.

Dr. Jewett Outlines Unique Characteristics

Doctor Jewett in his brief address emphasized the unique character of The Engineering Foundation, in that it is the only one dedicated wholly to the furtherance of the engineering profession and its contribution to human welfare, and in that the charter under which Mr. Swasey created the Foundation provides a latitude and flexibility that will enable it to serve effectively and indefinitely in spite of constantly changing conditions.

Doctor Jewett cited also that Foundation is: unique in having charter provisions for a governing board that definitely is not self-perpetuating, but made up of members elected independently and periodically by the participating technical societies, and in having absolute authority over Foundation's destinies placed in this board even during the continuing life of the founder; unique in its coöperative relations with the participating societies; truly great, not so much for the money it has available for expenditure, but in that it gives the engineering profession a definite medium through which to make lasting contributions for the benefit of mankind; the very essence of a true democracy, created and inspired by a great and typically American citizen.

Dr. Compton Indicates Opportunities

Doctor Compton, in discussing briefly some of Foundation's future opportunities for effective public service, gave 3 important suggestions: (*a*) the development of qualified research men and, later, the development and expansion of research fields; (*b*) the fostering of important new technical and scientific projects; (*c*) the fostering and further development of coöperative engineering and scientific research projects.

With reference to the development of men, Doctor Compton emphasized the fact that the national research fellowships available in recent years have been largely responsible for the improved scholarship that is beginning to enable the United States to take its proper place in important scientific fields such as, for instance, theoretical and mathematical physics. With reference to new projects, Doctor Compton cited the well-known growth or "fly" curve, as representing also the stages of development of an idea or of an enterprise, stating that Foundation might to very good advance "nurse forward-looking projects through the initial stages of slow development and toward the stages of established public acceptance and consequent self-support."

With reference to coöperative projects, Doctor Compton pointed out that they were of ever increasing importance as society becomes more complex, and that The Engineering Foundation could do an important work by supplying the vision and fundamental organization required to get such projects actually under way. As an example of this latter, he cited the Engineers Council for Professional Development that has been created and is being promoted "to care for some of the problems facing engineers individually and as organized groups," in which Engineering Foundation is assisting. Another example cited was the coöperative study of soil and foundation problems, looking toward a better understanding of the facts and the development of a better technique.

Chairman Charlesworth Presents Citation

As the closing feature of the inspiring occasion, Chairman Charlesworth first read and then presented to Mr. Swasey, a parchment document bearing a statement befitting the occasion and carrying the personal signature of each person present. The text of this memento follows:

To Ambrose Swasey, Founder: On this happy occasion, officers of the American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, American Institute of Electrical Engineers and of kindred technical societies and associations of scientists together with present and former members of United Engineering Trustees, Inc., and of The Engineering Foundation, and other friends, have gathered to celebrate the 20th anniversary of The Engineering Foundation and to honor you as the one whose foresight and generosity brought about in 1914 the establishment of that unique and beneficent institution.

To you the fraternities both of engineers and of scientists express high esteem as one of their most beloved members and generous benefactors.

In the 20 years since you made your first gift, there has been a steady growth in appreciation of your great conception of an institution through which the coöperative activities of engineers, scientists, and industrialists could contribute by research and in other ways to the advancement of the profession of engineering and the good of mankind. Great have been its contributions: they mark but the beginning of far greater service in the future.

For your 88th birthday 2 months hence, we wish you health and happiness and assure you of our gratitude and abiding affection. May many succeeding birthdays bring you the satisfaction of witnessing the accelerated growth and increasing usefulness of your great undertaking, The Engineering Foundation!

Those present and who signed the foregoing testimonial were:

For the American Chemical Society, L. H. Baekeland.

For the American Institute of Electrical Engineers, H. H. Barnes, Jr., W. S. Barstow, O. B. Buckley, H. P. Charlesworth, E. H. Colpitts, H. B. Gear, Bancroft Gherardi, H. H. Henline, G. R. Henninger, F. B. Jewett, J. A. Johnson, P. B. Juhnke, G. L. Knight, F. J. Meyer, H. H. Porter, E. W. Rice, Jr., C. E. Skinner, W. I. Slichter, R. W. Sorensen, L. B. Stillwell, W. H. Timbie, J. B. Whitehead, and H. R. Woodrow.

For the American Institute of Mining and Metallurgical Engineers, G. D. Barron, G. H. Clevenger, A. S. Dwight, H. O. Moulton, T. T. Read, J. V. W. Reynders, R. M. Roosevelt, A. J. Wadhams, and T. H. Wickenden.

For the American Society of Civil Engineers, O. H. Ammann, J. V. Davies, O. E. Hovey, C. W. Hudson, H. deB. Parsons, G. H. Pegram, J. H. Perry, Robert Ridgway, G. T. Seabury, F. L. Stuart, and A. S. Tuttle.

For The American Society of Mechanical Engineers, W. L. Abbott, W. L. Batt, C. E. Davies, H. N. Davis, W. S. Finlay, Jr., E. R. Fish, D. S. Jacobus, G. A. Orrok, R. I. Rees, G. A. Stetson, R. V. Wright, and D. R. Yarnall.

For The Engineering Foundation, A. D. Flinn, and J. T. Grady.

For the Franklin Institute, Howard McClenahan.

For the Rockefeller Foundation, Max Mason.

For the United Engineering Trustees, John Arms.

Miscellaneous, Herman Aaron, Parker and Aaron, Charles A. Baker, P. E. Bliss, Warner and Swasey, K. T. Compton, Massachusetts Institute of Technology, and H. W. Craver, Engineering Societies Library.

Conference Groups in Business Planned

A plan to organize permanent conference groups of executives in business and industry is announced by the Personnel Research Federation. Developed to meet the new problems which are being created by rapid economic, governmental, social, and technological changes, the plan aims to establish and to maintain bases for harmony in employee relations. Each conference group will be composed of the highest ranking personnel executive from 12 to 20 companies or institutions, and will meet monthly, or as often as may be necessary, to discuss common problems arising out of employer-employee relations. Groups will be formed in the principal centers of the country, conference participation involving no restriction upon independent action of members in their personnel activities.

The Personnel Research Federation was founded on the initiative of The Engineering Foundation in 1921; National Research Council and numerous other organizations interested in personnel coöperated. It is a federation of research and operating organizations and individuals organized for the purpose of bringing them into mutually beneficial coöperation in obtaining and applying knowledge about men and women at work in the widely varied activities of industry, commerce, government, and education. The industrial department of the Federation maintains a staff of investigators and research workers qualified in economics, statistics, engineering, and industrial psychology, and makes available to industrial members the latest studies of personnel problems contributed by leading universities and other research agencies as members or affiliates of the Federation.

Headquarters for the Personnel Research Federation are in the Engineering Societies Building, 29 West 39th Street, New York, N. Y.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Overcompounded D-C Generators in Parallel Without Equalizer

To the Editor:

The question of the operation of overcompounded d-c generators in parallel without an equalizer has been raised recently on several occasions. The problem is not of great practical importance, but it logically arises in a theoretical study of the parallel operation of d-c machines, and is discussed briefly in several textbooks. Unfortunately these texts are not in agreement, and as a consequence, many engineers are led into making an erroneous analysis of this problem and other related problems of primary importance.

In the text, "Direct Current Machinery" by Harold Pender, published by John Wiley and Sons, it is stated that if 2 overcompounded generators are operated in parallel and made to carry a given load with the equalizer removed and if the speed of one generator is increased, the current supplied by this generator will decrease and the current supplied by the other generator will increase. It is stated that this action will be accumulative so that all of the load will be shifted from the first generator to the other generator. Authors of several other texts hold that the contrary will occur.

At the annual convention of student Branches of the A.I.E.E. in the New York District held April 26, 1934, Sidney Rock and Erick Nelson, students at New York University, presented a paper based upon an experimental study which they contended disproved Professor Pender's statement. On the other hand, a "Letter to the Editor" published in the October 1932 issue of ELECTRICAL ENGINEERING, p. 745, by Professor Brainerd describes tests which he made that supported Professor Pender's view. It is the purpose of this letter to give a brief discussion which it is believed will clear up the points of disagreement.

Before going into the above problem, something should be said in general about the solution of such problems by graphical and analytical methods based upon steady state curves and steady state conditions. The change from one steady state point to another is always a transient change. In order for any graphical solution based upon steady state curves to apply and give correct results, it is necessary that the new operating point given by the curves, and all points between the initial and final steady state points, shall be stable points, and the final point must be a limit point toward which the transient change proceeds. Usually these conditions are properly fulfilled if the system is in stable operation over the parts of the curves involved. If there is any doubt, the transient change must be analyzed.

Now consider Fig. 1, which gives the wiring diagram of 2 overcompounded d-c generators operating in parallel without an equalizer, as described above. Assume that conditions are carefully adjusted so that the 2 generators are carrying a given load, indicated by points A and B in Fig. 2. Kirchhoff's law, which states that the sum of the voltages around a closed circuit must equal zero, holds at all times. Thus, while the current is steady, the sum of the induced voltages of the 2 armatures taken with the proper signs must equal the sum of the IR drops around the path *abcda* taken with the proper signs. If the induced voltage of generator 1 is suddenly increased by any means, Kirchhoff's law still holds, and therefore the sum of the drops must increase. Since there is inductance in the armature and field windings, the current will not change instantaneously. At the first instant the current will be the same as before the increase in voltage of generator 1 occurred. The additional voltage required to make Kirchhoff's law hold comes from the circuit inductance times the rate of change of the current. This equals $-L\frac{di}{dt}$, where L equals the total effective inductance around the circuit *abcda*, and it is assumed that the load current does not change appreciably, at least at first. It will now be seen that the current must increase in the same direction as the increase in voltage in the circuit in order to make $-L\frac{di}{dt}$ of the proper sign. This shows definitely the direction of the initial change of current due to an increase in voltage of generator 1. Since both generators are overcompounded, the initial change in current will cause a further change in the same direction, and the action will be cumulative. These conclusions are in agreement with those reached by Messrs. Rock and Nelson, and contrary to those given by Professors Pender and Brainerd.

The discussion referred to in "Direct Current Machinery" by Pender is based upon the steady state voltage regulation curves given in Fig. 2.

Briefly, in Professor Pender's discussion the total load is represented by the length AB. If the voltage of generator 1 is increased to the value indicated by the dotted curve, it is argued that, since the total load would not change appreciably, the line current would necessarily be given by the line $A'B'$, and since $A'C'$ is less than AC, the current carried by generator 1 would

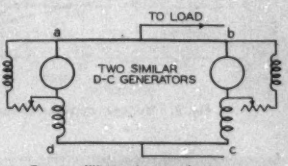


Fig. 1. Wiring diagrams for 2 overcompounded d-c generators in parallel without an equalizer

decrease. The unsoundness of this reasoning is now apparent. The points A' and B' are not stable points on the curves, and, as was shown, the transient change was not toward the points A' and B', but in the opposite direction. As a matter of fact, Professor Pender's method will in certain cases give a correct solution if the regulation curve of generator 1 is extended

sufficiently to the left and the curve for generator 2 is extended to the left in the motor region. Thus, in this case, the steady state curves give 2 solutions, and the transient analysis shows which is correct. Another point of interest is that during the transient change, the current and voltage changes do not follow the steady state curves because of the additional drops due to inductance which are not included in the steady state curves.

The actual transient solution of the current in the above problem showing how the current changes as a function of time is not difficult, but it is laborious and cumbersome if an attempt is made to take all factors into account. By making certain simplifying approximations, solutions may be obtained which are helpful in visualizing the manner in which the current changes.

As the simplest case, in Fig. 2 assume zero load current (each armature supplying only its shunt field current), constant shunt field currents, and constant speeds. Neglect the effect of mutual inductance between armatures and fields, and assume a straight line magnetization curve for each machine. Then, if the induced voltage of generator 1 is suddenly increased, the circuit conditions may be represented by the following linear differential equation:

$$L\frac{di}{dt} + Ri = Ki + E \qquad (1)$$

where

L = the sum of the self-inductances of the circuit *abcda*

R = the sum of the resistances around the circuit *abcda*

K = the resultant series magnetizing factor, which when multiplied by i gives the sum of the voltage changes due to the effects of the series fields and armature reactions

E = the difference of the 2 armature induced voltages set up by the shunt fields without the aid of the series fields, which difference, with the assumptions made, will be constant.

Set $R-K = N$; then eq 1 may be written

$$L\frac{di}{dt} + Ni = E \qquad (2)$$

Separating the variables and solving for i, there results

$$i = \frac{E}{N}\left(1 - \epsilon^{\frac{-Nt}{L}}\right) = \frac{E}{R-K}\left(1 - \epsilon^{\frac{-(R-K)}{L}}\right) \qquad (3)$$

When the machine is overcompounded, $K > R$; N is negative, and eq 3 becomes

$$i = \frac{E}{K-R}\left(\epsilon^{\frac{(K-R)t}{L}} - 1\right) \qquad (4)$$

Thus, with these approximations, the principal one being the neglect of saturation, a current curve is obtained which increases exponentially to infinity. The first part of the curve before saturation is reached should be reasonably close to the actual curve.

The problem is only slightly more involved if an initial load is assumed, but this solution will not be given here. If it is desired to take into account the effect of saturation, Froelick's equation may be used. The differential equation then becomes

$$L\frac{di}{dt} + Ri = [ai/(b + ci)] + E \qquad (5)$$

Clearing of fractions and collecting terms gives

$$(b + ci)L\frac{di}{dt} + (Rb - a - Ec)i + Rci^2 = Eb$$

Solving for $\frac{di}{dt}$ gives

$$\frac{di}{dt} = (K_1i^2 + K_2i + K_3)/L(b + ci) \qquad (6)$$

where

$K_1 = -Rc$
$K_2 = -Rb + a + Ec$
$K_3 = Eb$

Solving this differential equation gives

$$t = \int dt = \int \frac{L(b + ci)}{K_1i^2 + K_2i + K_3)}\,di + c' \qquad (7)$$

where C' is a constant of integration. With given values for the constants for any given machines, eq 7 may be evaluated by the use of ordinary integral tables. C' can be evaluated by means of the given initial conditions.

In conclusion it may be said that in many of the discussions of this problem there has been a failure to go back to the basic fundamentals involved. Also it should be pointed out that experimental results may be misleading where the set up is unstable and it is not clearly kept in mind that the problem is transient in nature. In an experimental problem of this character it is difficult to get the correct adjustments and values. Many times in such cases an analytical solution or analysis is more dependable than an experimental one. However, in 2 or 3 attempts, the writer has always checked experimentally the analytical conclusions given above for this problem.

Very truly yours,

O. W. Walter (M'29)
(College of the City of New York, N. Y.)

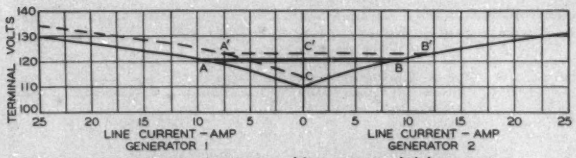


Fig. 2. Voltage regulation curves of 2 overcompounded d-c generators

Information on Oliver Heaviside

To the Editor:

The fiftieth anniversary issue of Electrical Engineering (May 1934, p. 814) contained a biographical sketch of Oliver Heaviside and stated that no pictures existed of him. This is not correct, however, as several pictures have been published. An article by F. Gill in the *Bell System Technical Journal*, July 1925, p. 349, contains one picture. This particular picture is also reproduced as a frontispiece in the 1925 edition of "Electrical Papers" published by the Copley Publishers of Boston.

Oliver Heaviside (HM'18)

In the October 1928 issue of *Electrical Communication* p. 71, is an article by Rollo Appleyard entitled "Pioneers of Electrical Communication—Oliver Heaviside." This contains several photographs of Heaviside and, in addition, views of the Heaviside family and of the family residence.

I am enclosing a copy of what seems to me to be the best of these pictures which I obtained from Mr. Appleyard 2 years ago and which, I feel, is desirable to publish in some future issue of Electrical Engineering."

Mr. Appleyard apparently went to considerable pains to learn the date of Heaviside's birth. From the records at the General Register Office, Somerset House, London, and the Town Hall Archives, Saint Pancras, London, he found the date and place recorded as May 18, 1850 and 55 King Street, Camden Town, London. The date given in the anniversary issue was 1848.

Very truly yours,

Carlton E. Tucker (A'22, M'28)
(Associate Professor of Electrical Engineering, Massachusetts Institute of Technology, Cambridge)

Editor's Note: The information given in the May 1934 issue of Electrical Engineering, while based upon a careful search of the available records, is apparently not correct, and we are glad to be able to submit that given above by Professor Tucker.

Personal Items

H. M. TURNER (M'20) associate professor of electrical engineering, Yale University, New Haven, Conn., has been appointed chairman of the Institute's technical committee on communication for the year 1934–35. He was born at Hillsboro, Ill., in 1882 and studied electrical engineering at the University of Illinois receiving the degrees of B.S. in 1910 and M.S. in 1915. From 1910 to 1912 he remained at the university as an instructor, and then became an instructor at the University of Minnesota, where he organized courses in transient phenomena and radio. At the time of the war he was in charge of technical instruction of Signal Corps personnel, and came to the school for officer candidates at Yale University as assistant professor in 1918. In that year he was appointed an assistant professor of electrical engineering at Yale University, and was appointed associate professor in 1926, devoting his entire time to graduate instruction including courses in transient phenomena, wave propagation, and electronics, and directing research. Professor Turner has been a member of the Institute's committee on instruments and measurements since 1926, and of the communications committee since 1927. He is a member of the Institute of Radio Engineers, International Scientific Union, American Association for the Advancement of Science, Franklin Institute, Sigma Xi, and Eta Kappa Nu, and has published a number of papers in technical journals.

N. R. STANSEL (A'03) industrial engineering department, General Electric Company, Schenectady, N. Y., has been appointed chairman of the Institute's committee on electrochemistry and electrometallurgy for 1934–35. He was born at Allenton, N. C., in 1877. After receiving the degree of B.S. from North Carolina State College in 1898 he remained as an instructor of physics for 3 years, then entered Cornell University for postgraduate work, receiving the degree of M.M.E. in 1903. He was employed by the Federal government for 8 years, then entered the a-c engineering department of the General Electric Company at Schenectady. He was subsequently transferred to the industrial sales and industrial engineering departments, and became manager of the office at El Paso, Tex. He returned to Schenectady in 1921 and has since been engaged in the industrial engineering department on work connected with electrochemistry and electrometallurgy. His book "Industrial Electric Heating" has recently been published. Mr. Stansel was a member of the general power applications committee, 1929–30, and has been on the committee on electrochemistry and electrometallurgy since 1930.

F. M. FARMER (A'02, F'13) vice president and chief engineer of Electrical Testing Laboratories, New York, N. Y., has been reappointed chairman for the year 1934–35 of the Institute's technical committee on research, of which he was chairman for part of the past year. A biographical sketch of Mr. Farmer is given in ELECTRICAL ENGINEERING for February, 1934, p. 231, and a photograph on p. 1038 of the July 1934 issue. He has been a member of the research committee since 1929 and is also a member of the committees on power transmission and distribution and coördination of Institute activities. Recently he was elected vice chairman of the Standards Council of the American Standards Association.

C. M. DAVIS (A'08) engineer, transportation department, General Electric Company, Erie, Pa., has been appointed chairman of the Institute's technical committee on transportation for the year 1934–35. He was born at Chicago, Ill., in 1884 and completed the electrical engineering course at the University of Michigan in 1908, receiving the degree of B.S. The following year he received his master's degree from Union College, Schenectady, N. Y., and immediately entered the test department of the General Electrical Company there. Later he was assigned to the consulting engineering department, where he worked under Dr. Steinmetz. In 1913 he was transferred to the railway engineering department, becoming administrative assistant of the department in 1926. The department was moved to Erie in 1929, and Mr. Davis was named assistant engineer in 1930, the name of the department meantime having been changed to transportation department. Recently he was named engineer in charge.

M. E. REAGAN (A'20, M'30) section engineer, automatic switching section, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been appointed chairman of the Institute's technical committee on automatic stations for the year 1934–35 He was born at Bridgewater, Iowa, in 1894 and after graduation from the University of Illinois in 1917 became inspector of substations for the Kansas City Railways Company, Kansas City, Mo. In 1920 he entered the employ of the "Westinghouse company as a design engineer on automatic and remote control of power and substations. Since 1927 he has been engineer in charge of automatic switching, supervisory control, and carrier current applications. He has been a member of the automatic stations committee of the Institute since 1929.

A. E. LOGAN (Enrolled Student) Proctor and Gamble Company, Cincinnati, Ohio, with his co-author S. W. HANNAH (Enrolled Student) has been awarded the Institute's 1933 North Central District prize for Branch paper and has received honorable mention in the 1933 national awards for Branch paper for the paper entitled "The Measurement and Control of the Synchronous Machine Torque Angle." Mr. Logan was born at Marysville, Mo., in 1911 and moved to Colorado 10 years later. He received the degree of B.S. in E.E. from the University of Colorado in 1933. It was during his senior year that the prize winning paper was prepared. As holder of a fellowship he returned to the university for another year and received the degree of M.S. in E.E. in 1934.

J. C. LINCOLN (A'07, F'32) chairman, board of directors, Lincoln Electric Company, Cleveland, Ohio, has been awarded the Samuel Wylie Miller medal of the American Welding Society in recognition of his contributions to the advancement of the science of electric fusion welding.

H. M. TURNER

N. R. STANSEL

M. E. REAGAN

C. M. DAVIS

R. W. GRAHAM

U.S. Bureau of Mines Photo

L. C. ILSLEY

W. F. DAVIDSON

Mr. Lincoln is one of the early pioneers of arc welding and has devoted most of his life to its research and development as an industrial tool. He is a graduate of Ohio State University, and was on the staff of C. F. Brush, inventor of the arc light, before joining the Elliott-Lincoln Electric Company, from which he formed the present company in 1896. It is reported that in 1916 he first used the electric arc in the structural field in the remodeling of an industrial structure; 3 years later the first motor redesigned from cast iron to arc welded steel was completed under his direction, and more recently he introduced the shielded arc. Mr. Lincoln has been a member of the electric welding committee of the Institute since 1927, and has served on 2 other committees.

L. C. Ilsley (A'14) supervising engineer, electrical section, U.S. Department of Commerce, bureau of mines experiment station, Pittsburgh, Pa., has been appointed chairman of the Institute's committee on applications to mining work. He was born at Thetford, Vt., in 1880, and studied at Worcester Polytechnic Institute, receiving the degrees of B.S. in 1903 and E.E. in 1905. Following short periods of time in the employ of the American Telephone and Telegraph Company and the General Electric Company he was employed by the Delaware, Lackawanna, and Western Railroad at Scranton, Pa., in 1906. Since 1910 he has been with the bureau of mines in connection with mine electrical safety work, and has been in charge of this work since 1918. Mr. Ilsley has written a number of technical papers on safety problems related to the use of electrical equipment in mines. He has been a member of the Institute's committee on applications to mining work since 1916, was a member of the safety codes committee from 1923 to 1927, and is now a member of the standards committee, on which he served from 1923 to 1932.

R. W. Graham (A'18, M'31) assistant electrical superintendent, Bethlehem Steel Company, Lackawanna, N. Y., has been appointed chairman for 1934–35 of the Institute's committee on applications to iron and steel production. He was born at Lindsay, Ont., Canada, in 1890 and emigrated with his parents to North Dakota in 1893. Following his graduation from the University of North Dakota in 1913 with the degree of E.E. he became an instructor in engineering at Cornell University for 3 years, and received the degree of M.E. in E.E. He then entered the electrical department of the Lackawanna Steel Company at Buffalo, N. Y. He entered the naval service in 1917 and was radio and communication officer of the U.S.S. "Arizona" at the time he returned to the Buffalo plant, which has since been absorbed by the Bethlehem Steel Company. In 1930 he was chairman of the Institute's Niagara Frontier Section.

W. F. Davidson (A'14, F'26) director of research, Brooklyn Edison Company, Brooklyn, N. Y., has been appointed chairman of the Institute's technical committee on electrophysics for the year 1934–35. He was born at Commonwealth, Wis., in 1890 and studied electrical engineering at the University of Michigan, from which he received the degrees of B.S. in 1913 and M.S. in 1920. In 1914 he entered the Westinghouse Electric and Manufacturing Company, but returned to the university 2 years later as an instructor. The war caused an interruption, and after 2 years service he returned in 1919, and became an assistant professor in 1920. In 1922 he resigned in order to organize research work in the Brooklyn Edison Company, with special reference to the problems of high voltage cables. This work was later expanded to include research and special testing activities in all fields of interest to the company. Mr. Davidson has been a member of Institute's research committee since 1925 and of the electrophysics committee since 1927, and is now secretary of the National Research Council's research committee for insulation.

N. B. Hinson (A'19, M'26) formerly assistant manager of operation, Southern California Edison Company, Ltd., Los Angeles, has been appointed chief engineer and chairman of the engineering committee of that company, reporting to the general manager. Mr. Hinson is a past-chairman of the Institute's Los Angeles Section.

W. M. Hoen (A'06, M'16) chief engineer, Ogleby Norton and Company, has recently returned from Moscow, U.S.S.R., where he has been since May 1930, and is now located at Hinsdale, Ill. For the first 2 years of this period he was chief engineer of a group sent to work on the iron mines, and after the completion of this work was engaged similarly on copper and gold mines and smelters, coming in contact with all the important mines of the U.S.S.R.

J. A. Cook (A'15, F'30) Lynn Gas and Electric Company, Lynn, Mass., has been appointed general manager of the company. He had been general superintendent of the electrical department for 9 years. Mr. Cook is a graduate of Massachusetts Institute of Technology, class of 1912, and was employed by the General Electric Company and the New York Edison Company before going to Lynn in 1925. He is a past-chairman of the Lynn Section of the Institute.

E. W. Judy (A'26) vice president and general manager, Duquesne Light Company, Pittsburgh, Pa., has been elected president of the Pennsylvania Electric Association. Mr. Judy has been identified with the public utility industry in Pennsylvania since he became superintendent of overhead lines of the Duquesne Light Company in 1923, previous to which he had been in western utilities. He was appointed operating manager of the company in 1927 and assumed his present duties 2 years later.

S. S. Hertz (A'17, M'27) has been appointed vice president and chief engineer of the Copperweld Steel Company, Glassport, Pa. Mr. Hertz is a graduate of Alabama Polytechnic Institute, class of 1911. Following employment with the Westinghouse Electric and Manufacturing Company and the Electrical Engineering and Manufacturing Company, he entered the Copperweld Steel Company in 1920, and became general sales manager in 1927.

P. M. Downing (A'98, M'08) first vice president and general manager, Pacific Gas and Electric Company, San Francisco, Calif., is a director of the Pacific Coast Electric Association. Mr Downing was a vice president of the Institute, 1925–27, and was on the power transmission and distribution committee, 1914–17 and 1927–28, and the power generation committee, 1928–29.

A. R. Schiller (A'20, M'27) vice president in charge of operations, Public Service Company of New Hampshire, Manchester, has been elected a vice president of the Twin State Gas and Electric Company to assume operation of the properties of that company which are located in New Hampshire. He will also continue the duties of his present position, to which he was elected in 1926.

B. L. Delack (A'11) formerly works manager, General Electric Company, Schenectady, N. Y., has been transferred to the staff of the vice president in charge of manufacturing and is devoting his time to the personnel problems of the company. Mr. Delack is a graduate of Clarkson College of Technology, and has been with the General Electric Company since 1903, becoming works manager in 1928.

John Fies (A'28) Dallas, Texas, has recently been appointed chief engineer of the R. B. George Engineering Corporation, which engineers, finances, and constructs municipal and industrial power plants and electric systems in the southwestern states. Mr. Fies has been a member of the automatic stations committee of the Institute since 1931.

E. J. Rutan (A'20, M'29) superintendent, test bureau, New York Edison Company, New York, has been elected secretary of the committee on electrical insulating materials of the American Society for Testing Materials. He has served on several committees of the Institute and is now a member of the instruments and measurements, and standards committees.

J. H. Foote (A'18, F'32) supervising engineer, Commonwealth and Southern Corporation, Jackson, Mich., has been elected secretary of the committee on copper wire of the American Society for Testing Materials. He has been a member of the Institute's committees on power transmission and distribution, 1929–31, and protective devices, 1932–34.

T. S. Taylor (M'21) professor of physics, Washington and Jefferson College, Washington, Pa., has been elected chairman of the committee on electrical insulating materials of the American Society for Testing Materials. He is also the Institute's representative on the committee on heat transmission of the National Research Council.

L. R. Hicks (A'12, M'28) electrical engineer, Gibbs and Hill, Rahway, N. J., is in charge of the engineering features of the cable installations in Baltimore, Md., and Washington, D. C., and other underground cable and conduit problems in connection with the electrification of the Pennsylvania Railroad.

W. C. Beckjord (A'12) vice president and general manager, Boston Consolidated Gas Company, Boston, Mass., has resigned to become a vice president of the Columbia Gas and Electric Company with headquarters at New York, N. Y. He was formerly a vice president of the American Light and Traction Company, New York.

B. M. Brigman (M'28) dean, Speed Scientific School, University of Louisville, Louisville, Ky., has been elected a manager for the year 1934–35 of the American Society of Mechanical Engineers. Dean Brigman is a member of the Institute's committee on legislation affecting the engineering profession.

J. D. Waddell (A'32) Beaver, Pa., is in the engineering office of the western division of the Duquesne Light Company at West Bridgewater, Pa.

J. O. Rogers (A'34) is operator in the power house of the Churchill River Power Company, Island Falls, Sask., Canada.

W. S. Hill (A'13, M'20) general superintendent, Grays Harbor Railway and Light Company, Aberdeen Wash., has been appointed chairman of the engineering and operation section of the Northwest Electric Light and Power Association.

R. D. Donaldson (M'17) vice president, Utility Management Corporation, New York, N. Y., has recently been appointed representative, in the corporation, for all southern property groups in the Associated Gas and Electric System.

W. G. Schneider (A'23) engineer, Electric Auto-Lite Company, Toledo, Ohio, has been elected a vice chairman of the committee on nonferrous metals and alloys of the American Society for Testing Materials.

O. B. Lyman (A'18, M'29) manufacturers agent, San Francisco, Calif., has been appointed northern California representative for the R. E. Uptegraff Manufacturing Company of Pittsburgh, Pa., manufacturers of a line of transformers.

W. G. H. Finch (A'22, M'26) for the past 14 years chief engineer of the Hearst radio activities, has resigned to become assistant chief engineer of the Federal Communications Commission, Washington, D. C.

B. L. Conley (A'19, M'24) formerly chief engineer, Sunlight Electrical Manufacturing Company, Warren, Ohio, is vice president and treasurer of the Kingston-Conley Electric Company, Jersey City, N. J., manufacturs of fractional horsepower motors.

G. L. Bascome (M'23) formerly sales engineer, National Valve and Manufacturing Company, Pittsburgh, Pa., has recently been appointed to the staff of the State Corporation Commission, Commonwealth of Virginia, Richmond.

C. C. Knox (A'20, M'30) formerly in the engineering department, Byllesby Engineering and Management Corporation, Pittsburgh, Pa., is now in Shanghai, China, where he is employed by the Shanghai Power Company.

G. S. Timoshenko (A'33) formerly teaching assistant in electrical engineering, University of Michigan, Ann Arbor, is in the department of electrical engineering at the Massachusetts Institute of Technology, Cambridge.

D. E. Foster (A'25) formerly chief radio engineer, General Household Utilities Company, Chicago, Ill., has joined the staff of the RCA License Laboratory, New York, N. Y.

Carl F. Scott (A'10, M'19) Pleasantville, N. Y., has been appointed engineer, appliance division, merchandise department, General Electric Company, Bridgeport, Conn.

E. F. H. Meacher (M'20) director, Delegue de l'Union d'Electricite, Paris, France, has recently been elected president of the International Conference of Large Electricity Distribution Undertakings.

Obituary

Frank Julian Sprague (A'87, M'97, F'12, HM'32, past-president and member for life) died October 25, 1934, as this issue of Electrical Engineering was going to press. A biographical sketch of Doctor Sprague is scheduled for inclusion in the next issue.

Calvin Winsor Rice (A'97, F'12) secretary, The American Society of Mechanical Engineers, New York, N. Y., died suddenly on October 2, 1934 from a cerebral hemorrhage. He was born at Winchester, Mass., on November 4, 1868, and received the degree of B.S. in electrical engineering from Massachusetts Institute of Technology in 1890. His first work was as assistant engineer of the Thomson-Houston Electrical Company at Lynn, Mass. When the company was absorbed by the General Electric Company he became an engineer in the power and mining department at Schenectady, N. Y. In 1895 he was sent to Cincinnati, Ohio, as district engineer for the company, but left shortly after to become electrical superintendent with the Silver Lake mines in Colorado. A year later he went to Montana as a consultant for the Anaconda Copper Mining Company, and then returned to New York where he held various engineering positions in the Kings County Electric Light and Power Company, Brooklyn, and the New York Edison Company, in which he was chief of the meter and testing department. Later he became vice president of the Nernst Lamp Company and a consulting engineer for the General Electric Company. Dr. Rice assumed the office of secretary of the A.S.M.E. in 1906, but he had already been active in engineering societies' work, for he participated in the first coöperative project of the 4 great national engineering societies, namely, the establishment of the John Fritz Medal. In 1902, as chairman of the Institute's building committee, he made efforts to secure a building primarily to house the Lattimer Clark library, the result of which was the gift by Andrew Carnegie of the Engineering Societies Building in New York. During this same year he suggested the plan of the Officers Reserve Corps and the Reserve Officers Training Corps to the chief of staff of the U.S. Army, and later assisted in working out the plan. Dr. Rice was a manager of the Institute, 1900–03, and a vice president, 1903–05. In 1926 he received the honorary degree of doctor of engineering from the Technische Hochschule in Darmstadt, Germany, and in 1932 became an honorary member of the A.S.M.E. Dr. Rice was a member of the Corporation of the Massachusetts Institute of Technology, and served as secretary and member

of the board of trustees of the New York Museum of Science and Industry. He held membership also in the American Association for the Advancement of Science and the American Committee of the World Power Conference, as well as in many organizations in Europe and South America. A medal of honor was awarded him at Cologne in 1931 by the Verein Deutscher Ingenieure in appreciation of his services in promoting mutual international interests of engineers.

George Herbert Harries (A'03, F'22, and member for life) Los Angeles, Calif., died on September 28, 1934. He was born at Haverfordwest, South Wales, on September 19, 1860. After varied experience as a printer, soldier, newspaper correspondent, and editor, he entered utility management when he became president of the Metropolitan Street Railway in Washington, D. C., in 1895. The following year he became president of the Washington Traction Company and associated companies, and in 1902 became vice president in charge of all construction and operation of the Washington Railway and Electric Company and controlled companies. In 1911 he became vice president of H. M. Byllesby and Company, management engineers of Chicago, Ill., and also president of the Louisville Gas and Electric Company, Louisville, Ky., and an officer of a number of companies throughout the country. He retired from the Byllesby Engineering and Management Corporation in 1930. During the war he was a major general, and was placed in command of a base section with headquarters at Brest, France. General Harries was president of the American Electric Railway Association in 1912–13, the Association of Edison Illuminating Companies in 1911–12, and the Illuminating Engineering Society in 1920–21. He was a member of The American Society of Mechanical Engineers, American Gas Institute, and other engineering societies.

Charles H. Wilson (A'91, M'92, and member for life) Mountain Lakes, N. J., formerly general manager of the long lines department of the American Telephone and Telegraph Company, died on September 30, 1934. He was born at Springfield, Ill., on February 13, 1861. After attending the schools in Quincy, Ill., he was employed by the Western Union Telegraph Company in Chicago, Ill., as an assistant electrician. Five years later, in 1881, he became assistant general superintendent of the Central Union Telegraph Company in Chicago. In 1888 he became superintendent of the Chicago Telephone Company, and in 1897 went to New York, N. Y., as general manager of the Southern Bell Telephone and Telegraph Company. He became general superintendent of the long distance lines department of the American Telephone and Telegraph Company in 1900, and general manager in 1915 of the same department, now renamed long lines. Mr. Wilson retired in 1919. Among the advances in which he took part were the laying of the first underground cables from New York to Philadelphia, enlarging use of leased lines by newspapers and press associations, and the inauguration, in 1915, of transcontinental service. During his career the number of telephones in use in the country increased from 71,000 to 11,800,000.

Elwood Grissinger (A'02, F'14) research engineer, Buffalo, N. Y., died on October 8, 1934. He was born at Mechanicsburg, Pa., on March 3, 1869, and received the degree of E.E. from Lehigh University in 1894. For 5 years he was employed by the Westinghouse Electric and Manufacturing Company, and was district engineer and salesman at Syracuse, N. Y., and Buffalo, N. Y. In 1899 he became a commercial engineer for several power companies at Buffalo, and in 1907 opened offices at Buffalo as a consulting mechanical and electrical engineer, where he designed electrical power systems for a number of manufacturing plants. He is credited with developing, about 1910, a relay telephone repeater for use in long distance transmission. The honorary degree of master of science was conferred upon him by Lehigh University for his work and discoveries in telephony.

Kikutaro Nogami (A'08) director, K. Nogami and Company, Osaka, Japan, died on August 1, 1934. He was born at Nishikunizaki on September 8, 1878, and was a graduate of the electrical engineering course at Tokio Imperial University. In 1903 he became chief electrical engineer of the Utsunomiya Lighting Company, and in 1905 became assistant electrical engineer at the Sumitomo Bessi Copper Mine, Iyo, Japan. He was appointed chief engineer in 1907, and later became identified with the company bearing his name.

Membership

Recommended for Transfer

The board of examiners, at its meeting held October 17, 1934, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Skinker, Murray F., asst. director of research, Bklyn. Edison Co., Bklyn., N. Y.

1 to Grade of Fellow

To Grade of Member

Alexander, Edward B., E.E., & asst. supt., elec. dept., N. Y. State Elec. & Gas Corp., Lockport, N. Y.
Anderson, Arvid E., engg. section, panel & equipment div., Gen. Elec. Co., Phila., Pa.
Brown, Vincent J., elec. sales engr., J. Leo Scanlon Co., Syracuse, N. Y.
Carpenter, Charles B., engr., Pacific Tel. & Tel. Co., Portland, Ore.
Cory, Harold M., elec. engr., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Darrin, Ralph M., mgr., central station dept., Gen. Elec. Co., Buffalo, N. Y.
Dewey, Glen H., sales engr., Gen. Elec. Co., Buffalo, N. Y.
Highmy, George W., sales engr., central station dept., Gen. Elec. Co., Buffalo, N. Y.
Fisher, Benjamin A., assoc. prof. of E.E., Okla. A. & M. Col., Stillwater.
Freudenberger, Philip D., designing engr., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Geary, Elmer A., chargeman, elec. drawing room, N. Y. Shipbuilding Co., Camden, N. J.
Hamilton, James H., assoc. prof. of E.E., Univ. of Utah, Salt Lake City.
Harder, Edwin P., engr.-elec., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Humphries, Powell H., asst. prof. of E.E., Tulane Univ., New Orleans, La.
Kramer, Andrew W., assoc. editor, *Power Plant Engg.*, Chicago, Ill.
Morris, Benn G., E.E., Gen. Elec. Co., Buffalo, N. Y.
Oglebay, Wm. J., supt. of distribution dept., Buffalo Gen. Elec. Co., Buffalo, N. Y.
Piasecki, Harry A., E.E., Buffalo Gen. Elec. Co., Buffalo, N. Y.
Pollard, George M., asst. supt. of operation, Buffalo Gen. Elec. Co., Buffalo, N. Y.
Rockwood, George H., member tech. staff, Bell Tel. Labs., Inc., N. Y. City.
Steeb, George, Relay Engr., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Townend, Harold L., E.E., Gen. Elec. Co., Buffalo, N. Y.
Veinott, Cyril G., E.E., Westinghouse E. & M. Co., Springfield, Mass.
Vidal, Henri B., sales engr., Westinghouse E. & M. Co., Niagara Falls, N. Y.
Werly, Berlyn M., E.E., Eastman Kodak Co., Rochester, N. Y.
Wing, Lesher S., chief engr., western div., Nat. Pwr. Survey, Federal Pwr. Comm., San Francisco, Calif.
Young, Wm. M., research engr., Taylor Instrument Companies, Rochester, N. Y.

27 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before Nov. 30, 1934, or Jan. 31, 1935, if the applicant resides outside of the United States or Canada.

Andreasen, I. A., Interborough Rapid Transit Co., N. Y. City.
Apsley, W. J. K. (Member), Pa. Water & Pwr. Co., Baltimore, Md.
Atkinson J. (Member), Westinghouse Elec. & Mfg. Co., Buffalo, N. Y.
Boyce, C. W. (Member), Niagara, Lockport & Ontario Pwr. Co., Medina, N. Y.
Boyles, R. G. (Member), So. Calif. Edison Co. Ltd., Los Angeles.
Brown, E. A. (Member), Westinghouse Elec. & Mfg. Co., Buffalo, N. Y.
Brown, H. J., Leaf Developments, N. Y. City.
Brown, L. K., N. Y. State Elec. & Gas Corp., Lancaster.
Brown, R. LeC., Consolidated Ashcroft Hancock Co., Boston, Mass.
Bunting, G. M., Mich. Bell Tel. Co., Saginaw.
Chaffin, R. B., Va. Elec. & Pwr. Co., Fredericksburg.
Cleveland, T. C., Niagara, Lockport & Ontario Pwr. Co., Olean, N. Y.
Cole, B. T., Westinghouse Elec. & Mfg. Co. Buffalo, N. Y.
Collamore, C. T., Bklyn. Edison Co. Inc., Bklyn, N. Y.
Colvin, A. L. (Member), Niagara, Lockport & Ontario Pw. Co., Angola, N. Y.
Coombs, D. S., 1125 Ellis St., San Francisco, Calif
Cooper, D., Canadian Industries Ltd., Brownsburg, Que., Can.
Cornell, O. K. (Member), Lockport, Newfane Pwr & Water Co., Newfane, N. Y.
Coryell, R. W., Rochester Gas & Elec. Corp., Rochester, N. Y.
DeBoer, D. J., Harza Engg. Co., Columbus, Neb.
Decker, G. E., So. Calif. Edison Co. Ltd., Los Angeles.
Deckman, G. C. (Member), Niagara, Lockport & Ontario Pwr. Co., Olean, N. Y.
Felton, C. H. (Member), Springville Municipal Lt. & Pwr. Plant, Springville, N. Y.
Ferguson, D., N. Y. Hospital, N. Y. City.
Fisher, E. C., Okla. Gas & Elec. Co., Harrah.
Friedrich, H. L., Westinghouse Elec. & Mfg. Co., Houston, Texas.
Gehring, M. C., Am. Tel. & Tel. Co., Toledo, Ohio.
George, G. C. (Member), N. Y. Pwr. & Lt. Corp., Albany.
Gienger, J. A. (Member), Eastman Kodak Co., Rochester, N. Y.
Gohlke, A. C., Cleveland Elec. Illum. Co., Berea, Ohio.
Gonseth, J. E. (Member), Automatic Elec. Co., Chicago, Ill.
Hammar, S. J., Wash. Water Pwr. Co., Spokane.
Harden, J. C., Ind. Bell Tel. Co., Indianapolis.
Hardy, J. R. G., 205 E. 78th St., N. Y. City.
Hayden, C. C., Southern Pacific Co., Oakland, Calif.

Herbein, R. C., Allentown High School, Pa.
Herr, M. D., Wash. Water Pwr. Co., Spokane.
Hooke, F. A. (Member), Gen. Elec. Co., Birmingham, Ala.
Horner, R. S., Am. Steel & Wire Co., Worcester, Mass.
Ide, G. W. (Member), Niagara, Lockport & Ontario Pwr. Co., Medina, N. Y.
Ingersoll, N. A. (Member), Niagara, Lockport & Ontario Pwr. Co., Angola, N. Y.
Jaeger, H. K. (Member), Robertson Elec. Constr. Co., Buffalo, N. Y.
Keller, T. M. (Member), El Paso Elec. Co., El Paso, Texas.
Kennelly, D. J., So. Calif. Edison Co. Ltd., Los Angeles.
Leeder, C. C., Gen. Elec. Co., Schnectady, N. Y.
Malti, M. G. (Member), Cornell Univ. Ithaca, N. Y.
Manz, O. W. Jr. (Member), Bklyn. Edison Co., Inc., Bklyn., N. Y.
Martooll, C. M., Bell Tel. Co. of Pa., Pittsburgh, Pa.
McCallum, J. R. (Member), N. Y. State Elec. & Gas Corp., Lancaster, N. Y.
Moore, E. R., Ind. Bell Tel. Co., Indianapolis.
Morreall, H. W., Kulpmont Steam Elec. Station, Mt. Carmel, Pa.
Olney, D. H., Wash. Water Pwr. Co., Spokane.
Parker, W. F. (Member), Board of Water & Elec. Commissioners, Dunkirk, N. Y.
Peters, R. G., Wash. Water Pwr. Co., Spokane.
Pingree, G. N., Gen. Elec. Co., Dallas, Texas.
Pittenger, H. W. (Member), Westinghouse Elec. & Mfg. Co., Buffalo, N. Y.
Posel, J. A. (Member), E. I. du Pont ed Nemours & Co., Inc., Niagara Falls, N. Y.
Popp, E. W. (Member), Buffalo Genl. Elec. Co., N. Y.
Provenzano, C. J., Buffalo Gen. Elec. Co., N. Y.
Raneri, R., P. W. A. Dept. of Interior, Washington, D. C.
Robison, H. H., Dallas Pwr. & Lt. Co., Texas.
Rouse, A. F. (Member), N. Y. & Queens Elec. Lt. & Pwr. Co., L. I. City, N. Y.
Schelkunoff, S. A. (Member), Bell Tel. Lab., N. Y. City.
Sellers, J. F., Allis Chalmers Mfg. Co., W. Allis, Wis.
Smedberg, J. W. (Member), Board of Pub. Utilities, Jamestown, N. Y.
Snavely, H. E., N. Y., N. H., & H. R. R. Co., Bronx, N. Y. City.
Spence, S. R., Canadian Nat. Carbon Co., Toronto, Ont., Can.
Spicer, M. S., Chesapeake & Potomac Tel. Co. of Va., Richmond.
Sukachoff, A. (Member), City of N. Y., N. Y. City.
Swindell, G. R., Humble Oil & Refining Co., Baytown, Texas.
Wachtel, C. P. (Member), Robertson Elec. Const. Co., Buffalo, N. Y.
Walker, C. P., City Office, Tallahassee, Fla.
Ward, R. P., A. & M. Coll. of Texas, College Station, Texas.
Weagraff, C. R. (Member), Water & Lt. Dept., City of Salamanca, Salamanca, N. Y.
White, C. W., So. Calif. Edison Co. Ltd., Los Angeles.
White, P. A., Pa. Pwr. & Lt. Co., Shenandoah, Pa.
Whittemore, L. E. (Member), Am. Tel. & Tel. Co., N. Y. City.

77 Domestic

Foreign

Haddow, A. B. (Member), Municipal Board, Naini Tal, United Provinces, India.
Whyte, W. L., Ceara Tramway, Lt. & Pwr. Co. Ltd., Fortaleza, Ceara, Brazil, S. A.

2 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Adams, William C., 801 S. Lynn St., Champaign, Ill.
Babloozian, Levon M., 776 N. Cass St., Milwaukee, Wis.
Gosinski, John N., Consumers Pwr. Bldg., Jackson, Mich.
Jordan, Henry, 7408A Christopher Columbus, Montreal, Que., Can.
Losoncy, William A., 14067 Cherrylawn Ave., Detroit, Mich.
Marks, Louis Wendell, 625 McClellan St., Schenectady, N. Y.
Roisland, Kornelius, 356 W. 34th St., N. Y. City.
Schultz, Carl H., 15 Cook St., Jersey City, N. J.
Simpson, Sidney, Deputy Loco. Supt., Eastern Bengal R. R., Kanchrapara, Bengal, India.
Spiegel, Wm. P., 116 Bergen Ave., Jersey City, N. J.
Stunts, Hans, 106 Peck Ave., Newark, N. J.
Wagoner, K. S., 320 Wisconsin, Oak Park, Ill.

12 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

ALLGEMEINE METALLKUNDE. By E. Piwowarsky. Berlin, Gebrüder Borntraeger, 1934. 248 p., illus., 10x7 in., paper, 14.40 rm.; bound, 15.80 rm. The main divisions of general metallography are discussed in this text in easily understood fashion, with emphasis upon general laws and basic relationships. The structure of metals, alloys, the properties of molten metals, solidification, solubility of gases in metals, mechanical and physical properties, crystallization and recrystallization, hardening and heat treating, and corrosion are considered.

ALTERNATING CURRENTS. By A. E. Clayton. N. Y. and Lond., Longmans, Green & Co., 1934. 334 p., illus., 9x6 in., cloth, $4.50. A textbook for students of electrical engineering which covers the essentials concisely, with emphasis throughout upon principles. The book covers the work usually done by second and third year students in English universities.

ARSENICAL and ARGENTIFEROUS COPPER. By J. L. Gregg with a foreword by H. Foster Bain. N. Y., Chemical Catalog Co., 1934. 189 p., illus., 9x6 in., cloth, $4.00. After an historical introduction and a valuable chapter upon the general properties and uses of copper, the book discusses the metallurgy of arsenical and argentiferous copper, its constitution, electrical, thermal, and mechanical properties, the corrosion of arsenical copper and brass, and the uses of arsenical copper. A good bibliography is included. The book is an exhaustive and authentic summary of existing knowledge of these coppers.

BILDWORT ENGLISCH. Technische Sprachhefte 11. MANAGEMENT. Berlin, VDI-Verlag, 1934. 33 p., illus., 8x6 in., paper, 1.50 rm. This pamphlet is one of a series intended to assist German-speaking engineers to read English, especially engineering English. This number is devoted to management. A brief outline of that topic is given in the English language, in which the greatest possible number of technical terms is introduced.

ELECTRICAL COMMUNICATION. By A. L. Albert. N. Y., John Wiley & Sons, 1934. 448 p., illus., 9x6 in., cloth, $5.00. A college text in communication engineering which treats all branches of wire and wireless telegraphy and telephony in their relations with each other in modern systems. The broad engineering features of communication apparatus and plant are described, with the object of providing a basic training. Numerous references to original papers accompany each chapter.

Die KOSTEN der LICHTBOGENSCHWEISSUNG. By F. von Meier. Berlin, VDI-Verlag, 1934. 32 p., illus., 8x6 in., 1.90 rm. This pamphlet reviews the elements that enter into the cost of arc welding and discusses the amount that each contributes to the total cost. Curves are given which enable the welding engineer to determine costs quickly and accurately for all ordinary classes of work.

LOGARITHMS NUMERICAL and GRAPHICAL for the Easy and Accurate Calculation of Commercial and Technical Problems. By N. R. Corke. Lond., Gee & Co. Ltd., 1934. 79 p., illus., 11x8 in., cloth, 8s 6d. This book, which is adapted to self study, is intended to equip the reader to use logarithms readily in technical and commercial calculations. The 4 chief practical applications of logarithms, the table, slide rule, logarithmic graph paper, and alignment chart, are explained and their uses for a variety of purposes illustrated. The book is unusually clear and practical, and calls for little mathematical knowledge.

RADIO RECEIVER MEASUREMENTS. By R. M. Barnard. Lond., Iliffe & Sons, Ltd., 1934. 116 p., illus., 8x5 in., cloth, 4s 6d. Modern methods for measuring the selectivity, sensitivity and fidelity of radio receivers are presented in detail, and the interpretation of tests in estimating receiver performance is discussed. The book is intended primarily for radio service engineers, but will also be useful to amateurs. The standards proposed are in general those of the Institute of Radio Engineers.

RECOMMENDED ENGINEERING DRAWING PRACTICE. By Institution of Engineers, Australia, Science House, Gloucester and Essex Sts., Sydney, N.S.W., 1934. 128 p., illus., 10x6 in., cloth, 4s 6d. This volume is nominally a second edition of "Mechanical Drawing Standards," published by the Institution in 1926. The work has, however, been extended to embrace the drawing practice of all the main branches of engineering and has been rewritten and revised. It is offered as a code, intended to promote uniformity of practice throughout the Commonwealth.

Les COORDONNÉES SYMÉTRIQUES en ÉLECTROTECHNIQUE. By A. Iliovici. Paris, J. B. Baillière et Fils, 1934. 284 p., illus., 8x5 in., cloth, 38 frs. Although the literature upon the application of the method of symmetrical coordinates to electric circuit problems has become voluminous in recent years, there are practically no books giving a general survey of the subject. This lack the present book aims to fill. It presents the principles of the method, explains the fundamental formulas, and shows how they are applied to the solution of problems of unbalanced polyphase circuits.

NATIONAL PHYSICAL LABORATORY, REPORT for the YEAR 1933. London, His Majesty's Stationery Office, 1934. 264 p., illus. 11x8 in., paper, 15s. (Can be obtained from British Library of Information, New York, N. Y., $3.50.) The report reviews the work done during 1933 by the various departments of the Laboratory. The important investigations in the fields of electricity, engineering, metallurgy, aerodynamics, physics, etc., are described in some detail, and a list of papers published by the staff is included. As a guide to the work done and in progress, the book will be useful to research workers and engineers in many lines.

Das WELTFERNSPRECHEN. Vortragreihe des Elektrotechnischen Vereins in Gemeinschaft mit dem Aussenministut der Technischen Hochschule Berlin. Edit. by F. Lubbecker. Munich & Berlin, R. Oldenbourg, 1934. 85 p., illus., 10x7 in., paper, 4.50 rm. A series of lectures, delivered last winter before the German Society of Electrical Engineers, dealing with the problems of international telephony. The history and organization of international service, the technique of international telephony and its economic importance are discussed by several authorities.

THEORIE der ELEKTRIZITÄT. Bd. 1: Einführung in die Maxwellsche Theorie der Elektrizität. By R. Becker. 10 ed. Leipzig & Berlin, B. G. Teubner, 1933. 265 p., illus., 9x6 in., cloth, 14.50 rm. This volume is a new edition of Becker's revision of the well known Abraham-Föppl "Introduction to Maxwell's Theory of Electricity," which first appeared in 1904 and has been one of the most popular texts. The new edition contains a series of revisions and additions which incorporate recent developments and improvements.

Engineering Societies Library

29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

Laytex, an Unusual Dielectric, Is Announced.—Announcement has been made by the United States Rubber Company of a new type of electrical insulation, called Laytex, which possesses a number of unusual qualities. Its principal application so far has been as a covering for wires, and it is believed by the manufacturer that its superior properties will require in time that all existing codes and specifications on wire insulation will have to be rewritten. It is claimed that of all known flexible insulation, Laytex is the most flexible, has the highest tensile strength and resistance to compression, and has the highest dielectric strength and insulation resistance. Because of these qualities, it permits thinner but superior walls which in turn make possible finished conductors lighter in weight and smaller in bulk. In certain applications, a reduction of 25 per cent in the outside diameter, and 50 per cent in the weight of the conductor are effected.

Laytex is derived directly from latex, the milk of the rubber tree. It is a noncoagulated, nonmilled dielectric, purified to remove proteins, sugars, and water solubles. It is maintained in its natural liquid state until the very last manufacturing process, which converts it into a solid dielectric, perfectly and uniformly applied upon a conductor by the dip or pass method. This method consists of running a conductor through a series of baths of liquid, depositing upon the conductor, with each dip, a film of dielectric which is almost immediately converted from liquid to solid. As the conductor travels vertically, any excess liquid flows back into the container. No mechanical support touches the insulation until it has become solidified.

Physical Characteristics. Physical characteristics of Laytex, as determined by tests, show that it has a tensile strength of 5,000 lb per sq in., an elongation at rupture of 750 per cent, and a set in a 2-in. gauge length of $^1/_4$ in. It will be observed that the tensile strength approaches that of nonflexible insulation, and it may be possible to adapt it to service conditions where metallic coverings are now necessary.

Electrical Characteristics. Tests on the electrical characteristics show that it has a dielectric strength of 800 volts per mil; an insulation resistance constant, $K = 54{,}000$, in the formula $R = K \log_{10} D/d$ where R is the insulation resistance in megohms per 1,000 ft, D is the diameter over the insulation, and d is the diameter of the copper conductor. It will be noted that the insulation resistance constant is more than twice as high as that of the best grade of rubber compound required by the A.S.T.M. specifications.

Moisture Absorption. The amount of water or moisture absorbed by Laytex after soaking in water, as determined by the change in specific inductive capacity, is stated to be remarkably low. Values specified are: (*a*) Specific inductive capacity after one day in water shall not exceed 4; (*b*) increase in specific inductive capacity from end of first to end of 14th day shall not exceed 10 per cent; and (*c*) increase in specific inductive capacity from end of 7th to end of 14th day shall not exceed 4 per cent.

Successful applications of this new dielectric have already been made during the development period in many fields. It has been thoroughly proved for a number of different uses, including emergency telephone wire, nonmetallic underground cables, portable cord, switchboard wire, and radio wire. The future of Laytex, in the opinion of the manufacturer, offers possibilities much too great for prediction.

General Cable Appointment.—According to a recent announcement, George Sherry has been appointed General Sales Manager of the General Cable Corp., New York.

Large Order to Delta-Star.—The Bureau of Power and Light, Los Angeles, has awarded a $140,889.00 contract to the Delta-Star Electric Co. of California, Los Angeles, covering sixteen 287,000-volt, 1,200-ampere, 3-pole motor operated disconnecting switches for installation on the 275,000-volt, double circuit transmission line connecting Los Angeles with Boulder Dam. These switches, designed in Chicago, will be manufactured in Los Angeles by Kelman Elec. & Mfg. Co., with whom Delta-Star has made manufacturing arrangements for production of Delta-Star designs in the western territory. According to the announcement the 287-kv switches, known as MR-239, will be the largest yet produced in this country.

Small Motor With Speed Reducer.—The Dunmore Company, Racine, Wis., announces a new motor with built-in speed reducer—type, K3-M, $^1/_7$-hp, equipped with a single gear reduction unit capable of carrying the full power of the universal type motor. Three gear ratios can be supplied from stock—5:1, $14^1/_3$:1, and 34:1, giving shaft speeds of 1,300, 448, and 191 rpm, respectively. The motor has a forced air ventilating system making it suitable for continuous duty.

New Fuses.—The Littelfuse Laboratories, 4507 Ravenswood Ave., Chicago, Ill., announces the latest addition to its specialized fuse family—"Tattelites." Tattelites are a line of neon discharge tubes having breakdown potentials of 100, 250, 500, 1,000, and 2,000 volts. They are really "voltage" fuses, protecting equipment against excessive voltages, whereas regular fuses protect against excessive currents. They operate by shunting out the overload. Applications are numerous; they prevent insulation breakdowns; protect voltmeters, ammeters, transformers, condensers, and gaseous rectifiers against voltage surges; make good radio lightning arresters, leak-off static charges from machinery; test for blown fuses, defective resistors, and condensers; indicate radio frequency, resonance peaks, high tension lines; and are used in making bleeders for d-c power supplies, etc. Tattelites are described in the new Littelfuse catalog No. 6.

Condensers for Condenser-Start Motors.—A wide variety of both electrolytic and oil-filled condensers for condenser-start motors is announced by the Aerovox Corporation, 82 Washington St., Brooklyn, N. Y. Obtainable in round rubber insulated or standard cans, and in rectangular cans with or without insulating jackets, any desired terminals, the electrolytic units offer large capacities at moderate cost. Hermetically sealing effectively prevents evaporation or absorption so that moisture content remains stable throughout long life. Special composition spacer—an exclusive Aerovox feature—protects units against surges. Internal metal parts are entirely of aluminum, eliminating electrochemical action and corrosion, and the containers are leak and seepage proof. Approximately three-quarters of a million of these units have been placed in service during past few years. Oil-filled units are intended for condenser-transformer motors and power factor correction, and are available in round and rectangular containers, various sizes and shapes and terminal arrangements. Each unit comprises a thoroughly dehydrated, oil-impregnated section in oil bath, encased in hermetically-sealed metal container.

Trade Literature

Asbestos Magnet Wire.—Bulletin, 6 pp. Describes round, square, and rectangular asbestos insulated magnet wire. General Cable Corp., 420 Lexington Ave., New York.

Luminous-Tube Transformers.—Bulletin GEA-1305C, 36 pp. Describes various types of transformers used in the operation of luminous-tube signs. General Electric Co., Schenectady, N. Y.

Grease and Oil Seals.—Catalog 25, 16 pp. Describes a new oil and grease seal for application to all types of machinery embodying shafts and particularly electric motors. National Motor Bearing Co., 1173—78th Ave., Oakland, Calif.

Shaftless Motors.—Bulletin 516, 8 pp. Describes various types of shaftless motors; construction, mechanical and electrical characteristics of such motors are outlined as well as their advantages for driving modern production machinery. Engineering data and tables are included. The Louis Allis Co., Milwaukee, Wis.

Published Monthly by

American Institute of Electrical Engineers

(Founded May 13, 1884)

Electrical Engineering

Registered U. S. Patent Office

December 1934
Volume 53
No. 12

The Official Monthly Journal and Transactions of the A.I.E.E.

J. Allen Johnson, President
H. H. Henline, National Secretary

Publication Committee

C. O. Bickelhaupt, Chairman
J. W. Barker
R. N. Conwell
L. A. Doggett
W. S. Gorsuch
H. H. Henline
L. F. Hickernell
E. B. Meyer
L. W. W. Morrow
L. M. Stein
H. R. Woodrow

Publication Staff

G. Ross Henninger, Editor
C. A. Good, Advertising Manager

PUBLICATION OFFICE, 20th and Northampton Streets, Easton, Pa.

EDITORIAL AND ADVERTISING OFFICES, 33 West 39th Street, New York, N. Y.

ENTERED as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918.

SUBSCRIPTION RATES—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii and the Philippine Islands, Central America, South America, Haiti, Spain and Spanish Colonies; $13 to Canada; $14 to all other countries. Single copy $1.50.

CHANGE OF ADDRESS—requests must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered due to incorrect address cannot be replaced without charge. Be sure to specify both old and new addresses and any change in business affiliation.

ADVERTISING COPY—changes must be received by the fifteenth of the month to be effective for the issue of the month succeeding.

STATEMENTS and opinions given in articles appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters.

REPUBLICATION from "Electrical Engineering" of any Institute article or paper (unless otherwise specifically stated) is hereby authorized provided full credit be given.

COPYRIGHT 1934 by the American Institute of Electrical Engineers.

ELECTRICAL ENGINEERING is indexed in Industrial Arts Index and Engineering Index.

Printed in the United States of America. Number of copies this issue—

18,500

This Month—

Front Cover

Clamping a 100 kw tube into its socket at the WLW 500 kw radio broadcasting station in Cincinnati, Ohio. (For a description of this station see I.R.E. Proc., v. 22, 1934, p. 1151–80.)
Photo courtesy Institute of Radio Engineers

Educational Series—No. 12

Mapping of Fields 1563
By ERNST WEBER

Special Articles

Loading a Bank of Dissimilar Transformers 1597
By J. A. BOCK

A Thermionic-Tube Measuring Instrument 1621
By TOM B. WAGNER

A.I.E.E. Papers

Characteristics of a Group of Engineers 1571
By THOS. SPOONER

Ratings of Industrial Electronic Tubes 1577
By O. W. PIKE and DAYTON ULREY

Resistance and Reactance of 3-Conductor Cables 1581
By E. H. SALTER, G. B. SHANKLIN, and R. J. WISEMAN

On the Schooling of Engineers 1589
By ALEX DOW

Coaxial Communication Transmission Lines 1592
By S. A. SCHELKUNOFF

Recommended Transformer Standards 1594
By H. V. PUTMAN and J. E. CLEM

Control of Transients in Welding Generators 1598
By F. B. HORNBY

Measurement of Noise From Power Transformers 1603
By A. P. FUGILL

Cathode Ray Tubes and Their Application 1608
By J. M. STINCHFIELD

Effect of Overloads on Transformer Life 1616
By L. C. NICHOLS

Measurement of Noise From Small Motors 1624
By C. G. VEINOTT

Efficiency Tests of Induction Machines 1628
By C. C. LEADER and F. D. PHILLIPS

Multiple Lightning Strokes 1633
By K. B. McEACHRON

Impulse and 60 Cycle Strength of Air 1638
By P. L. BELLASCHI and W. L. TEAGUE

News of Institute and Related Activities 1662

Winter Convention Technical Program Announced 1662

Announcement of A.I.E.E. Prizes for Technical Papers 1665

American Engineering Council—And Its Relation to the Institute 1666

Services of Engineering Societies Library Available 1668

Finding Work 1670

Letters to the Editor 1678

Membership 1686

Engineering Literature. 1687

Industrial Notes 1688

Employment Notes (See Advertising Section)

Officers and Committees (For complete listing see p. 1332–6, September 1934 issue of ELECTRICAL ENGINEERING)

—Turn to next page

Discussions of A.I.E.E. Papers

Instruments and Measurements

Calibration of the Sphere Gap—Meador 1652

Cross Current of a 5-Arm Network—Seletzky & Anderson 1660

Selsyn Instruments for Position Systems—Linville & Woodward 1660

A Telemeter With Pilot Coil Transmitter—Lunes & Bernarde 1660

Power Generation

A 7,000-Ampere Station Bus—Unland, Morton, Bacon 1646

A Survey of Hydroelectric Developments—An A.I.E.E. Committee Report 1651

The Annual Reference Index to ELECTRICAL ENGINEERING for 1934 will be issued in January 1935 and will be mailed without charge to all members or subscribers who request it. The index will be especially useful to those not subscribing to the A.I.E.E. TRANSACTIONS in that references to all discussions will be thoroughly correlated with references to their respective papers. As the edition will be governed by the number of requests, all those wishing a copy should write at once to A.I.E.E. Order Department.

1935 TRANSACTIONS

TO secure the A.I.E.E. TRANSACTIONS for 1935, your advance subscription must be on file at A.I.E.E. headquarters not later than Friday, December 21, 1934; that is, unless you entered last year your advance subscription for the 1934 volume and "for future editions until countermanded."

NOW a more comprehensive reference volume than ever before, the annual TRANSACTIONS contains the entire contents of the 12 issues of ELECTRICAL ENGINEERING for the current year, excepting only the advertising pages. In fact, the sheets for TRANSACTIONS are printed month by month while the forms for ELECTRICAL ENGINEERING are on the press. This economical means of production enables the continuance of the members' price of $4 per year for the cloth bound volume (paper bound volumes no longer are issued). However, inasmuch as the edition must be determined before the January issue goes to press, it is essential that subscriptions be entered in advance—and it is advisable to enter them "for future editions until countermanded"—although payment will not be required until the volume is ready for distribution.

IF you desire to maintain a permanent file of A.I.E.E. papers and discussions in this permanent form, you are requested to forward your subscription at once; otherwise, there can be no assurance that volumes will be available. For your convenience, an order blank ~~is~~ was provided on p. 18 of the advertising section of ~~this~~ the November issue.

Act Now!

Mapping of Fields

By ERNST WEBER, Fellow A.I.E.E.
Polytechnic Institute of Brooklyn, N. Y.

Field theory, as contradistinct to circuit theory, is shown in this article to become increasingly important in a large number of engineering problems. In addition to the more familiar electric and magnetic fields there are temperature, mechanical stress, hydraulic flow, and other field concepts all reducible to the same mathematical basis. An outline of some of the methods employed in dealing with stationary fields is presented in this paper, conjugate functional methods and conformal representation being considered in detail, preceded by a brief consideration of experimental reproduction, graphical mapping, and mathematical solutions of field problems. This is the twelfth of a series of special articles developed under the sponsorship of the A.I.E.E. committee on education.

IN engineering practice it is generally required to find solutions to problems in a simple and convenient form easily interpretable and easy to visualize. This accounts for the almost exclusive use of the "circuit concept" as contradistinct to the "field concept." Although all phenomena occur in space and time, and as such are field phenomena, it is possible to approximate them by time relations only, summarizing the actual physical constants by means of parameters, preferably of constant value. This elimination of the space concept has been responsible for much of the spectacular development of engineering science. However, as time goes on it becomes increasingly evident that the small group of scientific engineers has repeatedly had reason to reëxamine the basis of the circuit concept and to refine methods of computation by basic work in field theory.

This paper shall, in brief, outline some of the methods employed in dealing with stationary field problems, and is restricted to a survey rather than an exposition of the subject. The rather extensive bibliography can give only meager indication of all the work done in this branch of mathematical physics, and, therefore, only fundamental contributions have been included, selected in some cases because of valuable reference lists contained in the text.

Fundamental Properties of Fields

A *field* is defined as a region of space where in addition to the qualities of space proper there is a physical quantity assignable to each point as a continuous function of the coördinates. So, for example, a temperature field is defined as the relation between temperature T at any point within a certain region of space and its coördinates. Temperature is a *scalar quality* in so far as only numerical value and unit are needed to specify it completely. As another example, the electrostatic field is explored and defined by the field strength $\boldsymbol{E}$, which is a *vector*, needing for its complete determination in addition to numerical value and unit also directional specifications. It is, therefore, customary to distinguish between scalar fields and vector fields.[1]

There are certain types of fields which are of particular importance in theoretical physics because of their organized structure. Obviously, only univalued relations can have physical significance if causality is adhered to for macroscopic phenomena.

Consider, then, a vector field, defined in general by the field vector $\boldsymbol{A}$. Mathematically, differentiations and integrations are most important operations and if these lead to simple forms it may be concluded that the field structure is highly organized. An example is the gravitational force field $\boldsymbol{F}$. Integration along a path with end points P_1 and P_2 of the form $\int_{P_1}^{P_2} \boldsymbol{F}.d\boldsymbol{s}$ represents work done or energy expended by the field along this path. Obviously, the simplest force field must be one where this integral does not depend upon the path chosen but only upon the 2 end points P_1 and P_2, as is the case in the gravitational field. If integration follows such regularity some inherent restriction may be suspected on the rate of change in space of the vector, or in other words, of its differential quotients, and, indeed, it is possible to derive for the gravitational field the relation curl $\boldsymbol{F} = 0$ as an equivalent statement.[1] (In cartesian coördinates the vector notation curl $\boldsymbol{F} = 0$ is equivalent to the 3 scalar equations

$$\frac{\partial F_z}{\partial y} - \frac{\partial F_y}{\partial z} = 0, \frac{\partial F_x}{\partial z} - \frac{\partial F_z}{\partial x} = 0, \frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y} = 0.)$$

But if the vector has no circuitation it can be shown that there is a scalar function correlated with it such that $\boldsymbol{F} = -\text{grad}\ \Phi$ and the force field can be represented as the "derivative field" of a scalar field, the scalar being called "potential." Many of the physical vector fields exhibit this characteristic although it is not always possible to give such a simple explanation. (In cartesian coördinates the vector notation $\boldsymbol{F} = -\text{grad}\ \Phi$ is equivalent to $F_x = -\frac{\partial \Phi}{\partial x}$, $F_y = -\frac{\partial \Phi}{\partial y}$, and $F_z = -\frac{\partial \Phi}{\partial z}$.)

As another example consider the flow of a liquid within a channel where the velocity $\boldsymbol{v}$ is the representative field vector. The integration $\int\int_o \boldsymbol{v}\cdot d\boldsymbol{s} = \int\int_o v_n dS$ over a closed surface gives, as is easily seen if the density is constant, the total flow through this closed surface. ($\int\int_o$ indicates integration over a closed surface.) Thus, if this integral van-

1. For all numbered references see list at end of paper.

ishes, as is usually the case, no liquid is accumulating or disappearing. An exception would be an underground source of water of unknown location so that only the increase beyond the balancing value could be observed. Again this regularity must imply a relation of the differential quotients and it can be shown that div $\boldsymbol{v} = 0$, a special form of the equation of continuity of flow. (In cartesian coördinates the vector notation div $\boldsymbol{v} = 0$ is equivalent with the scalar equation $\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0.$) But if the vector has no divergence, its field can be represented as the derivative field of another vector field such that $\boldsymbol{v} = \text{curl } \boldsymbol{P}$, the new vector being called the "vector potential" in rather loose analogy to the scalar mother function introduced above.

The 2 types of fields are referred to as the potential field and the circuital field and their proper combination can produce any general field whatsoever. Field vectors for which curl $\boldsymbol{A} = 0$ and div $\boldsymbol{A} = 0$ admit of complete determination by the scalar mother function, the potential, defined through $\boldsymbol{A} = -\text{grad } \Phi$. Such fields are the most regular type and the most important ones in physics and engineering; their mathematical representation is the simplest and is usually summarized as "potential theory" proper, and constitutes the most extensively developed branch of mathematical physics.

Potential Fields in Engineering

The overwhelming importance of potential fields for general physics and engineering may be illustrated by Table I where several branches of science are enumerated and some of their important fields of applications indicated. Such a table can by no means be complete and the references are restricted to a few outstanding contributions. Even so the bibliography shows the difficulty in attempting to treat a field so wide and varied. In anticipation of greater interest in applications to electrical engineering, stress has been laid upon applications in this particular branch and the fundamental books or treatises concerned with the mathematically related branches are included in the bibliography.

For the sake of simplification and uniformity of expression the general notation Φ for scalar potential and $\boldsymbol{A}$ for field vector shall be used throughout. The interpretation in terms of a particular branch appears evident if Table I is consulted.

In a true potential field it is easy to find orientation. The surfaces where Φ = cons are called *equipotential surfaces*, and they never can intersect each other. The field vector can be used to define *field lines* in such a form that the vector always is tangential to these lines. These curves represent the shortest path from higher to lower potential if the greatest rate of change is considered. It can easily be proved that field lines and equipotential surfaces must be 2 families of orthogonal geometries. One family being known, the other can be traced without trouble. For a potential field vector generally

$$\text{div } \boldsymbol{A} = s(x, y, z) \tag{1}$$

where s is the distribution of sources and sinks assumed to be known. (A region of space where the divergence of the field vector does not vanish is called a source or a sink according to whether there is a positive or negative value of divergence.) Combining eq 1 with the definition of potential

$$\boldsymbol{A} = -\text{grad } \Phi \tag{2}$$

there is obtained generally

$$\text{div grad } \Phi = -s(x, y, z) \tag{3}$$

a linear differential equation of the second order, known as the potential equation. Its solution is usually obtained in 2 steps by first solving the homogeneous differential equation

$$\text{div grad } \Phi = 0 \tag{3a}$$

known as the Laplacian equation, and then determining the complete integral, *e. g.*, by the method of

Table I—Table of Potential Fields

Branch of Science	Potential Function Φ represents	Field Vector A represents	Important Applications	Reference numbers in list at end of paper
Electrostatics	Electrostatic potential	Electric field strength	High voltage problems Cable theory Transmission line theory (Communication and power)	1, 2, 6, 7, 9, 10, 11, 12, 15, 16, 18, 23, 24, 25, 30, 35, 36, 37, 38, 39, 46, 47, 48, 49, 50
Electrodynamics	Current potential (same values as electrostatic)	Electric field strength	Ground currents Electrolytic conduction Current distributions	1, 2, 6, 7, 15, 18, 40
Magnetostatics	Magnetostatic potential	Magnetic field strength	Permanent magnets Electrical machinery Transmission line theory Interference	1, 2, 6, 7, 14, 15, 16, 17, 18, 19, 20, 21, 22, 31, 41, 51, 52, 53
Thermodynamics	Temperature (isotherms)	Temperature gradient	Temperature distributions in solids, liquids Heating and cooling of machinery Current carrying capacity of cables	2, 3, 6, 11, 32, 54
Mechanics	Gravitational potential	Force	Gravitational problems	1, 6
Theory of elasticity	Stress function	Stresses	Torsion problems Static stress analysis Theory of deformations	2, 4, 6, 55
Hydraulics	Velocity potential	Velocity	Flow of liquids Hydrostatics Dam designs Streamlining of vessels	2, 6, 8, 13, 42
Aerodynamics	Velocity potential	Velocity	Flow of gases Streamlining Aeroplane design Profiling of wings	2, 5, 6, 8, 42

variation of constants. If the field does not contain any sources or sinks one is immediately led to eq 3*a* which, therefore, represents the fundamental formulation of the potential problem.

Solutions of the Laplacian equation are known in great numbers. The difficulty in treating special problems is, however, not so much to find a general solution for eq 3*a* as it is to satisfy the particular boundary conditions. A general solution of eq 3*a* contains for each coördinate 2 independent integration constants and the problem is relatively simple as long as there are for each coördinate 2 boundary surfaces, at different fixed potential values, each expressible in one single variable. This means that only very idealized problems can be treated and in addition the boundary surfaces must have simple forms. Most of the practical problems, therefore, devoid of simplicity, are not amenable to direct mathematical treatment.

It is this situation, which, in view of the tremendous importance of potential fields, spurred the search for methods of field mapping by whatever means possible. Scanning the various methods available in potential theory they can be grouped as follows:

a. Experimental reproduction.
b. Graphical mapping.
c. Semigraphical mapping.
d. Direct mathematical solutions.
e. Direct mathematical approximation.
f. Conjugate functional methods.
g. Conformal representation.

On account of the broad scope, the following paragraphs will give a short critical survey of the methods enumerated, with references, special emphasis being laid upon the last 2 most recent and powerful mathematical tools.

Experimental Reproduction

The functions Φ and A are common to all potential problems. Analogies may, therefore, be drawn between any 2 branches of applications and if there is one potential field that can easily be set up at will in the laboratory, all the other fields can be pictured with it. Such a convenient reproducing standard is the electrolytic field, the field of the electric current in an electrolytic trough. The electrodes may be formed into any shape whatsoever, supplied with any potential value, preferably at medium frequencies (400 to 600 cycles) and the potential distribution explored with a probe by means of a potentiometer. Usually a direct cross-sectional graph of the equipotential lines can be obtained.

In this way reproduction of the electrostatic field is often obtained for problems in electronic tubes where several different potentials are applied and where the potential distribution is a controlling factor in the amplification and control characteristics.[9,10] In high voltage cable design this method is used to study the electrostatic field as well as the temperature distributions under varying conditions, simulating the dielectric constants and thermal conductivities by electrolytes and electrodes of different electric conductivities.[11,12] Quite recently another interesting example can be found in the reproduction of a hydraulic problem,[13] evaluating the pressure field on a dam.

Another experimental reproduction method was employed for study of magnetic field distributions in armatures and slots of electrical machines to assist in the proper design. The field lines are shown by finely distributed colored glycerine forced into water flowing between glass plates so that very clear photographs of the stream lines could be obtained.[14,31]

Graphical and Semigraphical Mapping

Purely graphical methods have been developed chiefly for the electric and magnetic fields in space and for 2-dimensional arrangements. Having a good textbook available[15] it might seem superfluous to expand here were it not for the fact that usually no references are given to the original publications where much valuable information can be obtained.

Graphical mapping is essentially based upon the law of superposition, i. e., the fact that fields produced by a number of sources of vanishing dimensions superimpose upon each other without mutual effects. The fields of points and mathematical lines as sources are typical examples. Knowing the individual field picture the resultant for several sources can be easily drawn. The proper selection of field lines and equipotential lines may be guided by the flux principle devised by Maxwell,[16] who also gives examples for electric and magnetic fields.[17] Extensive history and literature on the subject may be found in the "Handbuch der Physik."[18]

In the case of 2-dimensional fields with any arrangements of given equipotential surfaces it is possible to combine certain mathematical properties of the potential field with graphical methods and secure field pictures otherwise not obtainable. Th. Lehmann[19] gave the fundamental theory and many applications to mapping problems of magnetic fields, so important, for example, in the design of large alternators,[19,21] in the computation of transformer leakage,[21] in the evaluation of mechanical forces,[21] and in special operating conditions of machines.[22] For the proper design of electric insulators of all types one needs the knowledge of the field distributions. The 2-dimensional case was developed by Lehmann,[23,29] and Mueller,[20] and the 3-dimensional case with rotational symmetry was suitably modified by Kuhlmann.[25]

The semigraphical methods are of utmost value in all design problems of large machines and high voltage apparatus, and probably constitute the tools most widely used for field mapping. Their disadvantage lies in the amount of labor involved to obtain correct field pictures, necessity for frequent redrawing, and the fact that each picture holds for one individual case only. Although the applications quoted here are in the vector fields of electrical engineering, these methods can be, and are, used for the other vector fields as listed in Table I.[2,5,8]

Direct Mathematical Solution or Approximation

The direct methods are the ones usually treated in the textbooks, and will be found in the fundamental

references of the first part of the bibliography. The current journals of the various scientific and engineering societies publish many contributions to this special field of applied physics or applied mathematics. Any attempt to give a bibliography of these would be futile on account of the immensity of the subject. A very good general survey is given by Kellogg.[6]

As emphasized in the introductory part, the direct methods are applicable for simple boundaries only and solutions are known for the fundamental geometries in the various physical coördinate systems[1] in connection with the related orthogonal function systems.[6,35] Unfortunately it requires, in general, a series expansion to solve even simple potential problems which are in rather remote relation to practical problems, so that direct analysis seems a matter more of mathematical interest than of obtaining practical solutions. The semigraphical methods, in spite of their many disadvantages, have been preferred and are preferable from the engineering point of view, as long as acquaintance with the methods to be described in the following chapters was a rarity.

Conjugate Functional Method

Assuming familiarity with the fundamentals of complex quantities a few fundamental relations will be given to show the usefulness and practicability of conjugate functions for engineering use.

If z is the complex expression for the radius vector in a coördinate plane with origin O (see Fig. 1),

$$z = x + jy = |z| \cdot e^{j\varphi} \tag{4}$$

then any mathematical function of z may be written

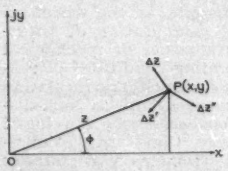


Fig. 1. Complex variable and differentiation in the complex plane

on expansion and separation into real and imaginary parts:

$$w = f(z) = u + jv = |w| \cdot e^{j\theta} \tag{4a}$$

Now z has a geometric meaning; w is, so far, purely fictitious. The function w will be examined more closely. Of all the functions of complex character obviously those will be easiest to study which exhibit some inner organized structure. As shown in the introduction, structure has to do with rate of change. Consider the differential quotient and its common definition analogous to the case of a real variable

$$\frac{dw}{dz} = \frac{d}{dz} f(z) = \lim_{\Delta z \to 0} \frac{\Delta w}{\Delta z}$$

Since Δz, as part of z, is also complex, $\Delta z \to 0$ means an infinity of different possibilities of approach toward P (in Fig. 1 only 3 such possibilities are indicated). A function w which would give different values for its differential quotient depending upon the choice of Δz cannot have much value for physical interpretation. Thus uniformity of $\lim \frac{\Delta w}{\Delta z}$ is demanded independent of the particular choice of Δz. Interestingly enough, this *one* condition, which is the only reasonable one to impose, leads straight to the class of "analytic" functions, the class which bears the closest relation to physical phenomena.

From this one condition the Cauchy-Riemann differential equations[26,27] can be derived:

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y}, \quad \frac{\partial u}{\partial y} = -\frac{\partial v}{\partial x} \tag{5}$$

which restrict the variability of the real and imaginary parts of the complex function and, in fact, constitute an interrelation such that if u is assumed, v follows immediately.[28]

Furthermore, if eq 5 are differentiated, the first with respect to x, the second with respect to y and both results are added, there is obtained

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0 \tag{6}$$

and similarly

$$\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} = 0 \tag{7}$$

which is the potential equation in 2 dimensions for a Cartesian system. Thus any analytic function of z represents with its real and with its imaginary part the mathematical expression for possible potential fields in 2 dimensions.

Consider as a special case the function

$$w = a \log z = a \log |z| + ja\varphi = u + jv \tag{8}$$

(Logarithms given are natural logarithms, i. e., to the base e.) It is customary to call the absolute value of the radius vector

$$|z| = r = \sqrt{x^2 + y^2}$$

and $\log r$ must represent a potential field. It is easily identified with the electric field of an infinitely long wire uniformly charged, the potential of which is given by[1,6,7]

$$\Phi = \frac{q}{2\pi\Delta} \cdot \log r = u$$

Here q is the charge per unit length and Δ the absolute dielectric constant.[29] The constant follows as

$$a = \frac{q}{2\pi\Delta}$$

Since the imaginary part of w also satisfies the potential equation it is interesting to ask what it represents. Putting

$$v = \text{cons}$$

the lines φ = cons, or radii vectors are obtained, which are the field lines. In general v = cons leads to a family of curves orthogonal to u = cons, i. e., to the equation of the field lines and is, therefore, called the *flow function*. It is this relationship which

accounts for the importance of complex functions in potential theory and which has led to the designation conjugate functions for u and v in the combination w.

Let the general rule be accepted of considering the real part of an analytic function as a real potential function

$$Re(w) = u = \Phi$$

and the imaginary part as the orthogonal flow function

$$Im(w) = v = \Psi$$

which defines the field lines. On account of eq 6 and eq 7 it may be asked what is represented by

$$Re(jw) = -v = \Phi$$
$$Im(jw) = u = \Psi$$

In this case, obviously, the field lines are the circles and the equipotential lines the radii vectors—the magnetic field of an infinitely long linear current is obtained.

The case given by $r = 0$ is rather embarrassing in the mathematical as well as in the physical sense, since nature must present herself at least to our senses in 3-dimensional and probably finite space; and to

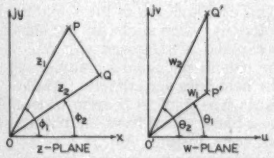


Fig. 2. Correspondence of points in 2 complex planes

have log r at the point where $r = 0$ assume a value $(-\infty)$ is a mathematical absurdity, but this cannot be prevented on account of our limited tools. To avoid these difficulties which always arise when it is attempted to follow the mathematical pictures of physical phenomena to the limits, $r \doteq 0$ is simply excluded and its infinitesimal neighborhood—whatever that may mean—is defined as a "singularity," a plain confession of the limitations. Nevertheless, the picture can thus be saved for finite value, of r, which is all that can be verified experimentally anyway. (A similar consideration ought to be given for the region $r = \infty$.)

The conjugate functions log z have been shown to represent at finite distances the fields produced by "source lines" and "circuital axes," according to the choice of u or v as the potential function. The most important conclusion is that the law of superposition can be applied for several such lines or axes and leads to the functional correlate to the pure graphical mapping method. Much use has been made of this functional construction of fields for electrical problems involving the electrostatic field of grids in vacuum tubes,[30] for the magnetic fields of any number of parallel wires carrying current with or without iron,[31] for the temperature distribution in multiconductor cables,[32] for the capacity effects in multiconductor cables,[33] for the flow of liquids,[34,2] and other problems.

Knowing the particular potential function the field vector is obtained according to eq 2 as

$$A_x = -\frac{\partial\Phi}{\partial x}, \; A_y = -\frac{\partial\Phi}{\partial y}$$

or expressed as a complex quantity

$$\bar{A} = A_x + jA_y = -\left(\frac{\partial\Phi}{\partial x} + j\frac{\partial\Phi}{\partial y}\right) \tag{9}$$

In this form $\bar{A}$ is often said to have the character of a "plane vector." This is not only misleading but accounts for unexplainable discrepancies in complex

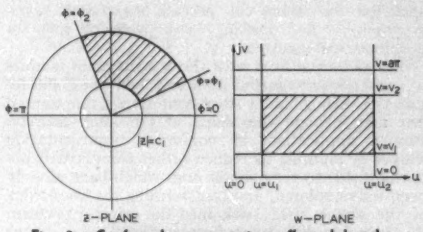


Fig. 3. Conformal representation effected by the analytic function w = log z

integrations. The notation $A_x + jA_y$ is but one possible combination of the 2 components which, properly understood, is more convenient than the vector notation now universally used in vector analysis.

Conformal Representation

The functional relation $w = f(z)$ can be interpreted in another interesting manner. Equation 4a has essentially the same form as eq 4 and obviously no objection could be raised to considering w as a complex representation of points $(u + jv)$ in a separate plane of its own. As in Fig. 2, a w-plane and a z-plane can be correlated so that any point $P(z_1)$ or $Q(z_2)$ corresponds to a point $P'(w_1)$ or $Q'(w_2)$, respectively, and any array of values z is correspondingly represented by an array of values w. This transformation of an array in z into one in w is completely determined by $f(z)$ the transforming function and, therefore, depends in its qualities upon $f(z)$.

If now $w = f(z)$ is an analytic function its derivative $\frac{dw}{dz}$ will be a definite function of z only

$$\frac{dw}{dz} = f'(z) \tag{10}$$

and will not depend upon dz by definition. Writing $f'(z)$ and dz as complex quantities in polar form

$$f'(z) = M \cdot \epsilon^{j\alpha}, \; dz = ds \cdot \epsilon^{j\beta} \tag{11}$$

there results for eq 10

$$dw = (M\,ds) \cdot \epsilon^{j(\alpha+\beta)} = dS \cdot \epsilon^{j\Theta} \tag{12}$$

Equation 12 shows the peculiarities of the transformation: the magnitude of dw bears a ratio M to

the magnitude of dz, which is constant for any one point whatever the direction of dw might be, but varies from point to point (since M is a function of z only); the direction of dw is rotated with respect to that of dz by an angle μ, again constant for any one point but varying from point to point. These 2 properties mean a geometrical transformation maintaining proportionality in infinitely small regions with preservation of all angular relations but effecting a complete deformation in finite dimensions. The main feature is that angles remain the same in both planes, since rotation by a constant angle takes place at each point, a characteristic which is responsible for calling this process a *conformal representation*,[36,2] and making it a powerful tool for mathematical analysis.

The potential field with the 2 orthogonal families of curves, equipotential lines and field lines, will retain this orthogonality when conformally represented but may change the shape of the lines entirely. Proper application of conformal representation should be suitable to reduce rather complicated potential fields to very simple ones which have already been fully explored, and transforming the knowledge of the simple field back into the original problem should solve this by transformations only. Since the only condition is that $f(z)$ be an analytic function, a study of the transformations afforded by various such functions should yield a rich crop of solutions to possible problems and those of practical value could be selected.

The function $w = a \cdot \log z$ from eq 8 can now be interpreted as a conformal representation. From

$$u = a \log |z|, \; v = a\varphi$$

it is obvious that

$$u = \text{cons}, \; |z| = \text{cons}$$
$$v = \text{cons}, \; \varphi = \text{cons}$$

or the orthogonal set of coördinates in the w-plane transforms into the orthogonal set of polar coördinates in the z-plane. The shaded areas in Fig. 3 are an illustration of this transformation; the corresponding values are

$$u_1 = a \log c_1; \; v_1 = a\varphi_1$$
$$u_2 = a \log c_2; \; v_2 = a\varphi_2$$

Obviously a complete annular ring from the z-plane would be a finite rectangle of height $(a \cdot 2\pi)$ in the w-plane and if $|z|$ would cover the total range $0 < |z| < \infty$, the infinite strip $-\infty < u < +\infty$ would be its conformal representation.

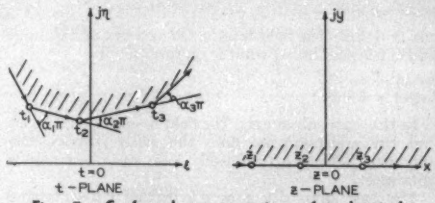


Fig. 5. Conformal representation of polygonal region

An example for this case is shown in Fig. 4 and the correspondence is obvious. One might say the plane condenser of the w-plane is stretched out into 2 planes lying side by side in the z-plane, compressing and lengthening the field lines accordingly. Mathematically the 2 planes $\Phi = \Phi_1$, $\Phi = 0$ seem to meet at the origin of the z-plane which from the physical point of view would seem absurd. But at $z = 0$ eq 8 gives a value for w which can be shown to be singular. Approaching $z = 0$ from left brings $w \rightarrow (-\infty + ja\pi)$, approaching $z = 0$ from the right gives $w \rightarrow (-\infty + j0)$, so that there is a physicomathematical discontinuity, $\frac{dw}{dz}$ at the point where $z = 0$ has no distinct value, and the representation cannot be a conformal one there. This solves the dilemma, since it requires the exclusion of $z = 0$ from the conformal region by a small half circle, representing an infinitesimal field line, and makes the strip in the w-plane finitely bounded on the left-hand side as shown in Fig. 4, where the last field line corresponds to the infinitely small half circle. This example may serve to illustrate some of the difficulties encountered in conformal representation which, while not serious in themselves, should serve as a reminder to always examine carefully the fundamental statements before proceeding further.

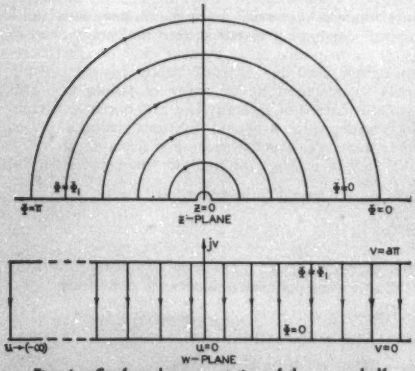


Fig. 4. Conformal representation of the upper half z-plane into an infinite strip in the w-plane. Note exclusion of singular point z = 0

Again, many examples of applications in all branches of science are available in the literature, such as the evaluation of the amplification factor and similar characteristics of vacuum tubes with small grid wires,[37,7] or with grid wires of finite diameter,[38] the capacity problems of bus bars,[39] the flow of current in a circular disk,[40] the determination of the magnetic field distribution in machines,[41] the flow of liquids and gases around cylinders and similar bodies,[2,39] profiling of wings of airplanes,[2,5,42] and other problems.

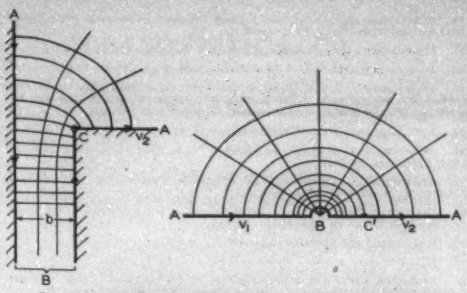


Fig. 6. Illustration of the electric field distribution for a rectangular edge opposite a plane, and its conformal representation upon the upper half plane

Conformal Representations of Polygonal Regions

One of the most important theorems in the domain of complex functions can be stated about as follows: Any finite polygonal region not containing singularities can be conformally represented on the upper half plane so that the boundary of the polygon is uniquely transformed into the real axis.[43,44] The function which performs this is given by[39,26]

$$z = C_1 \int \frac{dt}{(t - t_1)^{\alpha_1}(t - t_2)^{\alpha_2} \ldots (t - t_n)^{\alpha_n}} + C_2 \tag{13}$$

where C_1, and C_2 are 2 complex constants specifying the proper situation of the z-plane with respect to the t-plane and fixing the scale in the z-plane; $t_1, t_2, \ldots t_n$ are the vertices of the polygon, and $\alpha_1\pi, \alpha_2\pi, \ldots \alpha_n\pi$ the supplementary angles of the polygon at these vertices (see Fig. 5). The region represented is alway at the left-hand side if progressing along the boundary from t_1 to t_2 or z_1 to z_2, respectively.

Even a brief account of this invaluable theorem would take up more space than can appropriately be expected. Therefore, only a few remarks will be made and more emphasis placed on enumeration of some important applications. To make the representation a determined one 3 points in the z-plane must be arbitrarily assigned as to their position; conveniently 3 vertices will be chosen. All the other vertices as well as C_1 and C_2 have to be determined by proper correspondence of points and integrations over the lengths of the polygon sides in the t-plane. This usually presents one of the main difficulties in using Schwarz's theorem, as eq 13 is referred to, since the integration indicated there must be performed. This often leads to elliptic integrals and functions for even the relatively simple cases, and to hyperelliptic and unsolvable integrals in many important cases. Thus the method has serious limitations and various attempts have been made to eliminate these restrictions by approximation with polynomial expressions and the like.[26,28]

Notwithstanding the mathematical difficulties, where solutions are possible, they are obtained in one of the most elegant methods of mathematics. Imagine that instead of solving a differential equation of the potential with boundaries not amenable to explicit expression, except as sectional straight lines, one has but to transform the whole region into the upper half plane, join a transformation as Fig. 4 shows (and as was discussed in the preceding section) and there is obtained the field of the plane condenser. Of course, to utilize the homogeneous field properly it will be necessary to arrange the transformation from the z-plane to the w-plane so that the potential values are constant on the lines v = cons; Fig. 4 is only a very simple, special case of 2 potentials.

It remains now to illustrate the practical value by deriving the expression for the field vector. In the t-plane, where $t = \xi + j\eta$, the potential function Φ will be a function of ξ and η and follow Laplace's equation. The field vector, therefore, must be

$$A = -\text{grad}\,\Phi = -\frac{\partial\Phi}{\partial\xi} - j\frac{\partial\Phi}{\partial\eta} \tag{14}$$

Since, however,

$$\frac{dw}{dt} = \frac{dw}{dz} \cdot \frac{dz}{dt}$$

for the complete conformal representation (where $\frac{dw}{dz}$ transforms similar to Fig. 4 and $\frac{dz}{dt}$ according to eq 13) w must be an analytic function of t and

$$\frac{dw}{dt} = \frac{\partial w}{\partial\xi} = \frac{\partial u}{\partial\xi} + j\frac{\partial v}{\partial\xi} = \frac{\partial v}{\partial\eta} + j\frac{\partial v}{\partial\xi} \tag{15}$$

may be used. The first relation states the independence of the differential quotient on the way of approach and the last 2 terms involve the first eq 5. But eq 15 has close resemblance to eq 14, if, as in

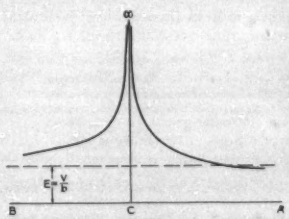


Fig. 7. Variation of the electric field strength along the rectangular edge BCA, computed according to eq 14

Fig. 4, the v-lines are identified with equipotential lines. One, therefore, simply has

$$A = \text{conj}\left[j\frac{dw}{dz} \cdot \frac{dz}{dt}\right] = -\frac{\partial v}{\partial\xi} - j\frac{\partial v}{\partial\eta}, \tag{16}$$

where conj symbolizes that all imaginary parts within the brackets shall be taken with their conjugate (negative) values. Thus, the field vector at any point in the t-plane, the original arrangement, is explained in terms of the transforming function eq 13 and the required joint transformation.

As an illustration, in Fig. 6 is shown the field distribution in t-plane and z-plane for a rectangular edge opposite a plane. The field lines concentrate

at the edge C and a high value of field strength has to be expected there. In Fig. 7 is given the variation of field strength $\boldsymbol{E}$ as computed according to eq 16 along the surface of the rectangular edge BCA, and it can be seen that near the edge C the value of E increases rapidly and, mathematically, reaches infinity. To avoid such highly stressed regions in electric fields, where breakdowns would occur first, it is necessary to round off the corners. Minimum values of the radius of curvature can be estimated from the field picture or computed by approximation methods.[45]

Many other applications have been made among which may be mentioned the design of high voltage insulators,[46,36] and of high voltage transformers,[47,48] the field distribution at the edges of a plate condenser[49] and its application to the proper shaping of the electrodes in order to avoid breakdown at very high voltages,[50] and numerous other electrostatic problems. The magnetic field distribution in the slots of dynamos[51,52] has been investigated as well as in large generators, where the leakage problem is predominant.[53] The temperature distribution in slots of high speed turbine-alternators is another interesting example[54] and finally there may be mentioned the solution of torsion problems[4] especially in the case of the angle iron.[55]

Although the field of conformal representation is the subject of many articles of which only a few have been included in the references which follow, the subject is as yet rather new. Applications to many problems are possible and altogether desirable, since a general solution can be obtained which would permit general conclusions and give analytic methods for improving designs and constructional features.

References

A few general texts on field theories and potential fields in particular are:

1. Vector Analysis, H. B. Phillips. John Wiley and Sons, New York, 1933.

2. Theory of Functions as Applied to Engineering Problems. Cambridge (Mass.) Technology Press, M.I.T., 1933.

3. Introduction to the Mathematical Theory of the Conduction of Heat in Solids, H. S. Carslaw. Macmillan and Co., London, 1921.

4. Die elastischen Platten, A. Nadai. J. Springer, Berlin, 1925.

5. Aerodynamic Theory, A General Review of Progress (Guggenheim Fund). J. Springer, Berlin, 1934.

6. Foundations of Potential Theory, O. D. Kellogg. J. Springer, Berlin, 1929.

7. Potentialfelder der Elektrotechnik, F. Ollendorff. J. Springer, Berlin, 1932.

8. Hydrodynamics, H. Lamb. Cambridge University Press, London, 1924.

Some books and papers giving solutions to special potential problems are given below. Where title is not given the subject of the paper is indicated at the point in text where reference occurs.

9. H. Barkhausen and J. von Brück. *E.T.Z.*, 1933, p. 175.

10. Y. Kusonose. I.R.E. *Proc.*, 1929, p. 1726.

11. Cable Geometry and the Calculation of Current-Carrying Capacity, D. M. Simmons. A.I.E.E. Trans., v. 42, 1923, p. 600–15.

12. Dielectric Field in an Electric Power Cable—II, R. W. Atkinson, A.I.E.E. Trans., v. 43, 1924, p. 966–81.

13. E. W. Lane, *Civil Eng.*, 1934, p. 510.

14. W. M. Thornton, *Electrician*, 1906, p. 959.

15. Electric and Magnetic Fields, S. S. Atwood. John Wiley and Sons, New York, 1932.

16. Electricity and Magnetism, J. Clerk Maxwell. Clarendon Press, Oxford, 1892, v. 1, p. 177 and on; v. 2, p. 13 and on.

17. Magnetische Kraftfelder, H. Ebert. J. A. Barth, Leipzig, 1905.

18. Handbuch der Physik, v. 12 and 15. J. Springer, Berlin, 1927.

19. Th. Lehmann. *E.T.Z.*, 1909, p. 995–1019; and *Revue Générale de l'Electricité*, 1927, v. 22, p. 1105; 1932, v. 31, p. 171; 1933, v. 34, p. 351, to name just a few of his many articles in that journal.

20. A. O. Mueller. *Archiv f. Elektrotechnik*, v. 17, 1926, p. 501.

21. Elektrische Maschinen, R. Richter. V. 1, 1924; v. 2, 1930; and v. 3 1932, J. Springer, Berlin.

22. Graphical Determination of Magnetic Fields, R. W. Wiseman. A.I.E.E. Jl., v. 46. 1927, p. 430–7.

23. Dielectric Phenomena in High Voltage Engineering, F. W. Peek. McGraw-Hill Book Co., New York, 1920.

24. Hochspannungs Technik, A. Roth. J. Springer, Berlin, 1927.

25. K. Kuhlmann. *Archiv f. Elektrotechnik*, v. 3, 1914, p. 203.

26. Lehrbuch der Funktionentheorie, W. F. Osgood. G. B. Teubner, Leipzig, 1928.

27. Functions of a Complex Variable, J. Pierrepont. Ginn and Co., New York, 1914.

28. Partial Differential Equations of Mathematical Physics, H. Bateman. Cambridge University Press, London, 1932.

29. A Proposal to Abolish the Absolute Electrical Unit System, E. Weber. A.I.E.E. Trans., v. 51, 1932, p. 728–42.

30. W. Schottky. *Wiss. Veroeff.* a. d. Siemens Konzern, v. 1, 1920, p. 64.

31. Electromagnetic Problems in Electrical Engineering, B. Hague. Oxford University Press, London, 1929.

32. G. Mie. *E.T.Z.*, 1905, p. 1.

33. The Direct Method of Calculation of Capacitance of Conductors, H. B. Dwight. A.I.E.E. Jl., v. 43, 1924, p. 1034–9.

34. Mathematische Strommuoslehre, W. Mueller. J. Springer, Berlin, 1928.

35. Electricity and Magnetism, J. H. Jeans. Cambridge University Press, 1927, p. 206 and on.

36. E. Weber. *Archiv f. Elektrotechnik*, v. 17, 1927, p. 174.

37. M. Abraham. *Archiv f. Elektrotechnik*, v. 8, 1919, p. 42.

38. Some Conformal Mapping Problems in Vacuum Tube Theory, B. Salzberg. Thesis for M.E.E., at the Polytechnic Institute of Brooklyn, 1932.

39. D. Gabor. *Archiv f. Elektrotechnik*, v. 14, 1924, p. 247.

40. J. H. Awberry. *Philos. Magazine*, v. 13, 1932, p. 674.

41. B. Hague. I.E.E., *Jl.*, v. 61, 1923, p. 1072.

42. Hydro-Und Aeromechanik I., L. Prandtl-Tietjens. J. Springer, Berlin, 1929.

43. H. A. Schwarz. *Crelle's Jl.*, v. 70, 1869, p. 105.

44. E. B. Christoffel. *Annali di Matematica*, v. 1, 1867, p. 95; v. 4, 1871, p. 1.

45. E. Weber. In reference 2, p. 136.

46. W. Wittwer. *Archiv f. Elektrotechnik*, v. 18, 1927, p. 81.

47. W. Groesser. *Archiv f. Elektrotechnik*, v. 25, 1931, p. 193.

48. J. Labus. *Archiv f. Elektrotechnik*, v. 19, 1927, p. 82.

49. G. Kirchhoff. *Berichte der Berliner Akadamie*, 1877, p. 101.

50. W. Rogowski. *Archiv f. Elektrotechnik*, v. 12, 1923, p. 1.

51. F. W. Carter. *Elec. World Engg.*, v. 38, 1901, p. 884.

52. R. Gans. *Archiv f. Elektrotechnik*, v. 9, 1920, p. 231.

53. K. Frey. *Arbeiten* a. d. Elektrotechn. Institut d. Technischen Hochschule Karlsruhe, 1925, v. 4, p. 65.

54. W Peters. *Wiss. Veroeff.* a. d. Siemens-Konzern, v. 4, 1925, p. 197.

55. E. Treffts. *Math. Annalen*, v. 82, 1921, p. 97.

"Science Series" Will Be Reprinted

In response to widespread demand, all articles in the "science series for engineers" will be reprinted in a single booklet. As the edition will be governed by the orders received, all those wishing copies should order at once. See page 1665 and page 4 of the advertising section for further details.

Characteristics of a Group of Engineers

An analysis of the characteristics of a group of development and research engineers is presented in this paper. From this analysis an attempt is made to point out the weaknesses that were responsible for some men being released during this period of abnormal business conditions, and, conversely, to show the elements of strength that permitted others to be retained. Such an analysis should be helpful not only to the young engineer entering industry and to the teachers who have prepared him, but also to his employers.

By
THOS. SPOONER
FELLOW A.I.E.E.

Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.

DURING the past few years of economic stress, employers have found it desirable to study and analyze the value of their individual employees as they never have done before. The necessity for considerable reductions in personnel has resulted in the release of many engineers with adequate technical training because it was judged that those men, although doing their work with reasonable efficiency, were, nevertheless, inferior to others associated with them.

Just as abnormal conditions of loading with consequent failure have resulted in making available valuable data on the strength of various mechanical structures, so perhaps a study of the abnormal requirements imposed on those employees who have not weathered the depression with their jobs intact may reveal weaknesses in a group that before had not been appreciated. Similarly, a study of those who have survived may indicate the elements of strength that permitted their survival.

It has been the author's privilege for some years to introduce a considerable number of research workers to their first regular jobs, and it has been his misfortune to assist some of them involuntarily to relinquish those jobs. It would seem to be interesting and perhaps valuable to examine critically and classify the causes that led to the release of those particular men rather than some of their fellow workers. Many of the men released were only slightly inferior to their associates who remained and in some respects were frequently superior, though a few were obviously misfits and had been retained only because of the scarcity of suitable technical help. Were their faults or weaknesses attributable to lack of satisfactory training, to the fact that they were in the wrong kind of work, to personal characteristics, or what were their major difficulties?

There has been much discussion and criticism lately of the curriculums of engineering schools. Can those men who were released legitimately lay their difficulties to unsuitable training, either of type or quality?

Many of these individuals were selected for their particular jobs by men who have specialized in that sort of thing, and they were under continual observation for a year or more during special training before they were assigned to their final positions. Were the assignments poorly made and was the specialized training not satisfactory? Again, as the result of inheritance or unsuitable environment (in or out of school), did these men have personal characteristics that stood in their way and that might have been improved by serious self-analysis and perhaps by sympathetic external guidance?

It is hoped that this analysis may assist in answering these questions and serve as a guide for young technical students and graduates. It also may be of assistance to those who select and give special training to such young men.

This analysis is confined to men who were engaged in research and development work, and might not apply so well to those in design and commercial activity. They are all men who the author has known for several or many years and with many of whom he has worked and played. The analyses of the reasons for their release, therefore, should be fairly reliable, especially since many of them were checked by others. It should be emphasized that none of these men are failures, but only that their fellows in similar work were judged to be more valuable. Many of these men very shortly were reabsorbed by industry, either by the Westinghouse company or some other concern, in a different capacity and some with better financial rewards than they previously had received.

Only technically trained men are being considered in this analysis and all were active experimenters, that is, none were in purely executive or consulting positions. Also labroatory assistants, whether on technical or manual work, are not included.

Points to be emphasized as a result of this study are these:

1. The great importance of temperamental traits in the success or failure of research and development engineers perhaps is not fully appreciated. More attention should be paid to these traits in the selection, guidance, and early training of prospective engineers.

2. Students should be taught the importance of temperamental traits and personality factors and how these factors will affect their future success even in noncommercial fields of work. This should be started at an early age.

3. Technical schools should consider the possibility of group activities which will involve several students working together on a single project. The weaknesses of an individual as a member of a group should be pointed out to him; and if his faults are such that they cannot easily be remedied, the student should be guided into

Full text of a paper recommended for publication by the A.I.E.E. committee on education, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Oct. 1, 1934; released for publication Oct. 17, 1934. *Not published in pamphlet form.*

activities where his individualistic traits will not be too much of a handicap.

4. Less emphasis in the schools should be laid on obtaining high marks in abstract studies and more on fitting the individual for his life work, taking into account his inherent temperamental and mental peculiarities and limitations. This will require a certain amount of individual work on the part of the instructors which may not fit in well with the present American method of mass production of technical school graduates.

5. There seems to be a definite correlation between success and induction into industry through a student training course.

Analysis of Men Released

The late B. G. Lamme is reported to have stated once that according to his observations, an engineer seldom failed because of deficiencies in technical knowledge, but usually because of some personal characteristic. This may profitably be kept in mind in studying figure 1 which is based on the analysis of the traits of men released since 1929.

It should be understood that each individual may and usually does have more than one point of weakness as will be discussed in more detail later. Each person, therefore, may come under 2 or more different classifications and under several items per class. These items are probably not in accordance with good psychological practice but they do represent the common types of criticism by which individuals often are judged. The "antisocial factors" are those that, if properly controlled at an early enough age, might have been improved. They are, of course, the factors that limit one's effectiveness in group activities. It may be wondered why "unimpressive personality" appears here instead of under "personality factors." It is believed that if an unimpressive person would exert himself a little in an effort to become interesting and to make himself noticed, he readily could eliminate this trait.

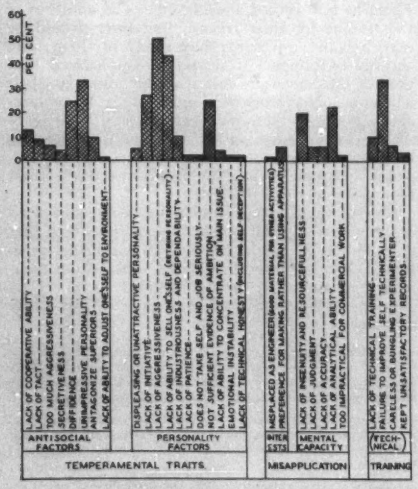


Fig. 1. Faults and weaknesses of men released

The percentages refer to the number of engineers deficient in the particular quality considered, based upon the total number released

It also may be questioned why "displeasing or unattractive personality" appears under "personality factors" instead of "antisocial factors." The reason is that a person may be displeasing or unattractive in spite of the fact that he may make a considerable conscious effort to be quite the opposite. In other words, he may be quite the reverse of antisocial in his desires and intentions.

The "inability to adjust oneself to his environment" is a difficulty experienced chiefly by foreigners whose training and background may be quite different from those in the United States. The items under "temperamental traits" and "misapplication" are largely inherent characteristics resulting from heredity and environment. Some of them could be altered considerably by proper supervision at an early age. Some never could have been altered appreciably. Most of them can be modified very little after a man has reached maturity.

It is felt that the characteristics under "misapplication" may interfere seriously with a man's success as an engineer though the lack of some of them might not be an important handicap in other lines of activity. These are the factors that should have been given particular consideration before a student took up the study of science or engineering. It is particularly unfortunate when a man is trained for engineering and his chief interest and capabilities lie elsewhere. It is probable that many cases of misapplication are avoidable.

Faults under "training" are believed to be due largely to weaknesses in the secondary and technical school education, though even here inherent individual characteristics will cause large variation.

It is interesting to note that the "temperamental traits" form such a large percentage of the causes of failure. The "antisocial factors" do not constitute a very large percentage, but they must be important in such a group as the one being considered here since nearly all research and development work of a large company necessarily must be of a coöperative nature. That the percentage of failures due to these factors is no larger is probably because in engineering and scientific schools and colleges coöperative activities have an important place. A "noncoöperator" is likely to be unhappy and eliminates himself from school or is removed arbitrarily before he finishes his technical training. The term "coöperative ability" is used to include success in getting along not only with those on an equal footing or in other allied activities, but also with one's subordinates as well. In the United States at least, it seems to work best when dealing with creative activities to consider one's subordinates as partners who are free to contribute ideas and not merely to carry out instructions. An executive who cannot work this way is probably not getting the most out of his subordinates.

"Diffidence" and "unimpressive personality" go together usually and are fairly large. It may be that some men are conscious of these defects and are guided into research because they believe that they

Table I—Summary of Faults of Men Released

Characteristic	Per Cent of Men With at Least One Fault Under the Particular Characteristic	Per Cent of Men With Faults of One Type Only*
Temperamental	54	37
Misapplication	45	6
Training	37	2

* There may be several items under one type.

will not be so handicapped in this type of activity, or it may be simply that they feel happier where social contacts are not so frequent or necessary.

The item "antagonizing one's superior" perhaps merits a moment's consideration. A man may be quite successful with one boss and a failure with another. It may be the fault of both or neither. Sometimes 2 strong personalities cannot get along together. Probably the only satisfactory solution is a separation and the sooner the better. Under "personality factors" the 2 big items are "lack of aggressiveness" and "lack of ability to sell oneself," the former showing that more than 50 per cent of the men had this failing. At first glance these 2 factors might be considered to be practically identical. This is not true although the majority of persons who have one of these failings also have the other. A man may be very quiet and nonaggressive and yet so conduct himself as to convince others of his capabilities and value. A man also may be aggressive, of course, without convincing others of his worth. It may be noted that "lack of initiative" and "lack of evidence of ambition" are the next 2 important items in this class. Without initiative a person will not be very valuable in most kinds of research, and if he does not display this quality he is in grave danger of being displaced. "Lack of evidence of ambition" is certainly a handicap. Any normal executive likes to see his subordinates display a reasonable amount of ambition either in the way of leadership or in establishing technical or scientific reputations for themselves. Without such an incentive a man is probably not working as hard and effectively as he should. The other items under "personality factors" are obvious and of minor importance from a percentage standpoint.

In considering the factors under "misapplication" and "training" it should be remembered that many of these men previously had been subjected to a very rigorous elimination process before being assigned to their particular research activities. A few had been hired when technical labor was scarce, and although known for some time to be somewhat unsatisfactory had not been eliminated previously because of the difficulty of replacing them with better material. Apparently very few were misplaced from the standpoint of interests. One or 2 undoubtedly would have been more successful in commercial activities and some would have been happier as artisans or designers. Several men were judged to fall in the "misapplication" class because of inherent limitations in "mental capacity." These limitations definitely prevented these men from going very far in their chosen profession. Earlier in life they should have been guided into activities in which these particular characteristics were not so essential.

A considerable number was lacking in "ingenuity and resourcefulness," which of course is a serious handicap, and a slightly larger number was lacking in "analytical ability." It is possible for a student to graduate from many technical schools with fairly good marks even if he be deficient in these qualities. It is very difficult, however, for him to make a success in research or development work without them.

Under "training" the one large item is "failure to improve self technically." This refers to study and reading beyond that just sufficient for the job immediately at hand. Such study is essential if a man is to keep up with new developments and continue to be valuable under changing conditions. Failure in this respect is due to laziness, lack of ambition, or sometimes to family or financial cares and worries. If a person has sufficient inherent scientific curiosity properly developed by suitable training, this seldom will be a serious fault.

Table I, taken from the same data as figure 1, gives some further interesting comparisons. It is interesting to note that 17 per cent had faults of all 3 major types. This table indicates very clearly that the temperamental faults constitute a large percentage of the total. It is particularly significant that

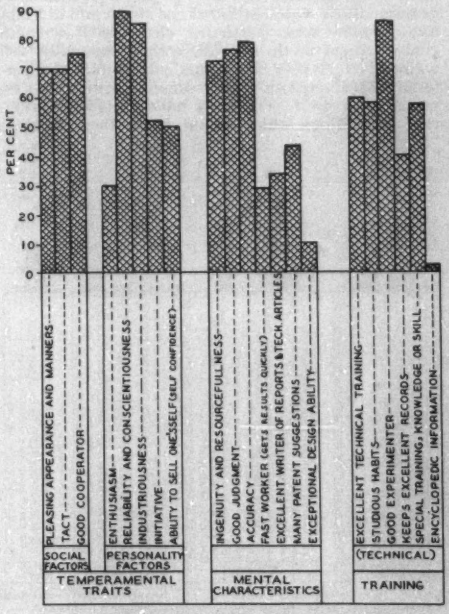


Fig. 2. Qualities in which the men retained excelled

The percentages refer to the number of engineers that excelled in the particular quality considered, based upon the total number retained

37 per cent of those men who were released had faults of this type only. It is also important to note that 84 per cent had temperamental faults of one kind or another. A considerable number was classed with characteristics under "misapplication and training," but it should be realized that the temperamental faults that many of these individuals also had were chiefly responsible for their release.

When the author attended technical school, he was led to believe, by inference at least, that to be a success the one thing necessary was to study hard and master the fundamentals of science and technology. The development of personality traits and the correction of temperamental faults scarcely were mentioned and certainly were not stressed. Perhaps more could be done by the schools in the formative period to bring home to the students the importance of their relations to their fellow men, not from a social standpoint but as a means of holding their jobs and advancing in their chosen profession. After a man becomes older it usually is too late to influence appreciably these characteristics.

Analysis of Men Retained

Now the other side of the picture will be presented. So far only those men who were released have been considered; it may be just as profitable to examine those who weathered the storm and attempt to determine what particular elements of strength enabled them to do so. Were they especially well trained? Did they have particularly pleasing personal characteristics which caused them to be especially favored? Did they have specific information or abilities which would make them hard to

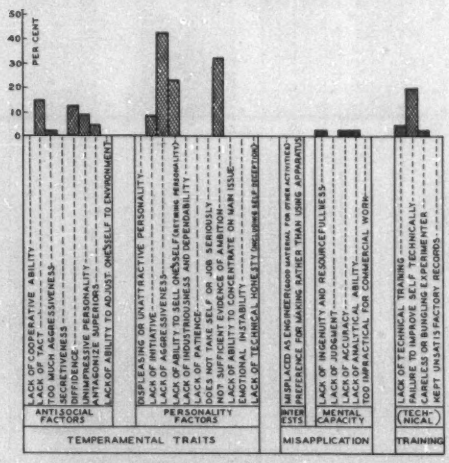


Fig. 3. Faults and weaknesses of men retained

The percentages refer to the number of engineers deficient in the particular quality considered, based upon the total number retained

Table II—Summary of Limitations of Men Retained

Characteristic	Per Cent of Men With at Least One Limitation Under the Particular Characteristic	Per Cent of Men With Limitations of One Type Only*
Temperamental	78	24
Mental capacity	24	2
Physical limitations	4	0
Training	40	6

* There may be several items under one type.

replace, or to what could they attribute the fact that they were among the more fortunate?

This classification is somewhat different since it deals with favorable qualities rather than with faults. It should be realized that a man may have serious faults that would have lead to his dismissal were it not for the fact that his virtues far outweighed them. This will be discussed later. Figure 2 gives an analysis of the favorable traits that made the men retained valuable. It would be expected that the "mental characteristics" and the "training" factors would be high, but it should be noted also that the "temperamental traits" are also fully as high. The "social factors" must be high because modern research on a large scale must be a cooperative activity and the ability to get on with one's fellow men is essential.

The "personality factors" are also very important. It is especially interesting to note that "reliability and conscientiousness" and "industriousness" are so high. If a man does not have these qualities he will not last long in these times unless he has some other outstanding qualities. It may seem surprising that enthusiasm is so low. Some of the best investigators go about their work quietly and never display marked outward signs of enthusiasm. Perhaps one of the most serious weaknesses of the average research investigator is his difficulty in interesting others in the results of his work. This is perhaps partly because of his characteristic of not displaying enthusiasm. He tends to be conservative because he realizes the difficulties in commercializing the results of his investigations.

Under "mental characteristics," ingenuity, resourcefulness, good judgment, and accuracy all rate high as they should, or these men would not have survived. Speed is not nearly as essential and rates somewhat low. Of course, speed is desirable, but not at the expense of accuracy.

Engineers are notoriously poor at writing reports and technical articles. That even 34 per cent of the men retained rate high is a pretty good showing.

Under "many patent suggestions" are included those who have averaged 2 or more per year. Some men have averaged many more than that. On the other hand, many very valuable research men seldom make a patent suggestion. Work of an analytical character may never result in a patentable product.

Except for a few special activities "exceptional design ability" would not be required. If many research men had this trait to a marked degree they probably would be misplaced.

The items under "training" are all high except the last, though there could well be some improvement in

the item of keeping records. A man who has an encyclopedic type of mind is likely to be weak in other desirable traits, particularly ingenuity. This percentage, therefore, is found to be low. If a man knows that certain information is available and where to find it, that is all that is essential.

It should be noted that all of the most important qualities for this group rate very high. A more detailed analysis would show that if a particular individual is not very strong in one or more of these items he makes up for the deficiency by strength in others.

All these men have received ratings in one or more items in each of the 3 main classes with the exception of 2 individuals who received ratings in 2 classes only.

Faults of Men Retained

As previously mentioned, some of the men retained have serious faults, but their favorable characteristics or abilities were so great that they were not dismissed. An analysis of this group under the same classification as for those released is given in figure 3. As might be expected, the patterns of figures 1 and 3 are somewhat similar, but the percentages for those retained are considerably less, or even zero for some traits.

It is particularly interesting to note that the "misapplication" items are reduced to a very low value, as should be the case if the process of elimination were carried out properly. That there should be *any* such cases is due to exceptional conditions which need not be discussed here.

The importance of "coöperative ability" is shown by the fact that the lack of this trait appears as zero in figure 3.

Only 2 items are larger in figure 3 than in figure 1, namely, "lack of tact" and "not sufficient evidence of ambition." A man may be lacking in tact and still be so valuable that his superiors will tolerate him because of his strong positive virtues. This is a handicap to advancement however, as will be considered later.

A man may be very useful in his present situation even if he does not display evidence of ambition, although he doubtless would be a better worker if he were more ambitious. This trait also should be considered later with reference to the data of figure 4.

One more factor under "temperamental traits" that perhaps should be noted especially is that the item "lack of initiative" is much lower in figure 3 than in figure 1.

It is evident from a comparison of figures 1 and 3 that while men may have serious faults and still retain their positions, these faults play a large part in the choice of those to be eliminated in times of stress and are probably nearly as important as their valuable traits.

Limitations of Men Retained

There is another analysis of those who survived the depression that can be made to advantage. Most normal men have certain ambitions and would like to advance as far as possible in their profession. Some wish for executive responsibility and others wish to be consultants or experts in some particular field. What limitations do these men have that may hinder their advancement? Such an analysis is, of course, somewhat speculative, particularly with reference to the younger men. The results of such an attempt are given in figure 4. The items follow fairly closely those of figure 1 with the elimination of some that did not apply since men with those characteristics would not have survived anyway. A few items have been added which were not needed for the data of figure 1.

The "antisocial" percentages are much lower than for those who were released, and some values are zero as would be expected. The "personality factors" rate rather high, particularly "lack of aggressiveness." If a man does not push himself it is unlikely that someone else will perform this service for him. It is interesting to note the considerable percentage who display no appreciable evidence of ambition. This is probably a fairly true picture since there are certainly a good many educated people who, if working in pleasant surroundings, are quite content to let things drift along as they are.

"Mental capacity" and "physical limitations" are quite small in percentage and need no particular comment.

Under "training," the "failure to improve self technically" is tied up to a considerable extent with "lack of ambition." It is perhaps a species of laziness and certainly denotes a lack of curiosity without which no research man is likely to go far.

There are certain "specialists" whose interests are so narrow that they are not fitted for executive duties involving the direction of several kinds of activities

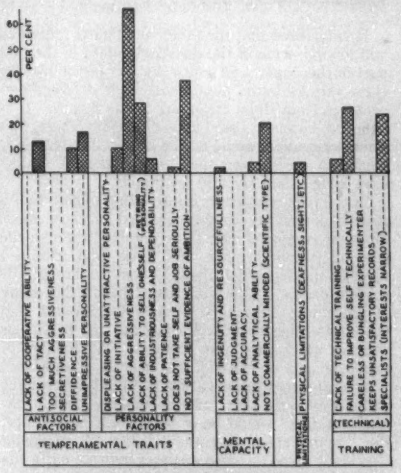


Fig. 4. Qualities that would tend to limit the advancement of men retained

The percentages refer to the number of engineers limited by the particular quality considered, based upon the total number retained

and who cannot become regular consultants because the demand for their services would be too limited. These men usually are reasonably content with their existing lots in life.

Some further comparisons may be valuable. These (table II) are taken from the data of figure 4 and therefore refer to the limitations to advancement. As may be seen, 10 per cent of the individuals had limitations in 3 of the 4 characteristics, namely, the first, second, and fourth. It is particularly interesting to note that 14 per cent had no evident limitations that would prevent them from stepping into positions of considerably greater responsibility when such positions become available. Some of these men will become impatient at the slowness of their advancement and will seek opportunities elsewhere. They may meet with large success or they may find themselves in a hostile environment which will ruin their morale temporarily or permanently.

It should be noted that figures 3 and 4 refer to the same men and both deal with their faults and limitations. That the results are not the same, is, of course, because in the 2 sets of data these men are viewed from different standpoints. In figure 3 they are considered from the viewpoint of their present occupations and responsibilities, while in figure 4 they are judged on the basis of larger responsibilities and a different type of contact with their associates. The percentages are, therefore, higher in figure 4 than in figure 3 for the same characteristics. Also, a few characteristics that appear in figure 3 are omitted in figure 4, and a few are added that are of little or no importance in considering the data of figure 3.

Discussion of Results

It is believed that the tables and figures presented will answer some of the questions raised in the first part of this paper. Of course another person making these ratings would obtain somewhat different percentages from those appearing in the figures. It is believed, however, based upon checks by others, that the discrepancies would not be large. The tendency seems to be to rate the "temperamental faults" even higher than given in the graphs.

Of the men released, it is interesting to note that a slightly larger percentage consisted of those hired direct as compared with those obtained through the student training course. Of those who remained through the depression about $^2/_3$ came in through the student course. This is in spite of the fact that many of those who were hired directly for research had special training or qualifications for the particular work in which they were engaged. The number of men originally on the staff was about $^1/_2$ of each kind.

In a research organization it would be thought without analysis, that "mental capacity" and "technical training" would be of paramount importance, the "temperamental traits" being of decidedly secondary value. These analyses indicate quite the opposite. It must be remembered, however, that those lacking in the 2 former traits are, to a large extent, eliminated during their school days and apprentice training. Many students, nevertheless, never should have been released to industry because of their mental limitations or their different interests.

From these analyses then, it would seem desirable in the training and guidance of students, to pay more attention to the "temperamental traits." Scientists and technicians are influenced just about as easily by likes and dislikes and prejudices as any other class of people. No matter how brilliant a man may be he cannot be successful in group activities unless he can obtain coöperation. He must have the respect and liking of his fellow workers. For his greatest success he must be sufficiently aggressive to convince others of the value of his activities and to some extent, at least, he must sell himself to his superiors.

In order to bring out a man's strength and weakness in coöperative activities (most important research and development are now of this kind), it might be desirable for the schools to sponsor thesis and research projects that instead of involving 1 or 2 men for each project might require a group of a dozen or more. Each individual might be rated on the basis of his effectiveness as a member of the group and his group shortcomings pointed out to him.

Finally, it is obvious to those who are brought into close contact with technical school graduates that there still are many who never should have majored in engineering or science. The obvious solution for this difficulty is psychological examinations in the secondary schools and better guidance in the choice of a profession by competent advisers. The technical schools themselves doubtless could be more critical in their entrance requirements and should be more drastic in their eliminations during the first year. As graduation time approaches students undoubtedly could be saved many future disappointments if they received more guidance in the selection of a vocation. A man with the temperamental traits suited to a sales engineer should not be allowed to choose design. A man who is a poor experimenter and a good teacher should be made to realize his points of strength and weakness before he leaves school and should be directed in his future activities accordingly.

Most of the foregoing is obvious, but it cannot be stressed too strongly. This is evident when it is realized how far from ideal present conditions are. Many attempts in the way of vocational guidance are being made for the skilled and unskilled workman, but all too little is being done for the technical school graduate in whom there is a large investment and on whose shoulders more and more of the world's problems are evidently soon to rest. Years are spent in cramming abstract knowledge into the students' heads, but almost no effort is being expended in preparing them to make the best use of it after they leave school.

It is hoped that these analyses will give the young man entering industry, the teachers who have prepared him, and the employers who will use him a more accurate picture of the nature of the strength and weaknesses of these young men. A consideration of the importance of the temperamental traits may lead to greater efficiency and the elimination of much disappointment and perhaps suffering on the part of those who from time to time under present conditions are forced to seek other employment.

Ratings of Industrial Electronic Tubes

To serve as a guide in the standardization of ratings of electronic tubes, the principal factors involved in the choice of tube ratings together with the more important terms commonly used, are presented in this paper. High vacuum tubes, gas and vapor filled tubes, and photo-electric tubes are considered separately, and the large number of factors which enter into the ratings of each of these 3 classes of tubes are discussed.

By
O. W. PIKE
ASSOCIATE A.I.E.E.
General Electric Co., Schenectady, N. Y.

DAYTON ULREY
ASSOCIATE A.I.E.E.
Westinghouse Elec. and Mfg. Co., East Pittsburgh, Pa.

THE proper determination and standardization of ratings of electrical apparatus is one of the most important and difficult duties with which an engineer is faced. This is particularly true in the case of electronic devices because of the great variety of applications for a given type of tube. Ratings here must guide the application engineer in obtaining maximum value on the one hand and must serve to determine the responsibility of the manufacturer in the case of inoperative apparatus on the other. The more important terms in use for rating vacuum tubes are described in this paper and the technical conditions governing the choice of tube ratings are presented.

Ratings should always be based primarily upon the *fundamental limitations of tubes* in order that they may be correct under the many conditions encountered in service. It is, therefore, necessary first to determine what elements of a tube may be independently or collectively subjected to damage by improper use and then to establish within what limits each may be operated consistent with the desired life and performance. Thus, in the case of rectifier tubes there are certain ratings based upon the ability of the cathode to provide emission, others upon the ability of the tube to withstand inverse voltage, and still others on the capacity of the tube to dissipate and distribute heat.

High Vacuum Tubes

Because of the greater simplicity of operation and the smaller number of fundamental limitations of high vacuum tubes, the ratings of this type are discussed first in this paper. Under this classification are considered only those tubes which have been sufficiently exhausted that their characteristics and operation are unaffected by such residual gases as may still be present. In practically all such tubes the principal consideration is the passage of a pure electron stream, either under or without the influence of one or more interposed grids, from a heated cathode to a relatively cold anode. These simple but essential features involve the following inherent limitations.

Cathode Ratings

Most modern high vacuum tubes have thermionic cathodes of tungsten, thoriated tungsten, or oxide coated alloys, each having its own peculiar advantages and limitations. For each, however, the electron emission increases exponentially with increasing temperature, and definite limitations must, therefore, be put on the heating voltage of any tube so as to insure sufficiently high temperature to provide the necessary electron emission and yet prevent too high temperature. The latter would result in early failure due to burn-out in the case of tungsten filaments or loss of emissive material in the case of thoriated tungsten and oxide coated filaments. While any variation from the rated cathode heating voltage is undesirable, a plus or minus 5 per cent variation is generally considered tolerable.

Maximum Plate and Grid Currents and Dissipation

A given cathode thus provides a rather definite maximum electron current which can be drawn safely and economically from it. This obviously introduces a fundamental limitation in any tube and is, therefore, a factor which should have a definite rating. This rating is stated in terms of maximum plate and grid currents.

The use of vacuum tubes in different types of circuits results in tube efficiencies varying over a wide range and the heat developed at the anode varies accordingly. In order to prevent excessive anode temperatures, resulting usually in evolution of occluded gases from overheated parts, it is necessary to establish maximum wattages which can be dissipated safely as heat by the anode. Likewise, the grid or grids have similar limitations and where tubes are operated in such a manner that electron current is drawn to the grid, maximum grid dissipation limits must be observed. Incidentally, the grid dissipation is in general higher than calculated by taking the product of voltage and current, since secondary electrons emitted from the grid diminish the grid ammeter reading proportionally, though do not lessen the grid bombardment. A grid may thus run red hot when the calculated input wattage is zero or even negative.

Maximum Plate Voltage

All tubes have fairly definite anode voltage limitations beyond which short life or even sudden failure

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Sept. 14, 1934; released for publication Oct. 5, 1934. *Not published in pamphlet form.*

will occur. The cause of failure may in such cases be an actual glow or arc between electrodes. Often, however, it is loss of emission due to excessive, though invisible, ionization of residual gases and the resulting bombardment of the electrodes.

High Frequency Ratings and Limitations

In certain industrial applications, as well as in radio, it is desirable to use vacuum tubes as oscillators or amplifiers at extraordinarily high frequencies—of the order of 10 to 100 million cycles. Under such conditions dielectric losses are developed in the glass and other insulating materials, eddy currents may be set up in metal parts, ionization of residual gases tends to persist, unusually high voltages may develop between adjacent parts and, therefore, ratings which are feasible at ordinary radio frequencies and below cannot apply. It becomes necessary, therefore, to rate such tubes in terms of frequency as well as in terms of voltage, currents, etc.

Gas and Vapor Filled Tubes

Generally speaking, all of the limitations mentioned above which are characteristic of high vacuum tubes, apply also to gas and vapor filled or ionic tubes. There are, however, a number of additional factors introduced by the presence of gas in the tube, and, since tubes of this class are of primary importance in industrial and power fields, their limitations and ratings are considered in more detail.

Maximum Average Anode Current

These tubes all have the common characteristic of being able to carry relatively heavy currents across the evacuated space between electrodes with a comparatively low voltage drop. This is accomplished at present by the use of thermionic cathodes, mercury pools, and cold cathode discharges. With all of these methods a certain voltage drop is set up across the tube. This results in losses which must be limited and it is, therefore, necessary to apply a current rating based upon tube heating. Inasmuch as in these devices the voltage drop is fairly constant for all values of current, this rating is given in terms of average current rather than root mean square current as in the case of a conductor. It is realized that even this is an approximation in the case of highly peaked wave forms. Of course, the design of tube conductors, such as leads, must be based upon the root mean square current and due to the very peaked wave forms which are encountered, this root mean square value is often many times the average.

Maximum Instantaneous Anode Current

In the case of thermionic cathodes, the available electron emission represents a limit on the maximum instantaneous current which may be carried across the space without harm to the tube. In polyphase circuits the instantaneous current requirement is often 6, and sometimes as much as 12, times the average current per tube. Thermionic tubes usually have an instantaneous rating of not over 6 times the average current rating, which is sufficient in most cases. However, since neither the average nor the instantaneous ratings may be exceeded, it is obvious that in some circuits the instantaneous current rating will be the limiting factor in attempting to get more power out of the tube while in other circuits the average current maximum will be reached first.

In the case of pool and cold cathodes the instantaneous current, from the standpoint of the cathode is more or less limitless. Thus, some pool tubes with an average rating of 10 amp can carry several thousand amperes instantaneously.

Maximum Anode Surge Current

In the design of electrical equipment using tubes, it has been found necessary in many cases to limit the abnormal current flow under short-circuit conditions, as it is not always economical to design tubes to withstand without harm extremely high transient currents. The maximum permissible transient current is sometimes termed the surge current rating and is the value of transient current to which a tube may be subjected occasionally without causing immediate failure or affecting the life unduly. As an example, this current sometimes determines the value of reactance desirable in the transformer windings of a rectifier.

Maximum Time of Averaging Anode Current or Load Time Constant

Electromagnetic devices usually have a high thermal capacity. Thus, a motor may stand severe overload for a period of perhaps half an hour before attaining dangerous temperatures. Because of the necessity of keeping the internal parts light in order to reduce the occluded gas content, tubes have comparatively low thermal capacity and, therefore, acquire thermal equilibrium in a few seconds or at most a few minutes. In the case of slowly repeating duty cycles it can be seen that some limit or integration period must be placed on the time over which the current is averaged.

For example, consider a tube which has an instantaneous current rating of 30 amp and an average current rating of 5 amp. Obviously it would not be safe to apply a load of 30 amp for one hour during every 6 hr, though this would allow only an average current equal to the average current rating of 5 amp. In other words, the period over which the current is averaged must be short enough that the highest temperature reached will not be in excess of that obtained if a steady current equal to the average current rating is kept on continuously. In the case of a tube having a 5-amp average current rating, this integration period, or load time constant, would probably be of the order of 30 sec. The maximum period, therefore, that the highest permissible current of 30 amp could be passed through the tube would be 5 sec out of any 30-sec period, since any greater value would cause the average current rating to be exceeded. In practice, a half-wave tube handles only half of each active cycle and the consideration is further complicated by wave forms. Thus, assuming substantially square wave form and with half wave rectification, 600 half cycles of current having a maximum value of 30 amp could be carried over a 10-sec

period, the current actually flowing for half this time.

Maximum Peak or Crest Inverse Voltage

Turning now to the voltage ratings of gas and vapor filled tubes, a great variety of circuits must be considered and it is necessary to get back to the tube fundamentals. At one time rectifier tubes were rated in terms of their d-c outputs, but this is meaningless except for one ratio of a-c voltage to d-c voltage. The fundamental is the ability of the tube to withstand instantaneous voltages. Thus, there is necessitated the maximum peak or crest inverse voltage rating and, in the case of tubes with grid control, the maximum peak or crest forward voltage rating as well. In obtaining the peak or crest voltage in any circuit it is necessary to take into account not only the type of circuit but also the frequency, the wave forms, and the presence of surges or transients which may increase the voltage to which the tube is subjected. In the case of complicated conditions it is often necessary actually to test for this voltage by means of a cathode ray oscillograph or a spark gap.

Cathode Ratings

For purposes of interchangeability and to permit of parallel operation, practically all thermionic cathodes are designed for constant voltage heating supply. The maximum and minimum currents at this voltage are often listed for calculation of efficiencies and design of heating transformers. Emission and life vary greatly with variations in filament temperature and hence with filament voltage. Thus, an overvoltage shortens life somewhat and undervoltage reduces the emission of the cathode, which may result in a change in tube characteristics or even immediate failure. It is, therefore, desirable that the heating voltage be kept as constant as possible and at least within plus or minus 5 per cent of normal, particularly where the voltage fluctuations are slow. It is always recommended, however, that the voltage be too high rather than too low, as overvoltage seldom results in rapid failure.

Cathode Heating Time

It requires a certain length of time to bring thermionic cathodes up to temperature. Attempts to draw current prior to the time that operating temperature is reached often results in harm to the tube. Simple, unshielded filaments are much quicker heating than enclosed filaments or cathodes. Thus the heating time varies from a few seconds, in the case of the former, to as high as 30 min, in the case of the latter. The slower heating cathodes are more efficient; therefore, there is always a compromise in the design of cathodes between efficiency and heating time. It is necessary to know the heating time of the cathode and provide either manually or with relays for the delay in application of anode voltage.

Tube Heating Time

In the case of mercury vapor tubes it is necessary to raise the mercury temperature to a point that will produce a vapor pressure sufficient to carry the current properly. The coolest point of the tube determines this pressure. Thus, a filamentary cathode mercury tube might have a cathode heating time of 5 sec but a tube heating time of 5 min. Tube heating time varies with the thermal capacity, ventilation, cathode watts, external heating, and with the type of circuit. Likewise, the characteristics of mercury vapor tubes vary with tube temperature and in the case of critical circuits or wide temperature variations it is often necessary to maintain the temperature constant by means of thermostatic devices. In rating mercury tubes it is, therefore, necessary to establish temperature limits. These were first given in terms of the ambient temperature but confusion resulted due to the fact that the relation between ambient and condensed mercury temperature, i. e., minimum bulb temperature is not constant. It varies greatly with the ventilation and with load. Temperature limits of tubes are now being given more and more in terms of condensed mercury temperature, and it is left to the application engineer to relate this properly with ambient.

The temperature characteristics of pool cathode tubes are substantially equivalent to thermionic cathode tubes except that the cathode requires no heating time.

On the other hand, inert gas filled tubes have characteristics substantially independent of tube temperature and are ready for operation as soon as the cathode has attained its normal temperature.

Tube Voltage Drop

It is necessary to establish the voltage drop across tubes in order to serve as a basis of efficiency calculation and for transformer design. In cold cathode gas discharge tubes this is rather high, often being in the neighborhood of 100 volts, while in the case of hot cathode tubes it ranges from 5 to 30 volts. Pool tubes have drops of from 10 to 30 volts. Drop, in the case of mercury tubes, is a function of temperature, and it is, therefore, possible and sometimes desirable to operate a tube at a high temperature for the purpose of reducing the drop and consequently the losses. Drop also varies slightly with current and in calculating efficiencies this must be taken into account. Thus, a 6-phase rectifier supplying 600 amp demands approximately 600 amp from each tube in turn. The drop used here should be that for 600 amp rather than for the average value of 100 amp.

Starting or Control Characteristics

In the case of ionic tubes having grids, the control characteristics are of utmost importance. In this type of tube there is a critical grid voltage for each anode voltage at which current starts to flow. This may be either positive or negative. (It should be remembered that with this type of control the stoppage of current is usually not accomplished by means of the grid.) Ratings usually include the critical grid voltage at a low anode voltage, such as 100 volts, and at the maximum rated voltage of the tube. In the case of negative control tubes the zero grid starting voltage is also usually given.

Grid Current Ratings

Another fundamental characteristic and limitation of ionic tubes is based upon current drawn by the grid. Grid current limits fall under 3 general classes: (1) Grid current before starting; (2) minimum grid current after starting; and (3) maximum rated grid current after starting. The first 2 are more properly characteristics than ratings and in general the lower values will be associated with superior tubes. These characteristics are best illustrated by a family of curves showing the variation with voltage, tube temperature, anode current, and circuit conditions.

The maximum rated grid current after starting, like the anode ratings, is expressed in terms of the average current, based upon grid heating, and in the case of hot cathode tubes, in terms of the instantaneous current based upon the added current requirement from the cathode.

Deionization Time

In many types of applications of ionic triodes, particularly in inverter circuits, the time required for the grid to regain control after current interruption is of fundamental importance. This interval during which a grid voltage, more negative than the critical value, fails to block off the anode current is termed the "deionization time." This is ordinarily of the order of microseconds, and is a function of tube geometry, condensed mercury temperature, plate and grid currents, plate and grid voltages, and of regulation of the grid circuit. It is, therefore, rather meaningless to specify a given value for the deionization time of any tube without limiting the conditions under which it applies. A complete description of this characteristic can only be given by means of a family of deionization time curves.

Photo-Electric Tubes

While photo-electric tubes have found rather large and varied fields of application, their fundamental limitations are relatively very few and consequently the matter of ratings is correspondingly simpler than in the case of other industrial tubes.

Maximum Anode Voltage and Current Ratings

Photo-electric tubes are essentially of 2 types—high vacuum and gas filled. In the high vacuum type there is a limit to the maximum anode voltage which may be applied without the development of undue leakage over the insulation between electrodes or breakdown of residual gases which may be in the tube. There is also a limit to the maximum anode current. Practically, however, these limitations are far beyond any ordinary requirement.

In many photo-electric tubes, an inert gas is used and the sensitivity may thereby be increased several fold due to gas ionization. Such tubes have a quite different anode voltage rating from the high vacuum type. This is because a glow discharge will take place between electrodes at about 100 volts with gas pressures which are otherwise optimum, and this in turn results in rapid deterioration of sensitivity. It is necessary, therefore, to establish a rather low but definite upper limit, ordinarily not over 100 volts, to the anode voltage which may be applied to the gas photo-electric tube. Since the glow voltage is also a function of intensity of illumination, it is also required that a high resistance be used in series with the voltage supply, thus dropping the applied anode voltage as the photo-electric current increases.

Maximum Ambient Temperature

In the more sensitive type of photo-electric tubes, operation at relatively high temperatures results, first, in a loss of photo-electric sensitivity and second, in the beginning of thermionic emission from the cathode. This latter effect makes a part of the total current independent of illumination and is, therefore, objectionable. It has been found necessary, therefore, to limit the maximum temperature to the order of 60 deg C.

Sensitivity

The sensitivity of photo-electric tubes, while more of a characteristic than a rating, is expressed in terms of microamperes short-circuit current per lumen of incident radiant flux. The luminous tungsten sensitivity is the sensitivity with the tube subjected to a tungsten filament at specified color temperature. A standardized temperature for the filament of the test lamp is 2,870 deg absolute.

Standardization of the Different Types of Tubes

No one doubts the value of and necessity for standardization of ratings of electrical equipment. It is particularly important in the case of tubes as they are usually replaceable items of equipment. Obviously, lack of standardization of base and outline dimensions, voltage and current levels and general electrical characteristics must lead to a great number of unnecessary tube types which would, of course, be detrimental to the art.

In considering different sizes of tubes it is suggested that all ratings, so far as practicable, and particularly average current ratings, should fit into a "preferred number" system. (See "Standardization and Profits Aided by Preferred Numbers," R. E. Hellmund. *Elec. World*, v. 104, 1934, p. 208–11.) Preferred numbers are based upon a geometric progression and have been found valuable in practically all types of standardization. It is, of course, necessary to divide the tube field into classes, such as high voltage control tubes, low voltage control tubes, high voltage rectifiers, low voltage rectifiers, each group being further divided into both the high vacuum and gas filled types, but within a given classification the use of the preferred number system will minimize the number of improperly spaced types of tubes.

The actual standardization of tube ratings by technical committees has only just started and it is hoped that this paper may serve as a guide for this work.

Resistance and Reactance of 3-Conductor Cables

The resistance and reactance of 3-conductor cables under balanced 3-phase loads have been studied in a series of tests in different laboratories, and the results are presented in this paper. Values of these constants are given for different types and sizes of 3-conductor cable, and the effects on the constants of several different factors are presented.

By
E. H. SALTER — MEMBER A.I.E.E. — Electrical Testing Labs., New York, N. Y.

G. B. SHANKLIN* — MEMBER A.I.E.E. — General Electric Co., Schenectady, N. Y.

R. J. WISEMAN* — FELLOW A.I.E.E. — Okonite-Callender Cable Co., Paterson, N. J.

EXPERIMENTAL data have been lacking covering the combined action of skin effect, proximity effect, and sheath losses in the determination of the effective a-c resistance of multiple conductor cables. With the advent of multiple conductor cables of the larger conductor sizes, the need for information concerning the probable losses in these cables became imperative.

Early in 1930, W. H. Cole of the Edison Electric Illuminating Company of Boston (Mass.) called attention to certain difficulties which had been experienced in the parallel operation of belted and shielded types of 3-conductor cables. As a consequence of these troubles measurements were made of the resistance, reactance, and impedance of 2 installed lengths of cable each about 57,000 ft long. The results of these measurements indicated values considerably in excess of those normally assumed in line calculations.

These conditions were called to the attention of the manufacturers involved and of Electrical Testing Laboratories with the immediate result that hurried laboratory measurements were made on various lengths of cable available. The results, in general, confirmed Mr. Cole's findings, though the values of effective resistance obtained were somewhat lower than those reported by Mr. Cole.

An investigation was then undertaken by Electrical Testing Laboratories on behalf of the high tension cable committee of the Association of Edison Illuminating Companies, and the Insulated Power Cable Engineers' Association on behalf of the cable manufacturers. The work reported herein is a result of the coöperative efforts of these 2 groups.

The investigation included the determination of the constants of belted and shielded types of cables with 167,000 to 1,000,000-cir-mil conductors and with several different thicknesses of insulation.

A description of one of the test methods used and the results of the various interlaboratory and field checks made to assure reliability of these results are given in the appendixes.

Results of Tests and Investigations—

1. Constants of 3-Conductor Cables

The original schedule of testing contemplated making practically all measurements on dry or unimpregnated cable because most of the test specimens had to be manufactured specially for this investigation and it was felt that considerable economy could be effected if the work could be done on dry cable. Accordingly, the first group of samples supplied were unimpregnated but were otherwise standard commercial cable.

In the course of the determination of the magnitude of proximity effects between conductors, a test was made on the stripped cable and then the conductors were spread 17 in. apart on the apexes of an equilateral triangle and a second test made. A marked decrease in effective resistance was noted when the conductors were separated 17 in. in the manner indicated, at which distance all proximity effects should be negligible. However, when a piece of impregnated cable was tested in this manner, little or no change was obtained in the effective resistance of the conductors.

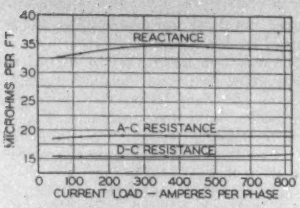
This indication of an apparent effect due to impregnation was first checked by crudely impregnating the conductors of a piece of dry cable and repeating the tests on the impregnated cable. The result tended to confirm the findings as to the effects of impregnation. As a final check, 2 15-ft pieces were cut from one of the samples of dry cable, one returned to the factory for regular factory impregnation and the second held for tests in the dry condition. The results of these tests were definite in their indication that all measurements should be made on cable which has been dried and impregnated in the usual manner.

When this conclusion was reached, 20-ft pieces were cut from all of the unimpregnated samples and returned to the various manufacturers for factory drying and impregnation. The bulk of the results reported herein are, therefore, those obtained in tests of the impregnated cable. As such they are believed to be representative of the characteristics of the normal run of cables as now manufactured.

The cables tested may be divided into 2 general classifications according to the conductor shape,

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Sept. 25, 1934; released for publication Sept. 27, 1934. *Not published in pamphlet form.*

* On behalf of a committee of the Insulated Power Cable Engineers' Association, composed of: R. J. Wiseman, *Chairman*, W. A. Del Mar, G. B. Shanklin, and D. M. Simmons.



Description of cable: 3 × 700,000 - cir-mil round conductor
220 mils, impregnated paper insulation; 141 mils, lead sheath

Fig. 1. Typical curves of a-c resistance and reactance of shielded cable with magnetic binder tape

i. e., round and sector. Under each of these classifications there were cables of 3 different types of construction, namely, the belted construction, the shielded cable with the steel binder tape (magnetic) and the shielded cable with each of several nonmagnetic binder tapes. (A description of these different types of construction is given in a later section "5. Parallel Operation of 3-Conductor Cables" of this paper.)

Certain types of results were soon recognized as typical of the various types of cable under test. Table I and Fig. 1 show such typical results. It was noted that the resistance and reactance versus current characteristics were practically horizontal straight lines for all *nonmagnetic* cables. The only deviation from the straight line appeared to be due to heating of the cable as it was loaded. However, the introduction of a steel binder tape changes the shape of these curves to those typical of circuits containing magnetic materials. This means that for complete information on the several types of cable it is necessary to show the complete range of data at various currents. In normal use, however, the values of most interest are those corresponding to full load operating conditions. In the preparation of summary tables the cable constants at a single current load have, therefore, been given, approximately, the maximum operating load. Furthermore, since it is in most cases more convenient to deal with the effective resistance as a ratio to the d-c resistance, only such ratios have been given.

Table II is a summary of all the available results of measurements made on the various sizes and types of cables. This table includes measurements made in all the various laboratories. In Fig. 2 is a graphic presentation of the various data on effective resistance, while Fig. 3 presents the results of the reactance measurements. In preparing these charts the results for the various types and conditions have been identified though only limit curves have been drawn in most cases.

In connection with certain check measurements made in coöperation with one of the cable manufacturers, attention was called to an unexplained condition noted in their tests, namely, that the effective resistance apparently differed with the phase rotation of the current. Further investigation confirmed this effect and appeared to show that it was inherent in the cable and was independent of the test or supply circuits. It was found that where the current phase rotation agreed with the rotation of the conductors due to lay (viewed from the supply end) the effective resistance was approximately one per cent higher than where the current phase rotation was opposite to the rotation of the conductors. However, theoretical considerations seem to indicate that losses cannot be dependent upon the direction of energy flow and thus an explanation of the effect of direction of phase rotation would require further investigation. The data reported herein are average values taken from direct and reversed measurements at each current value.

2. The Effect of Frequency on Cable Characteristics

In connection with the early work on the dry cables a study was made of the effect of frequency on the cable characteristics. In this study the cable constants were determined by the 2-wattmeter method at a given balanced 3-phase current load over a range of frequencies from about 20 cycles per second to 62.5 cycles per second. These measurements indicated a straight line variation with frequency for both the effective resistance and reactance, the effective resistance increasing from a value equal to the d-c resistance at zero frequency and the

Table I—Typical Results on Shielded Cable, Magnetic Binder Tape, With and Without Sheath

Reactance and A-C and D-C Resistance in Ohms per 1,000-ft of Conductor

	Three-Phase Current Load—Amperes per Phase							Surface Temp.
	100	200	300	400	500	600	700	
Cable Complete								
Reactance	0.0331	0.0342	0.0348	0.0348	0.0346	0.0344	0.0341	Start,
A-c resistance	0.0187	0.0191	0.0191	0.0190	0.0190	0.0190	0.0192	21.7C;
D-c resistance	0.0153	0.0153	0.0154	0.0155	0.0156	0.0158	0.0160	Finish,
A-c res./d-c res.	1.22	1.24	1.24	1.23	1.22	1.21	1.20	28.0 C
Minus Lead Sheath								
Reactance	0.0334	0.0344	0.0349	0.0349	0.0347	0.0344	0.0342	Start,
A-c resistance	0.0179	0.0185	0.0186	0.0185	0.0183	0.0183	0.0183	26.6C;
D-c resistance	0.0156	0.0156	0.0156	0.0157	0.0158	0.0159	0.0161	Finish,
A-c res./d-c res.	1.14	1.18	1.19	1.18	1.16	1.15	1.14	30.0 C
Minus Lead Sheath and Steel Binder Tape								
Reactance	0.0314	0.0314	0.0314	0.0314	0.0314	0.0314	0.0314	Start,
A-c resistance	0.0169	0.0169	0.0169	0.0169	0.0170	0.0172	0.0173	24.1C;
D-c resistance	0.0155	0.0155	0.0156	0.0156	0.0157	0.0158	0.0160	Finish,
A-c res./d-c res.	1.09	1.09	1.09	1.09	1.09	1.08	1.08	27.0 C

Description of Cable—3 × 700,000 cir mils, round conductor; shielded, steel binder tape; impregnated paper, 220 mils; lead sheath, 141 mils

reactance being directly proportional to frequency. The results of a typical set of tests are shown in Fig. 4.

3. Proximity Effects in Adjacent Cables

The values of a-c resistance indicated by laboratory tests were in the most cases lower than the values shown by the early field tests on long lengths of installed cable. It was suggested that possibly one reason why the field tests showed the higher values was that there were induced currents set up in adjacent cables in the duct banks. Such proximity effects would, of course, be reflected as higher losses in the cable under test.

In order to ascertain the probability of such an explanation a series of tests was run on samples of 3-conductor 700,000-cir-mil cable, each about 20 ft in length. A given sample was first placed in position and tested in the normal manner with no metallic bodies nearby. Then, without disturbing the cable under test, other pieces of similar cable were laid parallel to the test sample with 6 in. between centers. The cables laid parallel to the test sample were, of course, insulated from the test sample in order to prevent circulating currents which might exist due to possible unbalance in the short length of cable under test.

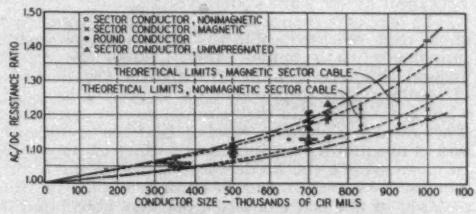


Fig. 2. 60-cycle effective resistance of 3-conductor cable at 30 deg C, expressed as a ratio to the d-c resistance

The results of these tests are shown in Table III and appear to indicate that under normal duct spacing of 6 in. between centers the proximity effects between cables are negligible. However, when the distance between cables is decreased to 3.5 in. an appreciable influence begins to be evident.

4. Mechanical Forces Between Conductors Under Short-Circuit Conditions

At the time of this investigation of cable characteristics, one of the laboratories, as a part of this investigation, studied the mechanical stresses developed in the binder tape of 3-conductor shielded cable under short-circuit conditions and their relation to the tensile properties of the tapes being used. This problem has been approached both from the theoretical and from the experimental side with much the same result.

A study of the field conditions surrounding the 3 conductors has indicated that under a phase to phase short circuit in which the current reaches a value of 20,000 amp the force to be resisted amounts to about 250 lb per foot of cable (3 × 350,000 cir mils, 220 mils insulation on each conductor). Assuming this force to be resisted by a binder tape one inch between turns, the stress in the tape would be of the order of 3,500 lb per square inch. The force exerted will vary as about the square of the current so that even under short-circuit currents of twice this magnitude the forces encountered would be effectively restrained by a tape binder of any of the materials now being used. In fact, the lead sheath alone would probably provide sufficient strength to resist these forces.

In order to check the above conclusions a series of tests was run in which various cable samples were submitted to momentary overloads of approximately 12,000 amp. This current was caused to flow through one conductor in one direction and back again in the opposite direction through the other 2 in parallel. Tests were made on each of 3 specimens of 3 × 350,000-cir-mil shielded cable—one with a steel binder tape, one with a wire stitched cloth binder tape and one with a butt-wound 7-mil paper binder tape. All were provided with a 125-mil lead sheath.

Each sample was subjected 3 times to the 12,000-amp momentary load. After each test the sample was examined carefully and measured for signs of movement. In no case could any perceptible movement of the conductors be detected.

The lead sheath was then removed from each sample and the binder tape tied at each end to prevent unwrapping. Each sample was again subjected to 3 12,000-amp tests and again there was no preceptible movement of the conductors.

5. Parallel Operation of 3-Conductor Cables

Since difficulties in the parallel operation of 3-conductor cables were the underlying cause for this investigation, it appears proper to treat here of those inherent conditions which will always be encountered when such cables are installed for parallel operation. Belted cable is the oldest type of 3-conductor cable

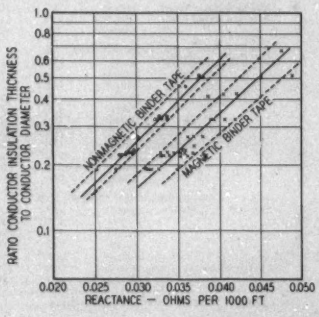


Fig. 3. 60-cycle reactance to neutral of 3-conductor sector cable

Conductor diameter of sector cable taken as that of round conductor of same cross section

Table II—A-C Resistance and Reactance of 3-Conductor Cables Under Balanced 3-Phase Load

Values Taken at an Average Conductor Temperature of 30 Deg C

Cable No.	Type of Construction	Shape of Conds.	Thick. of Insulation, mils	Thick. of Lead sheath, mils	Effective Resist., Ratio to D-C Resist.	Reactance[1]
	3 × 167,000-cir-mil (3/0 A.w.g.) cables, 200-amp load					
1	Shielded-steel binder	Sector	313	.125	1.04	0.0475
	3 × 350,000-cir-mil cables, 300-amp load					
2	Belted	Round	440 × 267	.125	1.06	0.0336
3	Belted	Sector	562 × 500	.141	1.04	0.0430
4	Belted	Sector	440 × 344	.125	1.05	0.0328
5	Shielded steel binder	Round	220	.125	1.08	0.0390
6	Shielded steel binder	Sector	350	.141	1.05	0.0488
7	" " "	Sector	220	.125	1.06	0.0418
8	" " "	Sector	345	.125	1.08	0.0447
9	" " "	Sector	345	.125	1.07	
10	" " "	Sector	220	.125	1.06	0.0406
11	" " "	Sector	345	.125	1.14	
12	" " "	Sector	220	.125	1.06[4]	0.0391
13	Shielded copper binder	Round	220	.125	1.06	0.0337
14	" " " "	Sector	350	.141	1.06	
15	" " " "	Sector	281	.125	1.06	
16	" " " "	Sector	345	.125	1.06	0.0380
17	" " " "	Sector	220	.125	1.04[4]	0.0321
18	Shielded bronze binder	Sector	345	.125	1.08	0.0377
19	Shielded cloth binder	Sector	220	.125	1.05	0.0323
20	" " " "	Sector	345	.125	1.06	0.0376
21	Shielded paper binder	Sector	220	.125	1.05	0.0326
	3 × 500,000-cir-mil cables, 400-amp load					
22	Shielded steel binder	Sector	345	.125	1.11	0.0404
23	" " " "	Sector	340	.125	1.13	
24	" " " "	Sector	220	.141	1.09	0.0380
25	" " " "	Sector	345	.125	1.11	0.0420
26	" " " "	Sector	220	.141	1.16	0.0369
27	" " " "	Sector	345	.125	1.16	
28	" " " "	Sector	375	.125	1.17	
29	" " " "	Sector	375	.125	1.11	
30	" " " "	Sector	220	.125	1.09[4]	0.0362
31	Shielded paper binder	Sector	375	.125	1.09	
32	" " " "	Sector	375	.125	1.08	
33	" " " "	Sector	375	.125	1.10	0.0351
34	" " " "	Sector	375	.125	1.10	0.0359
35	" " " "	Sector	220	.125	1.075[4]	0.0302
	3 × 600,000-cir-mil cables, 500-amp load					
36	Shielded steel binder	Sector	220	.125	1.13	0.0370
37	" " " "	Sector	220	.125	1.27	
	3 × 650,000-cir-mil cables, 500-amp load					
38	Belted	Sector	281 × 234	.125	1.13	0.0251
	3 × 700,000-cir-mil cables, 600-amp load					
39	Belted	Round	440 × 267	.141	1.18[3]	0.0318
40	" "	Round	440 × 267	.141	1.18	0.0312
41	" "	Sector	440 × 344	.125	1.13[3]	0.0296
42	"	Sector	440 × 344	.125	1.12	0.0290
43	Shielded steel binder	Round	220	.141	1.18[3]	0.0353
44	" " " "	Round	220	.141	1.21	0.0344
45	" " " "	Sector	220	.141	1.16	0.0337
46	" " " "	Sector	220	.125	1.21[3]	0.0358
47	" " " "	Sector	220	.125	1.13	0.0357
48	" " " "	Sector	220	.141	1.13	0.0354
49	" " " "	Sector	220	.125	1.13	0.0356
50	" " " "	Sector	220	.125	1.13	
51	" " " "	Sector	220	.141	1.14	0.0369
52	Shielded copper binder	Round	220	.141	1.20	0.0309
53	" " " "	Round	220	.141	1.19[3]	0.0313
54	" " " "	Sector	220	.125	1.10	
55	" " " "	Sector	220	.125	1.10	
56	Shielded brass binder	Sector	220	.125	1.12	0.0289
57	Shielded paper binder	Sector	220	.125	1.17[3]	0.0297
58	" " " "	Sector	220	.125	1.13	0.0293
	3 × 750,000-cir-mil cables, 600-amp load					
59	Shielded steel binder	Sector	220	.125	1.23[3]	0.0352
60	" " " "	Sector	220	.125	1.21	0.0328
61	" " " "	Sector	219	.125	1.24[3]	0.0329
62	" " " "	Sector	219	.125	1.19	0.0361
63	" " " "	Sector	219	.125	1.18	
64	" " " "	Sector	220	.125	1.14[4]	0.0338
65	Shielded nicaloi binder	Sector	219	.125	1.20	
66	Shielded copper binder	Sector	220	.125	1.23[3]	0.0282
67	" " " "	Sector	219	.125	1.21[3]	0.0280
68	" " " "	Sector	219	.125	1.19	
69	" " " "	Sector	220	.125	1.135[4]	0.0287
	3 × 1,000,000-cir-mil cables, 750-amp load					
70	Shielded steel binder	Sector	220	.157	1.19[4]	0.0314
71	" " " "	Sector	220	.157	1.42	0.0314
72	" " " "	Sector	219	.156	1.22[4]	0.0310
73	" " " "	Sector	219	.156	1.42	0.0327
74	" " " "	Sector	219	.156	1.19[3]	0.0338
75	Shielded everdur binder	Sector	219	.156	1.35	0.0274
76	" " " "	Sector	219	.156	1.26[3]	0.0253

1. For numbered references see adjacent column.

and consists of 3 conductors, each insulated, cabled together and wrapped with a belt of additional insulation. This structure is then enclosed in a covering or sheath, which in the case of impregnated paper insulated cable is usually of lead. Due to the nature of this structure, 3 insulated conductors within a sheath, the electrostatic field is quite complicated. Similarly, the geometry of the thermal field is not simple; however, the heat losses from the conductors and the insulation must pass through the body of the insulation to the sheath.

On the other hand, the shielded cable, which consists of 3 insulated conductors each covered with a copper shield, cabled together, bound up with a metal tape and finally sheathed, has a relatively simple field conformation. The copper shields serve, first, to give a configuration to the electrostatic field which is essentially that between concentric cylinders (i. e., radial) and, second, to aid in conducting heat losses from the body of the cable to the sheath. At the same time (and in consequence of the foregoing) the thickness of insulation between conductors and sheath is usually somewhat less than in the belted type of cable. This increased ability to dissipate the internal heat losses makes it possible to assign a higher rated current-carrying capacity and a higher maximum permissible operating temperature to a shielded cable of a given size than to a belted cable of the same conductor size built for operation at the same system voltage.

The measurements made in this investigation show that shielded cable has an inherently greater impedance than belted cable. When the copper ground shields are built into a cable the thickness of insulation on each conductor is necessarily somewhat greater than in the belted type of construction. This means a greater spacing between conductors and consequently an increased inductive reactance. In cases where the binder tape is nonmagnetic this increased reactance causes an increase in the impedance of the order of 2 to 4 per cent above that of the corresponding belted cable. However, when a steel binder is used the resulting impedance is from 10 to 20 per cent above that for the belted cable.

When cables are operated in parallel the load will be divided in such manner as to cause the total voltage drop in each cable to be the same. For the most economical operation, each cable should take a share of the load which is in the same proportion to its rated current-carrying capacity, especially as the full rated load condition is approached. Cables for parallel operation should be so designed as to satisfy this condition as far as possible.

The curves in Fig. 5 illustrate how the voltage drop at rated current for 15-kv cables of various conductor sizes differs for different constructions. The increase in the drop in the shielded *nonmagnetic* type above the belted type is due principally to the inherently higher current capacity for a given copper temperature. The still greater increase in the shielded *magnetic* type is due to the increased inductive reactance.

1. Reactance in ohms per 1,000 ft at 60 cycles, to neutral.
2. Dry cable, i. e., cable which had not been impregnated.
3. Special cable constructed with enameled strands.
4. All strands laid in same direction; each layer crushed.

These curves also show which particular cables as to construction and size will operate economically (i. e., carry their proper share of the load) in parallel with an existing cable. For example, suppose it is proposed to install a cable in parallel with an existing 350,000-cir-mil 15-kv cable of the shielded type with magnetic binder. It is shown in Fig. 5 that the voltage drop to neutral per 1,000 ft of this cable is 15 volts when carrying rated load. If the new cable is to be of the same length, then it is evident that the corresponding drop in it when carrying its rated load must also be 15 volts per 1,000 ft in order to have proper division of the total load between the 2 cables. Reference to Fig. 5 shows that the following cables fulfill this requirement:

145,000 cir mil (approximately 2/0 A.w.g.), belted
225,000 cir mil (approximately 4/0 A.w.g.), shielded, nonmagnetic
350,000 cir mil, shielded magnetic
535,000 cir mil (approximately 500,000), shielded, magnetic

Thus there are 4 cables which will give just the same drop as the original cable with proper division of the load. However, for all practical purposes any size of shielded, magnetic binder cable from say 300,000 to 600,000 or 700,000-cir-mil cable could be used. But if it is desired that the new cable be of the shielded type with nonmagnetic binder, then for any size materially larger than 225,000 cir mil it would be necessary to install a reactor in series with the new cable to get a proper division of the load. Similarly, still more reactance would be required with a belted cable materially larger than 145,000 cir mils.

On the other hand if the existing cable is of the belted type and larger than about 200,000 cir mils, a reactor must be added to it if proper division of load is to be had with a parallel cable of any other type.

These considerations suggest that:

a. Since magnetic forms of binder have been found unnecessary for strength purposes, only cables which do not employ magnetic materials be installed in new installations except, of course, where there are special conditions which justify or require the use of magnetic material.

b. Where a new cable is to be installed in parallel with an existing cable and one of the same conductor size will provide the desired additional capacity, it be of the same type as the existing cable.

c. Where a new cable for installation in parallel with an existing cable is to be of a different conductor size or construction, a study of the conditions along the lines indicated above is necessary to make the best selection.

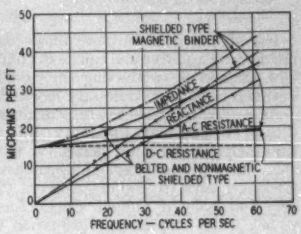


Fig. 4. Variation of a-c resistance, reactance, and impedance with frequency, for 3 - conductor 700,000 - cir-mil dry cable

6. Study of Component Losses

In the majority of cases the component losses were determined during the laboratory measurements by first determining the total loss of the complete cable sample, then repeating these measurements in order after removing the sheath, metallic binding tape (if any) and, in some cases, finally separating the conductors. Space does not allow detail presentation of these data but representative results will be discussed briefly and compared with theoretical calculations.

Cable without magnetic binder will first be considered. It is possible in these cases to make direct

Table III—A Study of Proximity Effects Between Cables; A-C to D-C Resistance Ratio

Condition	Surface Temp C at Start of Run	Ratio R_{a-c}/R_{d-c} — Three-Phase Current Load; Amperes per Phase: 60	120	240	360	480	600	720	Surface Temp C at End of Run
3 × 700,000-cir-mil Round, Shielded, Paper Binder									
Cable Complete									
A—Alone	23.7	1.184	1.184	1.183	1.183	1.180	1.176	1.171	27.9
B—1 cable 6 in. away	23.7	1.188	1.188	1.183	1.178	1.177	1.174	1.171	27.9
C—2 cables 6 in. away	23.7	1.190	1.189	1.184	1.180	1.179	1.176	1.169	27.9
D—2 cables 3.5 in. away	23.7	1.190	1.190	1.189	1.187	1.187	1.183	1.175	27.9
Sheath Off									
E—Alone	23.7	1.085	1.083	1.081	1.077	1.076	1.075	1.072	27.9
F—1 cable 6 in. away	23.7	1.082	1.084	1.081	1.077	1.075	1.075	1.073	27.9
G—2 cables 6 in. away	23.7	1.087	1.085	1.083	1.079	1.078	1.075	1.075	27.9
H—2 cables 3.5 in. away	23.7	1.105	1.098	1.095	1.093	1.093	1.090	1.088	27.9
3 × 700,000-cir-mil Round, Shielded, Steel Binder									
Cable Complete									
A—Alone	22.9	1.210	1.229	1.241	1.231	1.217	1.203	1.196	27.7
B—1 cable 6 in. away	22.9	1.208	1.228	1.245	1.233	1.218	1.205	1.192	27.7
C—2 cables 6 in. away	22.9	1.210	1.226	1.244	1.232	1.219	1.203	1.194	27.7
D—2 cables 3.5 in. away	22.9	1.212	1.231	1.249	1.229	1.219	1.205	1.200	27.7
Sheath and Steel Binder Off									
E—Alone	24.1	1.093	1.092	1.090	1.088	1.086	1.084	1.082	27.0
F—1 cable 6 in. away	24.1	1.091	1.092	1.090	1.088	1.086	1.085	1.080	27.0
G—2 cables 6 in. away	24.1	1.097	1.095	1.089	1.089	1.086	1.084	1.083	27.0
H—2 cables 3.5 in. away	24.1	1.110	1.107	1.105	1.105	1.105	1.102	1.097	27.0

comparison between measured and calculated results since the magnetic field is geometrical and undistorted.

The total losses of 3-conductor cable consist of the following component parts:

a. Conductor loss at zero frequency.
b. Skin effect loss in conductor.
c. Proximity loss in conductor.
d. Shielding tape loss (if any).
e. Metallic binding tape loss (if any).
f. Sheath loss.

For all practical purposes these component losses are directly additive and can be calculated separately. The method of conducting the calculations will be outlined briefly and necessary references made.

Skin effect loss has been fully dealt with by Dwight ("Skin Effect and Proximity Effect in Tubular Conductors," A.I.E.E. TRANS., v. 41, 1922, p. 189–95). A. W. Evan later published curves based upon Dwight's work (p. 250 of "A Set of Curves for Skin Effect in Isolated Tubular Conductors," *G. E. Rev.*, v. 33, 1930). As an approximation the skin effect of a sector conductor is assumed as equal to that of a round conductor of the same cross section.

Proximity effect loss has also been dealt with by Dwight (p. 535 of "Proximity Effect in Groups of Round Wires," *G. E. Rev.*, v. 30, 1927). His formulas are somewhat difficult to handle but short cut methods will be obvious to those who wish to go into the subject seriously. In the study under discussion, the proximity effect of sector conductors was assumed equal to that of equivalent round, solid bars of the same total cross section and resistance, and with the same thickness of insulation. This ignores the contact resistance of stranding and, of course, gives maximum proximity effect.

Shielding and binding tape losses were estimated on the assumption of continuous metallic cylinders of the same diameter and thickness, and twice the resistivity of the metal tapings. Clark and Shanklin developed the method used for calculating shielding tape loss ("High-Tension Single-Conductor Cable for Polyphase Systems," A.I.E.E. TRANS., v. 38, 1919, p. 917–69). The cylinder of binding tape was assumed in parallel with and part of the lead sheath.

Sheath losses have been fully dealt with by Dwight ("Proximity Effects in Cable Sheaths," A.I.E.E. TRANS., v. 50, 1931, p. 993–8). R. W. Atkinson presented a more convenient short cut method in the discussion of Dwight's paper (A.I.E.E. TRANS., v. 50, 1931, p. 998).

A comparison of the measured and calculated component losses for a number of the cables without magnetic binder listed in Table II is given in Table IV. It will be noted that with small size conductors, sheath loss is about 3 to 4 times calculated maximum proximity loss, while with large conductors it is approximately equal to proximity loss. Also, skin effect loss is about $^4/_5$ of this proximity loss. This means that with small conductors sheath loss predominates and proximity loss is not of much importance, while with large conductors proximity loss is of greater importance.

Now, skin effect loss and sheath loss are fixed quantities, determined by the physical dimensions of the cable and beyond the control of the manufacturer. Proximity loss, on the other hand, is variable and is the only component that gives the manufacturer any chance at all to reduce total losses appreciably. The range over which the manufacturer has such possible control is shown by the maximum and minimum curves in Fig. 2. When it is remembered that the carrying capacity of the cable varies as the square root of the losses it is at once apparent that there is only limited scope for improving the carrying capacity of 3-conductor cables by controlling proximity loss. From a practical standpoint it is of importance only with conductors of large size.

Cable with magnetic binder will be discussed later but it might be pointed out that here, also, proximity loss is the variable factor. (The term "proximity loss" for magnetic binder cable is meant to include all additional mutual and self-inductive losses in the conductor caused by eccentric magnetic field distortion.) In Fig. 2 it is shown that with magnetic binder there is a wider range for controlling losses by controlling proximity effect and, consequently, this effect is of more importance in this case.

Table IV—Comparison of Theoretically Calculated and Measured Losses in Nonmagnetic, 3-Conductor Cable

	Calculated Extra Losses %								Measured Extra Losses %			
Cable No. †	Sheath Loss	Binding Tape Loss	Shielding Tape Loss	Skin Effect Loss	Proximity Effect Loss	Total	Copper Temp Deg C		Sheath Loss	Binding Tape Loss	Remaining Losses	Total
2	3.4			1.3	1.6	6.3	33		4.0		2.0	6.0
3	3.0			1.1	1.0	5.1	52					4.0*
4	3.2			1.3	1.6	6.1	33		4.0		1.0	5.0*
13	3.6	0.8	0.7	1.3	1.6	8.0	33		4.0	0	2.0	6.0*
14	4.2	0.9	0.9	1.2	1.2	8.4	41					5.0*
15	3.5	0.7	0.7	1.1	1.1	7.1	47					6.0*
16	4.1	0.9	0.8	1.8	1.0	8.1	33		4.0	0	2.0	6.0
18	4.1	0.5	0.8	1.3	1.0	7.7	33		5.0	0	1.0	6.0
19	3.2	0	0.7	1.3	1.6	6.8	33			0		5.0*
20	4.1	0	0.8	1.3	1.0	7.2	33		4.0	0	2.0	6.0*
21	3.2	0	0.7	1.3	1.6	6.8	33		3.0	0	2.0	5.0*
40	9.5			4.8	6.3	20.6	33		10.0		8.0	18.0
42	8.8			4.8	6.3	19.9	33		8.0		4.0	12.0*
52	10.0	2.1	1.7	4.8	6.3	24.9	33		11.0	0	9.0	20.0
56	7.0	0.4	1.7	4.8	6.3	20.2	33		7.0	1.0	4.0	12.0*
58	7.0	0	1.7	4.8	6.3	19.8	33		8.0	0	5.0	13.0*
66	7.9	2.0	2.3	5.6	7.0	24.8	28		9.5	1.5	10.0	21.0
	6.0	1.5	1.5	4.2	5.4	18.6	69					16.0
	5.5	1.3	1.3	3.8	5.1	17.0	83					15.0
68	7.6	1.8	2.2	5.4	6.6	23.6	33		9.0	1.0	9.0	19.0
75	14.2	0.3	3.4	9.2	11.2	38.3	27.5		14.0	−1.0	22.0	35.0
76	14.2	0.3	3.4	9.2	11.2	38.3	27.5		16.0	1.0	9.0	26.0*

† See Table II for description of cables.
* Low loss cables. Subtract proximity loss from total calculated loss for comparison. All other cables have higher loss but never maximum solid bar proximity loss.

CONTROLLING PROXIMITY LOSS OF STANDARD CONDUCTORS

The manufacturers have made a complete study of this problem and it has been demonstrated that proximity loss of stranded conductors is governed entirely by contact resistance and distribution of circulating (eddy) currents between strands. Of these 2 factors, distribution of circulating current is the most important from a practical standpoint. Anything that tends to distribute this cross current between strands uniformly along the strand length

and not allow it to concentrate in spots at the strand surface will reduce proximity loss. In other words, uniform surface contact between strands both laterally and circumferentially is the most practical way of controlling proximity loss, the normal, inherent contact resistance being sufficient for this purpose.

This being accomplished, there will be still further reduction in proximity loss by increasing contact resistance between strands. In fact, perfect insulation between strands reduces proximity effect to a minimum regardless of method of stranding by entirely eliminating cross currents, as demonstrated by tests on cables with enameled strands (cables Nos. 74 and 76, Table II).

The most definite method of controlling contact resistance is to insulate the strands with enamel or other hard insulating films. Oxidized and tarnished strand surfaces will, under certain conditions, increase contact resistance but since this resistance also depends upon pressure between strands and both the degree of oxidation and the pressure at points of contact are difficult to control uniformly, this method has not worked out well.

As a matter of fact, complete or partial insulation of strands, as described above, is hardly desirable for a number of reasons. It makes sweating of connectors difficult and introduces impurities into the cable. Fortunately, this method is not necessary and proximity loss can be adequately and more practically controlled by uniform distribution of cross currents, accepting normal contact resistance.

The usual method of stranding is to lay alternate layers of strands in opposite directions. When the strands are tightly and compactly applied in this way but not rolled or crushed it leads to relatively high proximity loss because the circulating current is concentrated at those points of contact where the strands cross. Rolling or crushing the conductor will increase the area of strand contact and reduce the concentration of current. The more compactly the strands are crushed, particularly the outer layers, the greater will be the reduction in proximity loss.

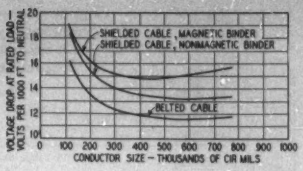
When the layers are in the same direction but not crushed there is line instead of point contact between strands and uniform lateral distribution of cross currents. Where a flexible conductor is desired this is an effective way of reducing proximity loss. This type of stranding, however, tends toward a loose and nonuniform arrangement of strands which in many cases is undesirable.

The most practical method of controlling proximity loss is to strand all layers in the same direction and crush each layer by rolling as the conductor is built up. This results in a neat, compact conductor cross section under good factory control and reduces proximity loss practically to the theoretical minimum. This compact rolling of strands also reduces the cable cross section and cost.

Cables Nos. 17, 35, and 69 in Table II have this compact arrangement of strands. The minimum curves in Fig. 2 are based upon theoretical minimum losses with zero proximity loss. If cables Nos. 17, 35, and 69 are compared with the minimum curve for cable with nonmagnetic binder it will be seen

Fig. 5. Voltage drop at rated load of 3 - conductor cables for 15-kv service

9 cables per duct bank



that there is very good agreement and that the proximity loss of these cables must have been close to zero. In making this comparison the smaller diameter of the compact strand cables and the resulting decrease in sheath loss should be taken into account.

Other Points in Connection With Losses

A study of the measured and calculated component losses in Table IV brings out a number of interesting points. It will be seen that the measured and calculated sheath losses agree quite well and that the proximity loss is the only variable, falling between maximum, solid bar, and zero proximity losses, as determined by the method of stranding and the condition of the strands. The same comparison is shown in Fig. 2, where the maximum curves represent maximum measured proximity loss for stranded conductors and is always less than the solid bar proximity loss given in Table IV. It will be noted that only the points for unimpregnated cable and round conductor cable of larger diameter than sector fall above the maximum curves in Fig. 2.

It is not possible to calculate theoretically the component losses in cable with magnetic binder because of the field distortion. An empirical study of such cable, however, leads to some interesting conclusions. Component losses were measured for most of the cables with magnetic binder in Table II. Space does not allow inclusion of these data but a typical set of measurements is given in Table I.

It will be noted that sheath loss is less and proximity loss greater than for a corresponding cable with nonmagnetic binder. The magnetic binder acts as a shield and reduces the flux interlinkages with the sheath, thus reducing sheath loss. At the same time, this binder distorts the field inside the cable and causes an increase in proximity loss. These 2 changes more or less balance and it is for this reason that there is little difference in total losses of magnetic and equivalent nonmagnetic binder cables.

It is possible to shield the sheath entirely by wrapping the magnetic binder tape with little or no space between tapes. Cable No. 62 was made in this way and the measurements with and without sheath were exactly the same. The total losses in cable No. 62 were, however, practically the same as those of standard cable with the binding tape spaced $^1/_2$ to $^5/_8$ in. The reason for this was that while sheath loss was eliminated there was a corresponding increase in proximity loss from field distortion.

The steel binding tape in cable No. 62 was of ordinary commercial grade in which the magnetic and

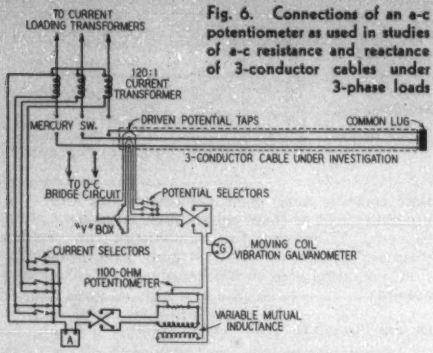


Fig. 6. Connections of an a-c potentiometer as used in studies of a-c resistance and reactance of 3-conductor cables under 3-phase loads

electrical properties were disregarded. Cables Nos. 63 and 65 were constructed exactly the same with the exception that high resistivity transformer steel (*DX*) and high permeability (Nicaloi) steel were used, respectively. Comparison of these 3 cables shows that the magnetic and electrical properties of the binding tape have no practical effect on total losses. It also shows that the magnetic losses in the binding tape itself are negligibly small. These results are due to the very large "air gap" in the magnetic path.

Proximity loss predominates under all conditions in cable with magnetic binder. It is for this reason that there is a greater spread between minimum and maximum loss curves for magnetic binder cable in Fig. 2. With cable having nonmagnetic binder sheath loss, a fixed quantity plays a prominent part and proximity loss is reduced. This leads to a lesser spread between the maximum and minimum curves.

Appendix A—Test Method Used by Electrical Testing Laboratories

The length of sample selected for the test specimens was 15 to 20 ft, the preliminary investigations having indicated that measurements could be made on specimens of this length with sufficient accuracy to report final values reliable to better than 0.5 per cent. Accordingly, the procedure was developed particularly for specimens of this order of length, though it is equally applicable to longer specimens.

After cutting specimens to the desired length, the lead sheath was removed from 4 in. of cable at one end and 15 in. at the other end. At the 4-in. end, the insulation, binder tape, shielding tapes, etc., were cut off square with the end of the lead, leaving only the 3 bare conductors protruding. These bare ends were then sweated into a large cup made from copper pipe, so placed that the cup and solder came within about $^1/_4$ in. of the end of the sheath.

At the other (15-in.) end, the binder tape or belt insulation was removed and cut off smoothly at the edge of the sheath. The insulation was then removed from the outer 2 in. of each conductor and individual lugs were sweated on. The 3 conductors then represented a *Y* or star connected system or load.

Two inches in from the edge of the lead sheath at the "15-in." end, 3 holes $^3/_8$ in. in diameter were drilled through the sheath, binder, and shielding tapes—one hole being centered over the "back" of each of the 3 conductors. At the center of these holes a smaller hole was drilled through the insulation and into the conductor for about $^1/_4$ in. Copper pins were then driven down into these openings to serve as potential taps.

The fall of potential along each conductor from the driven potential tap to the common end (i. e., cup end) was measured in terms of resistance and reactance by means of an a-c potentiometer and mutual inductor connected in the secondary circuit of a current transformer, the primary winding of which was connected in series with the conductor being measured.

A few preliminary measurements showed that comparatively large errors might be introduced by using a potential lead connected to the "neutral" point at the cup end of the cable. An artificial neutral was, therefore, provided with the aid of 3 equal noninductive 10-ohm resistors connected across the driven potential terminals; all question of induced electromotive force in the neutral potential lead was thereby eliminated. At the same time, the 10-ohm resistance was high enough to avoid any troublesome correction due to shunting current and yet low enough not to reduce galvanometer sensitivity. A schematic diagram of the general test circuit is shown in Fig. 6.

The use of this potentiometer arrangement makes it possible to determine the equivalent resistance and reactance of the cable directly in terms of a standard resistance and standard mutual inductance. For instance, if the symbols used are as follows:

T = current transformer ratio
M = setting of mutual inductor, henries
S = standard resistor, ohms
P = total resistance of potentiometer, ohms
N = resistance of that portion of the potentiometer inserted to obtain a balance, ohms
K = tangent of angle introduced by current transformer
w = angular velocity, radians per second

the relations for the effective resistance and reactance of the specimen of cable under investigation are:

$$R = \frac{1}{T} \cdot \frac{NS}{S+P} - \frac{wMK}{T}$$

and

$$wL = \frac{wM}{T} + \frac{K}{T} \cdot \frac{NS}{S+P}$$

where

R = effective resistance, ohms, and
wL = reactance, ohms

Since the reactance of the cables measured was of the same order as the resistance, the use of current transformers with phase angles not larger than 10 min of arc ($K = 0.003$) makes the last term of each of these expressions negligible. The relations then become

$$R = \frac{1}{T} \cdot \frac{NS}{S+P}$$

$$wL = \frac{wM}{T} \text{ or } L = \frac{M}{T}$$

which are the equations used in the determination of effective resistance and reactance in these measurements.

Table V—Results of Interlaboratory Checks

Data in the same line are for cables of identical construction

Laboratory	Cable Number*	A-C:D-C Resistance Ratio	Laboratory	Cable Number*	A-C:D-C Resistance Ratio
I	8	1.08	II	11	1.14
I	24	1.09	IV	26	1.16
I	25	1.11	II	27	1.16
III	32	1.08	I	33	1.10
III	31	1.09	I	34	1.10
I	36	1.13	II	37	1.27
I	49	1.13	III	50	1.13
I	48	1.13	IV	51	1.14
I	54	1.10	III	55	1.10
I	59	1.23	V	61	1.24
I	66	1.23	V	67	1.21
I	71	1.42	V	73	1.42

* Identification number. See Table II for description.

By means of the mercury switch shown in Fig. 6, a change could be quickly made from the a-c potentiometer to a d-c double bridge for the measurement of the ohmic resistance of the conductors. The use of a reflecting galvanometer with the Kelvin bridge made it feasible to measure these resistances to better than 0.1 per cent.

In making measurements of this nature it is possible to work either with the cable at or near room temperature or after heating under load to a temperature approximating operating temperature. However, due to the necessity for getting results promptly the measurements were made with the cable as nearly as possible at room temperature. This required making the measurements quickly in order to avoid heating.

When making a series of measurements it was the practice to take the d-c resistance before and after each a-c measurement. In general, these did not differ by more than one per cent even at the high current loads. The average of the 2 d-c resistance measurements was then used in the computation of ratios involving the d-c resistance.

Following each test the data were computed and curves plotted. If the results appeared satisfactory, the lead sheath was removed and a second test made. The cable was then torn down step-by-step, the measurements being repeated at each step. In this manner it was anticipated that the losses could be analyzed as to their sources.

Appendix B—Interlaboratory Checks

In order to eliminate the possible effects of differences between various laboratories, numerous check tests were made in which the same or similar pieces of cable were measured in each of 2 or more laboratories. The general results of these interchecks, Table V, showed good agreement although there were some exceptions. It is considered that such measurements should show agreement to within 1 to 2 per cent. Where individual measurements have shown deviations from the group which exceed this amount, the data have not been included in the graphic presentation in Fig. 2.

Appendix C—Check Measurements Against Field Test

Early in 1931 a field test was arranged by W. H. Cole of the Edison Electric Illuminating Company of Boston. The cable under test had been manufactured in 1930 and at that time a-c resistance and reactance measurements were made on specimens of the cable both at the Electrical Testing Laboratories and in the manufacturer's laboratory. The final installation covered 37,020 ft of this cable and offered an excellent opportunity to check the results obtained in the laboratories on short samples.

The results of these measurements together with the original E.T.L. and factory results are shown in Table VI. It will be noted that a very close agreement is shown between all measurements with one exception where the factory measurements were made on the cable on a reel (instead of being laid out straight). It is likewise interesting to note that these field measurements show the same dependence upon phase rotation which had been found earlier in the laboratory.

Table VI—Check Against Field Tests of Installed Cable

All values expressed as a ratio to the d-c resistance

Tested	Length of Cable Tested	Current Load, Amps per Phase	A-C Resistance	60-Cycle Reactance
E.E.I. Co. of Boston	37,020 ft	204.3	1.113	1.816
		291.3	1.114	1.822
		392.2	1.118	1.835
		442.9	1.112	1.822
		443.6*	1.124*	1.812*
Manufacturer	Short sample	400	1.128	
		600	1.128	
	Full reel	600	1.155	
E.T.L.	15 ft	200 to 600	1.12	1.82

Note: 3 × 700,000-cir-mil, sector conductor cable, 220 mils paper, Type *H*, nonmagnetic binder.

Data from field tests furnished through the courtesy of W. H. Cole, superintendent, street engg. dept., Edison Electric Illuminating Company of Boston, Mass.

* This test made after reversing phase rotation to agree with rotation of conductors viewed from supply end.

On the Schooling of Engineers

Two types of students, one fundamentally interested only in engineering, and the other more deeply interested in and capable of leadership, are considered in this paper. For both, a broader training in the humanities is urged. Among the numerous points which it is stated should be brought to the attention of the student engineer is the necessity of realizing that human relationships, which cannot be reduced to a science, are among the most important considerations in later life.

By
ALEX DOW
FELLOW A.I.E.E.

The Detroit (Mich.) Edison Company

WHEN I last addressed an audience on the subject of the schooling of engineers, I spoke as an executive who retained so much of his inherited bent toward engineering that he still comprehended the operation of a student mind; a mind exceedingly desirous of engineering success and, to that end, rejecting as impedimenta all offerings of schooling in what we have for ages called the humanities. The intervening 8 years since that address have pushed me further from engineering, and submerged me deeper in problems for which I have an inherited dislike—problems of finance, of law, of politics; problems which do not admit of an engineering solution; problems of which no complete solution satisfying every factor is possible; problems where no rule of physics or mathematics will aid a solution, because the relations of the factors are neither reasonable nor constant—because the factors are of disproportionate values, measurable only on the unstable scale of their reactions on human beings. And in these years I have been confirmed in my earlier opinion that there remains something to be done toward a broadened education of those

Full text of a paper recommended for publication by the A.I.E.E. committee on education, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 29–25, 1935. Manuscript submitted Oct. 20, 1934; released for publication Oct. 30, 1934. *Not published in pamphlet form.*

students who have chosen to be engineers, who have on them the urge to be engineers, and whose innate mentality finds happiness in exactness of expression and completeness of reasoned result.

Ability in Nonengineering Lines Desirable for Success

The purely engineering mind does not take kindly to the humanities. The student who seeks and rejoices in a complete solution of a technical problem, tends to believe that such a solution should be possible for every problem. Wherefore he is apt to belittle an offered study in which the preceptor is forced to admit that the answer in most cases may be either "yes" or "no," that there will be in every case an unsatisfied remainder. Nevertheless, the engineer who rises above purely technical achievement must solve problems in human nature. He has then ceased to be concerned solely with the qualities of matter, and the forces inanimate. If he is a notable success in his engineering, he will surely in time be offered opportunities wherein he will need the aptness of the executive who knows that it is imperative to decide quickly, even though the decision may be imperfect; he will see that he must avail himself of other human beings as assistants or delegates, even though these are not to his heart's desire; and find that he must recognize and allow for an infinity of variables, requiring in him at the one end of his knowledge of the humanities, a silent comprehension of mass psychology, and at the other end an occasional outspoken exhibition of what is colloquially called "horse sense."

If our school intent is only to produce human calculating machines, interpreters of rigid specifications, supervisors of exact tests, there is nothing to criticize in the engineering training which is now offered by the schools. Furthermore, those schools which now require that there shall be a certain devotion, in the earlier years, to what I shall continue to call the humanities, already recognize that a thorough technical schooling is not the end-all of their effort. I assume that we desire scholarly engineers, and not merely expert technicians.

As one who has neither taught nor studied in any university I speak with deference to those who from year to year are seeking to send out graduates broadly equipped for life in this complex world; and of all of you I ask recognition that I speak as one who has been the immediate employer of many school trained engineers. Among these I have found representatives of each extreme; I have found the man who did not seek to be more than an accurate calculator, estimator, inspector, content if his field results agreed with his desk figures. And I have found the man who looked upon engineering skill as an aid toward leadership—who sought appreciation from those who could measure and value him as an all-around man of affairs, doing good work for his world and incidentally doing well for himself. The first man sought, as his compensation, a fair return on his investment in engineering education. The other held the value of his service to be the measure of his gain, and was willing to venture boldly and be judged by results. No schooling can guarantee to produce the latter type. The possibility must be born in the boy. But the schooling may (and I say it should) extend the mental horizon and increase the social value of the first type.

Assuming that the social sciences are to be presented to engineering scholars, the teacher must recognize that trait (already noted) of the student engineer mind: an impatience of all incomplete solutions, even though the acceptance of an incomplete solution may open out an impasse. If teachers, who cannot modify their technique, are assigned to this duty, the time set aside for study of social subjects by student engineers will be wasted, with the probability of forbidding future interest in the despised subjects. Your student recognizes immediately the value of (let us say) mathematics. He is willing to follow the mathematician into pure physics, the excursions into which have to him the character of research. Those humanities of which he can see possible uses to his first purpose, are more likely to be tolerated or welcomed by the student. Let us see what these are and how they should be presented.

Language—Most Important of the Humanities

Let us consider first language; inability to speak and write English is entirely too common among engineer scholars, and after school days will be recognized by the young engineer as a handicap. The courses in English which are offered as parts of a literary course, are definitely not attractive. Still more so is this the case with a literary college course in any foreign language. I hold that at least one foreign language should be required, up to the point of reading it. The foreign language course is rdinarily directed toward the acquisition of facility in speech and in writing. The engineering student need not seek fluency of speech. He needs only the necessary vocabulary and knowledge of grammar sufficient to permit his intelligent reading of engineering literature. And the reflex from the limited study of the foreign language (especially of its grammar) will contribute to precision in English.

I do not know how English should be taught to engineering students. Our public schools nowadays start off on the wrong foot. The young child acquires a talking and reading acquaintance with his language, but is not taught its grammar nor given a vocabulary greater than he will acquire in his everyday life. English was taught otherwise to me. At 10 years of age I knew that prepositions governed the objective case and that adverbs qualified verbs, adjectives, and other adverbs. Also, I knew that "to admit" was not the equivalent of "to acknowledge" and that "a remainder" was not ipse facto "a balance"; and so forth and so forth through a hundred exhibits that my memory could produce were it taxed to do so. That method is one for childhood; not for 18-year-olds. But I persist in believing that the study of English can be made interesting, and I know that skill in the use of language should be rated at least as highly as skill in, say, the use of the slide rule.

Accounting and Economics Should Be Taught

Beginning with English and with at least one foreign language, I would continue with accounting and economics. Accounting has many variations but its principles are the same wherever taught. Its usefulness as an engineering tool should be evident to the student. There should be included a course in the analysis of costs of completed work; and somewhere therein there should be a warning that the synthesis of costs of proposed work is not necessarily a complement to analysis.

As to economics—I cannot find that there is any accepted science of economics. Therefore it cannot be taught as a science. The engineering student is inclined to make a jest of economics. I do not blame him. When he finds that one teacher insists that commercial activity is proportional to the quantity of a circulating medium; that another utterly disregards such proportionality; that a third says there is no inherent value in gold outside of its limited use in the arts; while a fourth teaches that the control of gold means the control of commerce—these differings of doctors provoke the laughter of the student engineer. The absence of an accepted vocabulary of economics is another defect. It disconcerts a student to find that a term may mean something quite different when used by another writer, and that even the one writer may impose different meanings thereon. I would make the presentation of economics almost sketchy, possibly a sequence of lectures setting forth the several theories which have been formulated and offered to the world, and comparing their agreements and contradictions. I would tie my study of economics into history, showing the recognizable errors of the past. But I should not recommend to the engineering student the acceptance of any economic theory whatever. Let him see that his future work will inevitably be restrained or facilitated by so-called economic conditions, and that his recognition of conditions at any time existing, and the trends thereof, will be helpful to him in the long game of life.

History, and Its Relation to Other Humanities

Naming now those humanities which are not useful in the day's work of the engineer, in my opinion the most important of these is history. It should be taught as it is not taught today. The historian suffers from a complex similar to that of the narrow engineer in that he feels laid upon him the burden of finding the facts and making a record thereof. To me the charm of history is not in proving who wrote such a letter, or broke such a treaty, but in showing the origins and scopes of social movements throughout the ages. Into history there can be tied the recognition of economic forces. If we are to teach history of the current year it should be shown why one nation needs for its safety, or even for its existence, free and world-wide access to the seaways; whereas the vital sea need of another nation is only that there shall be no interception on the narrow seas of the colonial grain with which, like Rome of old, it must feed its people. It should be shown how engineering progress, beginning with the earliest roads and irrigations, has affected the fate of peoples; how in 40 years of the nineteenth century the British invention and adoption of steam power changed the régime of a nation, and indeed of an empire; and how the development of communications and of electric transmission of power has in this century altered the social and economic balances of the habitable world. I would make history the backbone (so to speak) of all teaching of the humanities. To the student engineer a presentation of arrived results, though these have been neither sought nor predicted, has attraction which in his mind is missing from pure speculation.

Beyond these recommendations I have no present mind to go. If history be taught as it should be taught, there will be necessary recognitions not only of the economics involved but of the personal and mass psychology involved in the changing conditions of races, and peoples, and governments. Even philosophy can and should be shown to have had its influence upon that sequence of events which we call history. And you cannot crowd a personally necessary training in techniques, and also an education in all the humanities into the 4-year course to which we are at present committed. I do not suggest making that course longer. If circumstances permit our student to spend further time at school I would rather, after he completes his 4-year course, have him go into the field for a couple of years; and thereafter come back with a reasoned choice of the study or studies he wishes to pursue.

Versatility Essential to Leadership

Throughout this talk I have had in mind the probability that the successful engineer will in later life find himself busy in work which is not pure engineering, work in which his engineering training will teach him to analyze and organize its processes, but in which he is dealing with human beings whose desires change from year to year and whose rated capacities are not engraved upon individually attached nameplates. Our engineer may be a partner in a manufacturing or constructing firm, meeting problems in finance, in personnel, and in sales methods. He may be offered (or may have pressed upon him) public duties to his city, his state, or even to the nation. In any of these environments he will be helped by his engineering training, but if he is to be successful, he must refrain from the belief that human beings can be depended upon to do what they should do, subject to set factors of safety. He cannot even restrict himself to his own commercial, or social, or governmental functions. If he is to lead, he must see broadly what is going on in each contiguous phase of life. If he is depended upon by thousands of employees, or by city, or state, or national populations to guide affairs in the way they should go, he must recognize that leadership does not lead if it restricts itself to narrow duties, if it binds itself to a formula and fails to mark and follow the expediency, or the necessity, inherent in immediately observed conditions.

Coaxial Communication Transmission Lines

A nonmathematical discussion of the mechanism whereby energy may be transmitted over long distances at high frequencies by the use of "coaxial conductors" is presented in this paper. A coaxial system consists of a cylindrical conducting tube within which a smaller conductor is coaxially placed. Such conductors, which reduce interference and cross-talk, are applicable for the transmission of telephone, telegraph, and television signals over a very wide range of frequencies.

By
S. A. SCHELKUNOFF
Membership Application Pending

Bell Tel. Labs., Inc.,
New York, N. Y.

THE technical possibilities of the use of "coaxial conductor" systems for bands of frequencies as wide as 1,000,000 cycles or more are discussed in a recent paper by L. Espenschied and M. E. Strieby ("Coaxial Conductor Wide Band Transmission Systems," ELECTRICAL ENGINEERING, volume 53, Oct. 1934, page 1371–80). A comprehensive mathematical discussion of coaxial transmission lines is given by the author in another paper ("The Electromagnetic Theory of Coaxial Transmission Lines and Cylindrical Shields," *Bell System Technical Journal*, volume 13, Oct. 1934, page 532–79). The present paper attempts to give a nonmathematical discussion of the physical mechanism by which physical energy is conveyed along a coaxial pair, dissipated in it, or transferred between it and other neighboring systems. It is believed it will be of interest to engineers who may not wish to follow through the mathematical treatment.

MECHANISM OF TRANSMISSION OF ENERGY

A coaxial transmission system is comprised of a central wire surrounded by a coaxial shield which is employed as the return conductor. The laws of transmission of energy along such a system do not differ in any essential respect from those governing a parallel pair. If one member of the parallel pair were to be replaced by a cylindrical shell coaxial with the other wire and at the same distance from it, the capacity per unit length would become about twice as great and the inductance about $^1/_2$ as great, so that at high frequencies, where the influence of the resistance on the surge impedance of the line is negligible, the surge impedance of the coaxial line is about $^1/_2$ the surge impedance of the parallel pair.

Within a coaxial pair (figure 1) the lines of magnetomotive intensity H are coaxial circles and the lines of electromotive intensity E_ρ are substantially radial. The word "substantially" is used because although most of the energy travels *along* the pair, a slight amount of it moves radially into the imperfect conductors, where it is dissipated in heat.

By electromagnetic theory this radial movement of energy implies the presence of the longitudinal component E_z of the electromotive intensity parallel to the conductors. This E_z, negligible for most purposes, is an important factor in calculating the a-c resistance of coaxial pairs and in matters of interference and cross-talk. Being tangential to the cylindrical boundaries between different mediums comprising the coaxial pair, it is continuous across them while the radial component E_ρ is practically annihilated on entering the conductors. In the conductors themselves E_z and H constitute the principal field, and energy moves there almost exclusively outward (or inward, as the case may be) and not lengthwise as in the dielectric between the conductors. Because of heavy absorption of energy by the conducting substance, the field is rapidly attenuated in this outward direction.

A quantitative idea of the rate of decay can be gained by considering the simplest case of a plane wave, in which E and H are uniform all over the wave front (figure 2). The formulas for the propagation of such a wave in a homogeneous medium are very similar to those of wave propagation in transmission lines, the permeability μ playing the rôle of series inductance, while the conductivity g and the dielectric constant ϵ take the part of the shunt conductance and capacity, respectively (see figure 3). In metallic substances the conductivity is large and the dielectric constant can be neglected, so that the propagation constant is expressed simply as $\sqrt{j\omega\mu g} = \sqrt{\pi\mu f g}\,(1 + j)$ nepers per centimeter. (Here the conductivity g is expressed in mhos per centimeter and the permeability μ in henries per centimeter. Also, $\omega = 2\pi f$ where f is the frequency.) In copper, for instance, $\mu = 1.256 \times 10^{-8}$ henries per centimeter and $g = 5.80 \times 10^{6}$ mhos per centimeter, so that at 1,000,000 cycles the attenuation constant is 151 nepers or 1,315 decibels per centimeter. The phase change is 151 radians per centimeter, so that the wave length in copper is 0.415 millimeters. Both

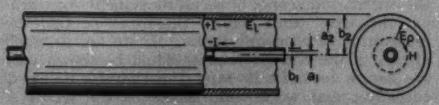


Fig. 1. In a coaxial transmission line the lines of magnetomotive intensity are circles and those of electromotive intensity not very different from radii

Full text of a paper recommended for publication by A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Sept. 28, 1934; released for publication Oct. 18, 1934. *Not published in pamphlet form.*

the attenuation and the phase change are thus exceedingly rapid.

In the outer conductor of the coaxial pair the wave is not plane, but it could be regarded as such without introducing a serious error, because the "attenuation" (in the more general sense) of the wave due to the outward divergence is slight and the attenuation due to the energy absorption is very great. This fact will be useful when the shielding afforded by the outer conductor is discussed later in this paper.

A hollow conductor has an optimum thickness

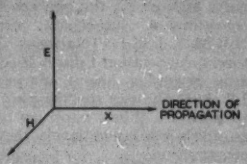


Fig. 2. Relative orientation of the field components in a plane, plane-polarized electromagnetic wave

from the point of view of its resistance; this optimum thickness equals $^1/_4$ of the wave length for this particular metallic substance. If the conductor is made thicker while keeping the diameter of the active surface (that is, the surface of the greatest current density) fixed, the electric current in the added metal will flow in opposition to the original current and if the same total current is to be maintained, the current density must be raised throughout the conductor, thus resulting in increased energy losses and increased effective resistance. (A somewhat different picture of this phenomenon is presented by S. A. Schelkunoff in "A Skin Effect Phenomenon," *Bell Laboratories Record*, volume 11, Dec. 1932, page 109–12.)

Interference and Cross-Talk

There has now been established a sufficient background for approaching the important problem of interference and cross-talk. Consider a coaxial pair above the ground (figure 4). The ground together with the outer conductor of the coaxial pair forms a parasitic transmission line so that in effect the system is comprised of 2 continuously coupled transmission lines, one carrying current I and the other I_g.

The electromagnetic field of a radio station or of static is impressed upon the ground circuit and produces in it current I_g, which in its turn produces the voltage drop E_t along the outer surface of the outer conductor of the coaxial pair. However, because of

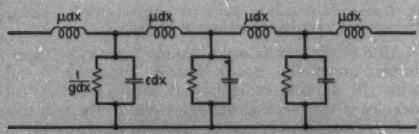


Fig. 3. This equivalent circuit of a transmission line with distributed constants is a model of a plane wave traveling through a homogeneous, isotropic medium

the rapid attenuation previously discussed, this gives rise to only an exceptionally weak "induced" voltage drop along the inner surface of the conductor. Besides, on the inner surface, the abrupt change in the properties of the medium causes almost a complete reflection, practically annihilating the magnetomotive intensity and doubling the voltage drop.

This matter of interference can also be considered from a somewhat different point of view. For all practical purposes the field of the coaxial pair does not extend beyond the outer surface of its outer conductor, and, similarly (except at very low frequencies) the field of the ground return line is limited by the inner surface of that same conductor. The outer conductor, therefore, represents the entire distributed mutual impedance between the 2 transmission lines. At zero frequency, this mutual impedance is the d-c resistance of the conductor, but otherwise it has a reactive component due to the magnetic interlinkage taking place within the space occupied by the outer tube. The mutual resistance between 2 coupled circuits can be measured by that average amount of dissipated energy which is proportional to the product of the electric currents flowing in those circuits, and similarly the mutual inductance can be gauged by that average amount of stored magnetic energy which is proportional to the product of those same currents. (The self-resistance of the circuit can be measured by that amount of dissipated energy, which is proportional to the square of the current in the circuit. An analogous statement applies to the self-inductance.) As the frequency increases the electric current I of the coaxial pair tends to concentrate on the inner surface of the outer conductor and the current I_g of the ground return line moves toward the outer surface. The 2 currents

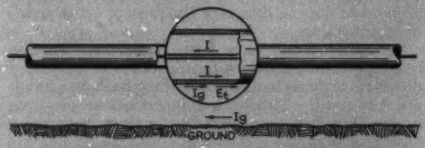


Fig. 4. The outer conductor of the coaxial pair and the ground form a parasitic transmission line playing an important rôle in interference phenomena

become more and more separated, the regions of high density of one overlapping the regions of low density of the outer, and the mutual energy of dissipation as well as the mutual electromagnetic energy are thereby diminished.

The problem of cross-talk between 2 coaxial pairs is quite similar. Besides the 2 given transmission lines there is a parasitic line comprised of the outer conductors of the 2 pairs. The induction takes place from one pair into this parasitic line and thence into the second pair. Obviously, this cross-talk is exceedingly small. It is largely because of this freedom from interference that the coaxial pairs have been used as lead-ins between antennae and radio stations and seem to be promising as broadband transmission systems.

Recommended Transformer Standards

A brief review of several important revisions and extensions of the A.I.E.E. standards for transformers recommended by the A.I.E.E. transformer subcommittee is presented herewith, in order that those interested may have an opportunity to become familiar with these recommendations and to offer helpful criticism before action on final standards is taken.

By
H. V. PUTMAN*
MEMBER A.I.E.E.
Westinghouse Elec. and Mfg. Co., Sharon, Pa.

J. E. CLEM†
MEMBER A.I.E.E.
General Elec. Co., Schenectady, N. Y.

DURING the past 2 years the A.I.E.E. transformer subcommittee has made several important recommendations for additions to and changes in the A.I.E.E. transformer standards. Most of these relate to insulation levels and dielectric tests. Their purpose has been to bring the Standards up to date in line with the present art of lightning protection.

Insulation levels have been established, impulse testing recommendations formulated, low frequency dielectric tests revised, and a bushing flashover standard proposed. Timely recommendations covering permissible short time overloads for transformers also have been made.

The purpose of the present report is to summarize briefly these more important recommendations in order that the industry may become more familiar with them and may offer helpful criticism before action on final standards is taken.

Insulation Levels

The first attempt of the subcommittee to supplement the present A.I.E.E. dielectric tests with impulse strength requirements was in 1930, when it was recommended[1] that transformer insulation in different voltage classes be coördinated with different numbers of line insulators. Later,[2] gap spacings were found to be a more convenient means of expressing the desired insulation level and the schedule of gaps now has been extended to include the distribution circuit voltages and also the 287.5 and 345 kv classes. At the last meeting of the subcommittee it was decided to list the insulation levels of transformers in terms of the gap spacing used for the impulse test rather than in terms of the coördination gap spacing. Table I gives a complete tabulation of coördination and test gaps.

The standard test gap used in making impulse tests consists of $^1/_2$-in. square-cornered square-cut rods coaxially spaced and overhanging their supports at least $^1/_2$ the gap spacing, and mounted on conventional insulators corresponding to the N.E.M.A.-E.E.I. (National Electrical Manufacturers' Association-Edison Electric Institute) standards giving a height above the ground plane[3] 1.3 times the gap spacing plus 4 in. (± 10 per cent tolerance). When gaps are used in the field to establish insulation levels they often are of other construction.

In establishing this schedule of test gaps it should be understood clearly that the subcommittee is only attempting to set up reasonable insulation levels for the design of transformers. It is not attempting to dictate to operating engineers the specific insulation levels that should be used in any particular voltage class. It does recommend that intermediate insulation levels be avoided because the steps indicated are now as close together as is practical.

Impulse Dielectric Strength and Test

An entirely new standard under this title has been proposed. Briefly it requires that transformers shall be able to withstand the following impulse tests with a 1.5x40 microsecond positive wave using the test gap settings given in table 1:

1. A wave not less than 90 per cent of the minimum wave permitted by the test gap.
2. A wave just sufficient to flash over the specified test gap.
3. A wave having a crest at least 10 per cent greater than the minimum flashover voltage of the test gap.

The effective wave front may vary from $^1/_2$ to $2^1/_2$ microseconds, the tail from 40 to 50 microseconds. The test gap is connected directly to ground.

Without the test gap, the transformer shall be able to withstand the following tests:

4. A wave of sufficient magnitude to flashover the bushing. Where oversized bushings are used they should be gapped for this test to the same impulse flashover as the standard bushing for the specified insulation level.
5. A wave as high as in test 3 or 4, but with means for maintaining the excitation voltage across all parts of the winding.

All 5 of these tests are to be made with the transformer under full power voltage excitation[4,5] and with the impulse synchronized within 30 electrical degrees of the 60 cycle voltage crest, on the negative half cycle.

For the foregoing impulse tests standard atmospheric conditions are assumed, namely, an absolute humidity of 6.5 grains per cubic foot and an air

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Oct. 19, 1934; released for publication Oct. 23, 1934. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

*Chairman, A.I.E.E. transformer subcommittee 1932–34.
† Present chairman of A.I.E.E. transformer subcommittee.

density corresponding to a barometric pressure of 760 millimeters of mercury and a temperature of 25 degrees Centigrade. The crest value of the impulse voltage wave should be adjusted to the voltage that would be obtained on the standard test gap under standard humidity and air density conditions. This may be done by making the following corrections to either the gap spacing or the impulse voltage generator setting, the former being preferable: For impulse tests 1 and 2, increase or decrease the gap length or applied voltage 2.5 per cent for each grain the absolute humidity falls below or above 6.5 grains per cubic foot, respectively; for impulse tests 3, 4, and 5, 2.0 per cent. In addition to the correction for humidity, the gap length or applied voltage should be corrected in inverse proportion to the relative air density based upon standard conditions of 760 millimeters of mercury and 25 degrees Centigrade.

The foregoing testing procedure has been in use on large power transformers for 2 years. This experience has demonstrated the practicability of commercial impulse tests.

At the time these testing recommendations were adopted it was thought that they constituted a reasonable demonstration of coördination with the gaps of table I. In view of more recent data on the characteristics of rod gaps at short time lags, it is known that these tests do not demonstrate coördination with the gap at short time lags.[6,7] It appears that they do not always impose as severe a test on the major insulation of the transformer as the present A.I.E.E. low frequency tests. The transformer subcommittee therefore is considering a slight readjustment of the impulse test voltages and the adoption of certain simplifications in the test procedure which experience has demonstrated are desirable. The same general procedure would be employed utilizing the following schedule of tests:

1. A wave just sufficient to flash over the specified test gap directly connected to ground.

2. A wave sufficient to flash over the bushing, provided standard bushings are used, and having a crest voltage bearing a definite relation to the 60 cycle test voltage.

Table I—Standard Spacing of Insulation Coördination and Impulse Test Gaps

Gap Spacing, Inches		Rated Circuit Voltage Normally Associated Therewith
Coördination Gap	Test Gap	
3/4	0.8	575 delta, 1,000 star
2	2.2	2,400 delta, 4,160 star
3	3.3	4,800 delta, 8,320 star
4 1/2	4.5	6,900 delta, 12,000 star 13,800 (15,000)
6 1/4	6.9	23,000 (25,000)
9 1/4	10.2	34,500
12 1/4	13.5	46,000
18 3/4	20.6	69,000
25	27.5	92,000
31 1/2	34.7	115,000
38 1/4	42.1	138,000
44 1/2	49.0	161,000
54 1/4	60.0	196,000
64	70.4	230,000
80	88.0	287,500
96	105.6	345,000

3. A full wave not less than 90 per cent of that required to flash over the bushing, or the test gap, if the bushing is oversized.

The subcommittee has given approval to this revised schedule as the basis for further study and discussion. The value of the multiplier to be used in test 2 is being carefully investigated.

Table II—Recommended Increases in Low Frequency Dielectric Test Voltage

Voltage Class	Test Gap Length	Present Test, Kv	New Test, Kv
23,000 star	6.9	47	49
6,900 delta, 11,950 star; 13,800 star	4.5	28	34
4,800 delta, 8,320 star	3.3	18 1/4	26
2,400 delta, 4,160 star	2.2	10	19
575 delta, 1,000 star	0.8	4	10

Revision of Low Frequency Dielectric Tests

Two important changes in the present standards for low frequency dielectric tests have been proposed. The first change would modify those paragraphs (13–400 and –401) dealing with graded-insulation transformers to call for an induced test voltage of 3.46 times normal (double line voltage plus 1,000 volts) which is now common practice. In transformers having reduced insulation the former induced test of 2.73 times normal would be replaced by the test corresponding to the next lower voltage class. This change also would provide for a high potential test on graded-insulation transformers at the test voltage corresponding to the voltage class of the neutral. These suggestions would bring paragraphs 13–400 and –401 of the present standards into accord with actual present-day practice.

The second change would increase the test voltages in the lower voltage classes, 23 kv and lower. It has been known for some years that the present A.I.E.E. tests in the distribution circuit voltages were not consistent with the required impulse strengths. In fact, service experience for years has resulted in a gradual increase in dielectric strength so that transformers are capable of withstanding much more severe tests. Also the proposed impulse tests would require insulation that is able to withstand higher low frequency tests than the present standards call for.

The proposed test voltages can be expressed conveniently by the empirical formula,

$$\text{Low frequency test voltage} = 4.5 \text{ kv} + (3.5 \times \text{length of test gap in inches})$$

This formula gives the desired increases in test voltage in the lower voltage classes, particularly in the distribution range, as indicated in table II. In voltage classes above 23 kv, it gives test voltages in accord with the present standards.

It was the opinion of the subcommittee that manufacturers should adopt these new test voltages as soon as possible and that users should include them

in specifications so that they may come into general use at an early date.

Transformer Bushing Flashover Standards

There never has been an A.I.E.E. Standard covering flashover voltages of transformer bushings. With the introduction of impulse testing it seemed highly desirable to establish standard impulse flashover voltages for transformer bushings.

It was thought sufficient to include in the standard only the impulse and wet 60 cycle flashover voltages as these would establish the bushing design since they are the significant requirements. It was also recommended that a common insulation level for bushings be established for both power and distribution transformers at flashover voltages 15 per cent higher than those of the coördination gaps of table I, using gaps, if necessary on power transformer bushings. These suggestions were not altogether satisfactory to the industry. There was a demand for the 60 cycle dry flashover voltages; also it was thought that the 15 per cent level was too low for power transformers in the lower voltage classes.

The subcommittee therefore has decided to recognize the practical fact that power transformers of necessity have larger bushings than distribution transformers and to propose a higher insulation level for bushings on power transformers in the lower voltage classes. The proposed flashover voltages for power transformer bushings are given in table III, which includes values for both 60 cycle dry and wet flashover and impulse flashover. The 15 per cent level is considered satisfactory for distribution transformers, but as yet the actual standard values have not been agreed upon.

In addition to the recommended standard flashover voltages, the subcommittee makes the following proposals to be included in the bushing standard:

Mounting for Test.

Bushings shall be mounted in a vertical position in a flat covered tank extending beyond the bushing not less than 25 per cent of the porcelain height. Under conditions of operation, the flashover voltage may be somewhat different.

Tolerance.

The tolerance on the 60 cycle bushing flashover voltages shall be within −5 per cent under standard conditions, but the tolerance on impulse flashover voltages has not yet been fully considered by the subcommittee.

Standard Conditions.

Temperature: 25 degrees Centigrade.
Atmospheric pressure: 760 millimeters of mercury.
Absolute humidity: $6^1/_2$ grains per cubic foot.
Water resistance and precipitation: 12,000 ohms per centimeter cube with $^1/_{10}$ in. per minute precipitation at a 45 degree angle.

Correction Factors.

1. The resistivity correction factors for wet flashover.

Water Resistance, Ohms per Cubic Centimeter	Correction Factor
3,000	1.28
4,000	1.19
5,000	1.13
6,000	1.10
8,000	1.04
10,000	1.02
12,000	1.00
20,000	0.99

The wet flashover voltage at 12,000 ohm resistivity is obtained by multiplying the measured flashover voltage by the correction factor corresponding to the actual resistivity of the water used in the test.

2. Air density and humidity correction factor for 60 cycle dry flashover tests.

For bushings with gaps in voltage classes 23 kv and higher, the measured flashover voltage shall be increased 3 per cent for each grain the absolute humidity falls below standard, and shall be decreased 3 per cent for each grain the absolute humidity exceeds standard.

For all bushings in all voltage classes, in addition to the foregoing correction for humidity, the measured voltage shall be corrected in inverse proportion to the relative air density based upon standard conditions of 760 millimeters of mercury and 25 degrees Centigrade for the range from 90 to 110 per cent of normal density.

3. Air density and humidity correction factor for impulse flashover tests.

For bushings with gaps in voltage classes 23 kv and higher, the measured flashover voltage shall be increased $2^1/_2$ per cent for each grain the absolute humidity falls below standard, and shall be decreased $2^1/_2$ per cent for each grain the absolute humidity exceeds standard.

For all bushings in all voltage classes, in addition to the foregoing correction for humidity, the measured voltage should be corrected in inverse proportion to the relative air density based upon standard conditions of 760 millimeters mercury and 25 degrees Centigrade for the range from 90 to 110 per cent of normal density.

It is recognized that the humidity and air density correction factors may have to be changed when more complete data are available.

Table III—Proposed Power Transformer Bushing Flashover Voltages and Gap Spacings

Kv Class	Transf. 60 Cycle Test, Kv	Test Gap, Inches	Equivalent Rod Gap,* Inches	1.5x40 Microsecond Positive Wave, Kv	60 Cycle Flashover, Kv Wet	60 Cycle Flashover, Kv Dry
4.3	19	2.2	3.4	80	27	40
8.7	26	3.3	4.5	95	35	50
13.8**	34	4.5	5.75	115	45	65
23†	49	6.9	8.1	155	60	85
34.5	70	10.2	11.4	215	85	115
46	93	13.5	15.0	270	120	160
69	139	20.6	22.3	385	170	225
92	185	27.5	29.6	500	215	285
115	231	34.7	36.7	600	265	350
138	277	42.1	44.0	710	315	415
161	323	49.0	51.2	815	365	475
192	393	60.0	62.3	980	440	575
230	461	70.4	73.0	1,135	515	665

* When tested in parallel with bushing gives 50–50 flashover with 1.5x40 microsecond positive wave.
** Includes also the 15 kv class.
† Includes also 25 kv apparatus, but the 60 cycle transformer test is 51 kv.

Short-Time Overloading of Transformers

It has long been recognized that power transformers of the oil immersed type may be loaded in excess of their ratings under certain conditions. The A.I.E.E. Standard No. 100 at present establishes recommendations for continuous overloads when ambient temperatures are different from those

of the rating standards of section 13. Within the past year the transformer subcommittee has planned to extend the scope of this publication by including recommendations for short-time overloads.

These recommendations have been completed for oil-immersed self-cooled transformers. The considerations upon which they are based and the proposed schedules of overloading were published in the October 1934 issue of ELECTRICAL ENGINEERING,[8] and constructive criticism of the proposal is invited.

REFERENCES

1. RECOMMENDATIONS ON BALANCING TRANSFORMER AND LINE INSULATIONS, V. M. Montsinger and W. M. Dann. A.I.E.E. TRANS., v. 49, 1930, p. 1478.

2. THE COÖRDINATION OF TRANSFORMER INSULATION WITH LINE INSULATION, V. M. Montsinger and W. M. Dann. A.I.E.E. TRANS., v. 51, 1932, p. 923.

3. Minutes of Meeting of N.E.M.A.-E.E.I. Joint Insulation Coördination Committee, Cleveland, Ohio, March 27, 1934.

4. PROGRESS REPORT ON IMPULSE TESTING OF COMMERCIAL TRANSFORMERS, Montsinger and Vogel. A.I.E.E. TRANS., v. 52, 1933, p. 409.

5. IMPULSE TESTING WITH DYNAMIC POWER CONNECTED, H. V. Putman, *Elec. World*, April 9, 1932.

6. FACTORS INFLUENCING INSULATION COÖRDINATION, F. J. Vogel, A.I.E.E. TRANS., v. 52, 1933, p. 411.

7. COÖRDINATION OF INSULATION, Montsinger, Lloyd, and Clem. A.I.E.E. TRANS., v. 52, 1933, p. 417.

8. OVERLOADING OF POWER TRANSFORMERS, V. M. Montsinger and W. M. DANN. ELEC. ENGG., v. 54, Oct. 1934, p. 1353–5.

Loading a Bank of Dissimilar Transformers

Formulas for determining the unbalance in load of 3 dissimilar single phase transformers operating 3 phase, delta-delta connected.

By
J. A. BOCK

Westinghouse Elec. and Mfg. Co., Sharon, Pa.

SOMETIMES it is necessary to operate 3 dissimilar single-phase transformers in a delta-delta connected bank. These units may have different impedance and voltage ratio or either different impedance or voltage ratio. When operated in this manner it is necessary to know the maximum load that can be carried by the bank. A similar condition exists in case there are several 3-phase banks in parallel and one of the units should fail.

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution. Manuscript submitted April 3, 1934; released for publication May 28, 1934. *Not published in pamphlet form.*

The object of this article is to present a set of formulas to determine the maximum load that can be taken from this bank of dissimilar transformers, and the unbalance of current and voltage. It is assumed that the primary voltages and the secondary line currents are balanced.

Let

E_A', E_B', E_C' = primary voltage
E_A, E_B, E_C = secondary voltage
I_a, I_b, I_c = line current
I_A, I_B, I_C = winding current

N_A, N_B, N_C = turn ratio $\dfrac{\text{secondary}}{\text{primary}}$

R_A, R_B, R_C = resistance in ohms = $\dfrac{\%\ IR \text{ drop} \times E^2}{\text{kva} \times 10^5}$

X_A, X_B, X_C = reactance in ohms = $\dfrac{\%\ IX \text{ drop} \times E^2}{\text{kva} \times 10^5}$

The resistance and reactance are referred to the secondary side.

$E_A' = E_B' = E_C'$
$\dot{E}_B' = \alpha^2 E_A'$
$\dot{E}_C' = \alpha E_A'$

$\alpha = -0.5 + j\,0.866,\ \alpha^2 = -0.5 - j\,0.866$

The symbol ˙ is used to denote a complex quantity. Voltage E_A' is used as the reference vector.

$$I_a = I_b = I_c$$
$$\dot{I}_c = -j\sqrt{3}\,I_A \tag{1}$$
$$\dot{I}_b = \alpha^2 \dot{I}_a$$
$$\dot{I}_c = \alpha \dot{I}_a$$
$$\dot{I}_A = \dot{I}_B + \dot{I}_a$$
$$= \dot{I}_B + \alpha \dot{I}_a \tag{2}$$
$$I_C = \dot{I}_B - \dot{I}_a \tag{3}$$
$$\dot{E}_A = N_A E_A' - \dot{I}_A(R_A + j\,X_A) \tag{4}$$
$$= N_A E_A' - (\dot{I}_B + \alpha \dot{I}_a)(R_A + j\,X_A) \tag{5}$$
$$\dot{E}_B = N_B \dot{E}_B' - \dot{I}_B(R_B + j\,X_B) \tag{6}$$
$$= N_B \alpha^2 E_A' - \dot{I}_B(R_B + j\,X_B) \tag{7}$$
$$\dot{E}_C = N_C \dot{E}_C - \dot{I}_C(R_C + j\,X_C) \tag{8}$$
$$= N_C \alpha E_A' - (\dot{I}_B - \dot{I}_a)(R_C + j\,X_C) \tag{9}$$
$$\dot{E}_A + \dot{E}_B + \dot{E}_C = 0 \tag{10}$$

Substituting eqs 5, 7, and 9 in eq 10 and solving for $\dot{I}_B$, we have

$$\dot{I}_B = \frac{N_A E_A' + N_B \alpha^2 E_A' + N_C \alpha E_A' - \alpha \dot{I}_a(R_A + jX_A) + \dot{I}_a(R_C + jX_C)}{R_A + R_B + R_C + j(X_A + X_B + X_C)} \tag{11}$$

$\dot{I}_a$ can be found from eq 1. After $\dot{I}_B$ is known $\dot{I}_A$ can be found from eq 2 and $\dot{I}_C$ from eq 3.

Substitute the currents $\dot{I}_A$, $\dot{I}_B$, and $\dot{I}_C$ in eqs 4, 6, and 8 to find the voltage across the 3 phases. These voltages when substituted in eq 10 should equal zero.

The scalar values of the currents may be calculated from $\dot{I}_A$, $\dot{I}_B$, and $\dot{I}_C$. If any of the currents exceed the values which the corresponding windings can carry without overheating, then the load on the entire bank must be reduced to prevent overloading.

The above formulas assume the load is at 100 per cent power factor. If the load is at some other power factor, the currents should be multiplied by the vector corresponding to it; thus, if the load is at

80-per cent power factor lagging, the factor to multiply the current by would be $0.8 - j\,0.6$.

Example

There are 3 1,000-kva transformers available, 2 of which have a voltage ratio of 33,000 volts to 2,300 volts, 0.0328-ohm resistance and 0.2275-ohm reactance. The third unit has a voltage ratio of 33,000 volts to 2,200 volts, 0.029-ohm resistance and 0.0983-ohm reactance. The load is to be at 80-per cent power factor lagging. What is the maximum load that can be carried and what is the voltage unbalance?

$N_A = 2{,}200/33{,}000 = 0.06666 \qquad N_B = N_C = 2{,}300/33{,}000 = 0.0697$

$R_A = 0.029$ ohm $\qquad X_A = j\,0.0983$ ohm

$R_B = R_C = 0.0328$ ohm $\qquad X_B = X_C = j\,0.2275$ ohm

$I_A = 455$ amp, $I_B = I_C = 435$ amp } Maximum current winding can carry

$I_a = -j\sqrt{3}\,(455)\,(0.8 - j\,0.6) = -473 - j\,631$

$I_b =$

$$\frac{33{,}000\,[0.06666 + 0.0697(-0.5 - j\,0.866) + 0.0697(-0.5 + j\,0.866)]}{2(0.0328 + j\,0.2275) + (0.029 + j\,0.0983)}$$

$$\frac{-(-0.5 + j\,0.866)(-473 - j\,631)(0.029 + j\,0.0983) + (-473 - j\,631)(0.0328 + j\,0.2275)}{2(0.0328 + j\,0.2275) + (0.029 + j\,0.0983)}$$

$$33{,}000\,[0.06666 + 0.0697\,(-0.5 - j\,0.866) + 0.0697\,(-0.5 + j\,0.866)] = -100 + j\,0$$

$$-(-0.5 + j\,0.866)\,(-473 - j\,631)\,(0.029 + j\,0.0983) = -32 - j\,74.16$$

$$+(-473 - j\,631)(0.0328 + j\,0.2275) = \underline{+128.3 - j\,128.4}$$

$$-3.7 - j\,202.56$$

$$2\,(0.0328 + j\,0.2275) + (0.029 + j\,0.0983) = 0.0946 + j\,0.5533$$

$$I_b = \frac{-3.7 - j\,202.56}{0.0946 + j\,0.5533} = \frac{(-3.7 - j\,202.56)(0.0946 - j\,0.5533)}{(0.0946 + j\,0.5533)(0.0946 - j\,0.5533)} = \frac{-112.6 - j\,17.1}{0.315}$$

$= -357 - j\,54.3 = 361$ amp

$I_A = (-357 - j\,54.3) + (-0.5 + j\,0.866)(-473 - j\,631) = 426.5 - j\,148.8 = 451$ amp

$I_C = (-357 - j\,54.3) - (-473 - j\,631) = 116 + j\,577 = 589$ amp

$E_a' = 33{,}000\,(-0.5 - j\,0.866)$; $E_c' = 33{,}000\,(-0.5 + j\,0.866)$

$E_A = 0.06666 \times 33{,}000 - (426.5 - j\,148.8)(0.029 + j\,0.0983)$
$2{,}200 - 28 - j\,37.6 = 2{,}172 - j\,37.6 = 2{,}175$ volts

$E_B = 0.0697 \times 33{,}000\,(-0.5 - j\,0.866) - (-357 - j\,54)(0.0328 + j\,0.2275)$
$= -1{,}150 - j\,1{,}992 - 0.4 + j\,82.9 = -1{,}150.4 - j\,1{,}909.1 = 2{,}230$ volts

$E_C = 0.0697 \times 33{,}000\,(-0.5 + j\,0.866) - (116 + j\,577)\,(0.0328 + j\,0.2275)$

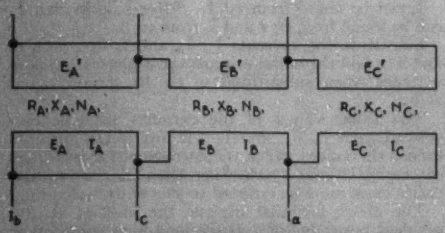
$= -1{,}150 + j\,1{,}992 + 127.6 - j\,45.3 = -1{,}022.4 + j\,1{,}946.7 = 2{,}200$ volts

Check:

$$\begin{array}{r} 2{,}172 - j\,37.6 \\ -1{,}150.4 - j\,1{,}909.1 \\ \hline -1{,}022.4 + j\,1{,}946.7 \\ \hline -0{,}000.8 - j\,0{,}000.0 \end{array}$$

Under these conditions transformer C is carrying 136 per cent load. So the load on the bank must be reduced in the ratio $\frac{100}{136}$, or the maximum load the bank will deliver is 2,220 kva.

Assuming the normal line voltage is 2,300, then $E_A = 94.4$ per cent, $E_B = 97$ per cent, and $E_C = 95.6$ per cent. The maximum unbalance is $97 - 94.4 = 2.6$ per cent.



Three-phase transformer connections, showing symbols used

Control of Transients in Welding Generators

The fundamentals of d-c arc welding generators are reviewed in this paper, and the effect of transient currents and voltages upon performance is described. It is then shown how the transients may be controlled by internal arrangements which reduce the induced voltages in the stator circuit and at the same time increase the series reactance of both the field and armature circuits. A new welding generator designed with these features is next described; it is a modification of the split pole type of self-excited machine. Also, comments on the technique of testing welding generators are presented.

By
F. B. HORNBY
ASSOCIATE A.I.E.E.

General Elec. Co.,
Lynn, Mass.

SELF-REGULATING generators for use in arc welding, generally known as "single operator welders," differ from conventional d-c machines in 2 main and very important respects. The welding generator is a changing flux instead of a constant flux machine and never operates under steady load. These 2 fundamental differences are so great that new conceptions and new methods of treatment are necessary if the operation and design of welding machines

Full text of a paper recommended for publication by the A.I.E.E. committee on electric welding, and scheduled for discussion at the A.I.E.E. winter convention Jan. 22–25, 1935. Manuscript submitted Oct. 22, 1934; released for publication Oct. 25, 1934. *Not published in pamphlet form.*

are to be understood. Much of the theory of self-regulating generators is well known, but a review of the major points may help to clarify other points and give a better conception of the machine and its operation.

The voltampere curve of a conventional type of d-c generator is shown in curve *A* of figure 1. The steady state voltampere curve of a welding generator is shown in curve *B* of figure 1. In the conventional generator the slight droop is caused by resistance and crowding of the flux due to armature reaction. In the welding generator these effects are of minor importance. The drooping characteristic is caused by a definite and major reduction in armature flux. This change in flux may be due to series turns, armature reaction, or other means, and may result in reducing the total flux or in shifting the flux from one circuit to another. The important point is that a large change in armature flux must take place if the drooping curve *B* is to be obtained.

An arc welding generator under open circuit conditions is primarily the same as a conventional type of generator; the application of load to the machine produces the change in flux necessary to obtain the drooping characteristic. Variations in welding current necessitate changes in flux in the machine. If a change in welding current does not produce a corresponding change in armature flux, then the generator will have the same characteristics as the conventional type of machine.

I-Fundamentals of Generator Transients

Changing flux always tends to produce voltages which cause currents to flow and these currents oppose the change in flux. Any eddy currents produced in the iron or copper of the machine will tend to prevent the change in flux. If the changing flux threads a field coil, it will produce currents in the field circuit, which also tend to prevent the change in flux. All of these effects retard the flux change, and produce a time lag between the change in welding current and the change in flux. This time lag will cause the generator to operate at some point between the conventional generator steady state curve *A*, figure 1 and the welding generator steady state curve *B*, or on the dynamic curve, shown as curve *C*, figure 1. The greater the time lag between current and flux, the more nearly the slope of the dynamic curve *C* approaches the slope of the conventional curve *A*, and conversely, the shorter the time lag, the more nearly the slope of the dynamic curve approaches the slope of the steady state curve *B*. If the time lag between current and flux could be eliminated entirely, the generator would operate on the steady state welding curve *B*. The dynamic curve of a welding generator is of the greatest importance, for a welding generator always operates under the transient conditions produced by welding.

The transient currents induced in the iron as eddy currents and in the field circuit as circulating currents arise as the flux initially tries to follow the change in the welding current. These transient currents are dependent upon the rate of change of the welding current and upon the impedance of the circuits. The

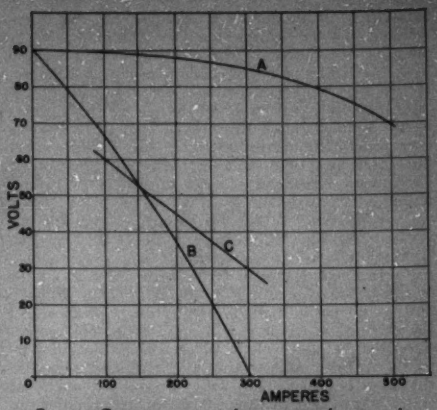


Fig. 1. Operating curves of conventional type and arc welding type of d-c generators

A. Volt-ampere curve of a conventional type of d-c generator
B. Steady-state volt-ampere curve of a welding generator
C. Dynamic volt-ampere curve of a welding generator

flux is prevented from changing with the welding current by the presence of these induced currents and, therefore, the time lag between the change in the welding current and the change in flux is dependent upon the magnitude and the rate of decay of the induced currents. In view of these facts it is apparent that any factor which will reduce the rate of change of the welding current or increase the rate of change or reduce the magnitude of the induced currents will decrease the time lag between welding current and flux. This will bring the dynamic curve *C* nearer to the steady state curve *B*.

The slope of the dynamic curve has a very definite effect upon the operation of a welding generator. The steeper the slope, the more nearly constant the welding current, for in a machine having a very steep dynamic curve, large changes in arc voltage produce small changes in welding current. The steeper the slope the smaller the transient short-circuit current, for this peak current approaches the steady state short-circuit current as the slope increases. A steep dynamic curve denotes small time lag between welding current and flux and results in greater recovery voltage. When the arc is broken, the value of the voltage recovery depends upon the flux in the machine at that instant. Thus, if the flux is able to follow the change in current closely, considerable flux will have been established by the time the arc is broken, with resultant high voltage recovery.

Reactors and Internal Reactance

The transients in the early type of welding generator were of such a magnitude that good welding could not be obtained. A reactor added to the welding circuit greatly improved the welding char-

acteristics by producing a steadier arc and easier welding and so became standard equipment. The reactor limits current surges during sudden changes in the arc and under short circuit, produces comparatively high transient voltages for maintaining the arc, and reduces the rate of change of welding current. Limiting both the rate of change of welding current and the magnitude of the surge are the most important functions of a reactor. Introduction of the reactor results in a closer approach of the dynamic curve to the steady state curve.

Transformer reactors are an interesting and important step in the improvement of arc welding equipment. In the transformer reactor a secondary winding is connected in series with the field circuit of the welding generator. The relation of primary and secondary is such that the voltage produced in the secondary winding will oppose the voltage induced in the field coils of the machine, thereby partially or fully neutralizing the transient effect in the field circuit. This will materially reduce the transients in the welding generator and produce an effect similar to very large external reactance. It is of interest to note that the necessary reactance in a transformer reactor is much less than in a plain reactor.

A welding generator or any d-c machine has a considerable amount of reactance in the armature, commutating, and series fields. Generally this reactance is not very effective, due to the transient currents flowing in the field circuit and other parts of the generator. If these transients are eliminated or materially reduced, the reactance is released to the welding circuit and the effective reactance becomes much larger. The internal reactance produces voltage kicks similar to those produced by external reactors. If the reactance of the machine can be utilized, then transient high voltages will be available for maintaining the arc the same as they are when external reactors are used.

Consider the hypothetical case of a welding generator in which there is no time lag between changes in welding current and flux; in this generator, the dynamic curve will be the same as the steady state curve. Due to the steep voltampere curve, a considerable change in the length of the arc could be made without materially affecting the value of the welding current. Voltage recovery would be instantaneous, for by the time the arc is broken, the flux would have returned to the open circuit value. There would be no transient surges or peak values of current on short circuit. Since this machine will have minimum induced currents the inherent reactance of the generator will be effective, and transient high voltages will be produced for maintaining the arc. It is interesting to note that the welding machine inherently without transients, and the welding machine having the transients reduced by external reactors have substantially the same characteristics.

This discussion suggests that it is possible to produce a welding generator having controlled transients without an external reactor. This generator will have all of the characteristics of the conventional type using external reactors or transformer reactors. From the broad point of view this is logical, for if the addition of an external reactor results in satisfactory welding characteristics, then it should be possible to incorporate these characteristics in the generator itself and make the external reactor unnecessary.

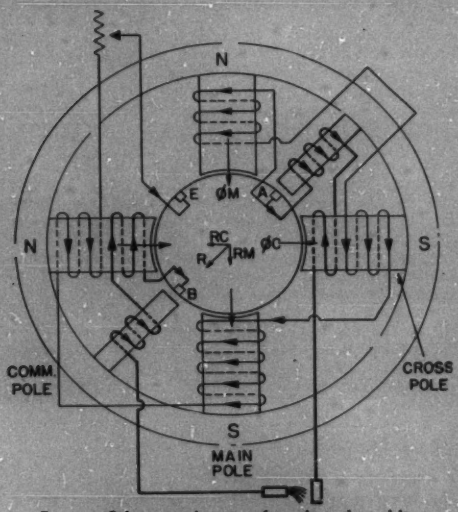


Fig. 2. Schematic diagram of a split pole welding generator having controlled transients

II-A Controlled Transient Welding Generator

The previous sections of the paper have indicated the possibility of designing a welding generator to give excellent characteristics without the use of external reactance. The next few sections of the paper describe how this objective has been accomplished.

Briefly, it has been found possible to incorporate in the design of a split pole welding generator sufficient reactance and freedom from transient excitation changes, to give characteristics fully equivalent to those heretofore obtained by the use of an external reactance. Complete elimination of the transients is economically beyond the scope of commercial machines. Machines using reactors have limited transients and make good welding machines. Therefore, if the transients are reduced so that the same characteristics are obtained without the reactor, the generator will be a good welding machine.

The split pole type of welding generator as designed by S. R. Bergman (see "A New System for D-C Arc Welding," by S. R. Bergman, A.I.E.E. Transactions, volume 50, 1931, page 678–80) offers a simple method of controlling transients. The theory of this machine has been amply covered in the past, therefore a brief résumé of the principle of operation is all that is necessary in this paper.

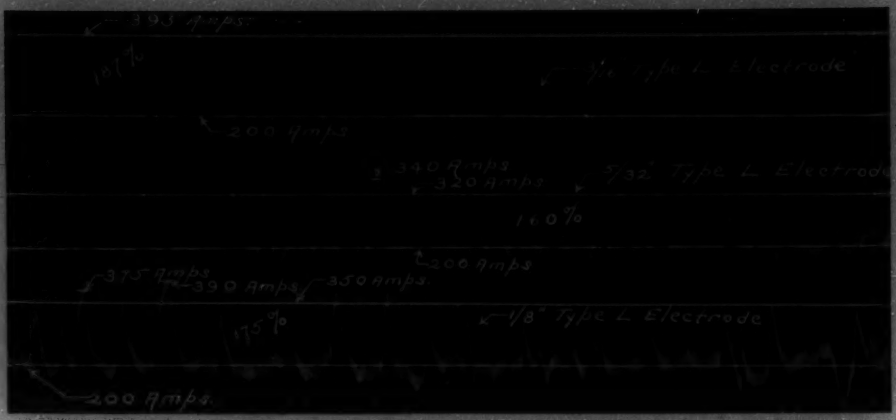


Fig. 3. Reproduction of oscillogram of welding operation illustrating the effect of changing the size of electrode
200-ampere 16-volt arc. All conditions constant except for diameter of electrode

Description of the Generator

The generator is shown schematically in figure 2. The armature is the conventional 2 pole type. The field is divided into 4 poles with adjacent shunt coils connected for the same polarity. This scheme offers 2 distinct flux paths, one through the main poles and one through the cross poles. Shunt fields are connected in series to form a single circuit. Armature reaction and series fields are used to produce current control.

The armature reaction can be resolved into components, one through the main poles and one through the cross poles. The armature reaction in the main poles is in the same direction as the shunt field and will tend to increase the main flux. High saturation in the main pole prevents this increase and holds the flux as nearly constant as is possible with saturation. The armature reaction in the cross poles opposes the shunt field and reduces and finally reverses the flux in the cross pole circuit. Since the line voltage is the algebraic sum of the main and cross voltages, reducing or reversing the cross voltage reduces the line voltage.

Methods of Eliminating Transients

Transient or eddy currents in the iron are reduced to a minimum by laminating the entire magnetic structure. The transient voltage induced in the field circuit by the changing cross pole flux normally produces the greatest detrimental effect and it is here that the greatest improvement can be made. Since the rise in flux in the main pole is in the opposite direction to the change in the cross pole, the voltages induced in the 2 coils are in opposition. Unfortunately, it is necessary to minimize the rise in main flux.

If the field circuit could be loaded with a reactance the transient current that would flow would be definitely limited. Since it is transient current that causes flux time lag, the limitation of the transient current by a reactance in the field circuit will be quite effective. In the split pole generator the main fields may be used as a loading reactance. In this case, the number of turns in the main field should be as large as possible. Since the 2 fields are in series, a large number of turns on the main field results in high number of ampere turns. This magnetomotive force is consumed by the saturation in the main pole and since this saturated portion was needed to limit the effect of armature reaction, no difficulty is encountered from this point. There is a limit to the number of turns on the main pole, but the possible number is high enough to make the main coil a very good loading coil.

Limiting the duration of the transient field current is just as important as limiting the magnitude. Once the ampere turn ratio between main and cross fields is fixed by design, changing the number of field turns does not appreciably change the ratio between steady state field current and transient field current. Changing the number of field turns will change the time constant of the field circuit and the duration of the transient current. If the number of turns in the fields is reduced, the duration of the transient is reduced and its effect on the welding circuit is limited.

Internal Reactance

The reactance of a split pole machine is higher than the reactance of a conventional generator. The split pole generator has reactance in the armature due to leakage flux in the pole face and around the slots, the same as a conventional machine. In addition to these conventional sources of reactance, the cross pole circuit offers a definite path for reactance flux. This flux flows through the pole, magnetic frame, and back through the opposite

cross pole. This flux threads the cross coils, but since transient currents in the field circuit are minimized, the flux is free to move and the reactance is very effective. Transient currents in iron or field reduce the usual leakage reactance and the reduction of these transients increases the effectiveness of armature and leakage reactance as well as making available the reactance due to the cross flux. Moreover, in a split pole generator the series turns are concentrated on 2 of the 4 poles. This requires twice the number of series turns as used in a differentially wound machine and gives the split pole machine twice the series turn reactance.

In conclusion, the controlled transient generator is of the split pole type with a completely laminated magnetic structure. The number of turns in the cross field coils is small and these are connected in series with the main coils having a large number of turns. The result is a generator in which the time lag between current and flux is reduced to a minimum and the effective reactance increased so that the machine has characteristics similar to one with an external reactor.

III-Testing Welding Generators

One of the most difficult problems confronting the designer is the determination of the characteristics of a welding generator. There are a number of well-known tests, but these do not give a definite means of evaluating the welding machine. This is to be expected since definite agreement on the desirable characteristics of welding generators, backed by conclusive test and theory, has not been reached.

The final criterion of a machine is its operation under actual welding conditions. In order to obtain a true evaluation of a welding machine it is necessary to operate the set for a considerable length of time under various welding conditions, for it is very difficult to obtain true results from short-time welding tests. It takes considerable time for the operator to get the feel of the set and the condition of the weld specimens materially affect the operator's views. Perhaps the greatest single factor against a short-time welding test is the operator himself. Unless specially trained for testing, operators will unconsciously evaluate a set in terms of the welding generators they have been operating, and this is usually true irrespective of the quality of their regular machines. It has also been found that welders who attended their welding school only a few years previously will invariably favor a welding machine similar to the machine on which they learned to weld. Of course, considerable progress can be made in evaluating a generator by means of so-called blindfold tests, wherein the operator works with a number of electrodes without knowing the sets to which they are connected and attempts to pick out the generator which he considers the best welding machine. In any case, the short-time welding test leaves much to the imagination and the results have to be used with the greatest of care.

Oscillograms of actual welding are of doubtful value, due to the extreme difficulty of controlling the conditions under which the oscillograms are taken. Practically any kind of oscillogram may be produced by the proper selection of wire, work, and operator. An example of the variations that may be obtained in oscillographs by minor changes in conditions is shown in figure 3. This oscillograph was taken under carefully controlled conditions: an expert welding operator made the test after considerable practice, the temperature of the machine was constant, the type of wire was the same in each case, each weld was made on a cold plate of the same thickness and composition, and the length of arc and value of current were the same. The weld at the bottom was made with $^1/_8$ inch, the middle with $^5/_{32}$ inch and the top with $^3/_{16}$ inch electrode. The difference in results is obvious and illustrates that extreme care must be used in taking oscillographs of welding. Changes in type of electrode, temperature of parts, speed of weld, or any other condition materially affects the results.

Steady state tests are naturally easy to obtain and are reliable. While the value of regulation, efficiency, saturation, and other steady state tests is unquestioned, these tests do not give an evaluation of the machine as a welding generator.

Short-circuit tests are not actual conditions encountered in welding but they can be carefully controlled and give a good method of testing for transients. From this test, oscillograph measurements of the short-circuit surge current give a very good criterion of the transients in the machine. The reverse of the short-circuit test, or the voltage recovery test, made by placing the machine under short circuit and then suddenly opening the circuit, is also subject to close control of the conditions, and again gives a very good criterion of the transients, as well as the voltage kick.

Effective reactance tests made by applying alternating current to the terminals of the welding generator have little value unless the results can be compared directly with other machines of similar type. Under these conditions, the reactance value gives a very good comparison between the effective reactance of the sets. Since it is quite difficult to test with currents high enough to produce saturation, the reactance value obtained is useful only when compared with similar types of tests.

Considering the various methods of testing, it becomes evident that still further and more reliable methods are highly desirable. It is very likely that a better understanding of the desirable welding characteristics will, in turn, produce better methods of testing and evaluating welding generators.

The results presented in this paper show that a very wide range of generator characteristics can be obtained by design and circuit changes, and that it is quite possible to incorporate within the generator itself all of the features required to obtain welding characteristics in conformance with accepted requirements. However, there is considerable disagreement in regard to relations between the welding generator characteristics and the production of good welding so that it is desirable to conduct further research to determine more accurately the characteristics which should be incorporated in an ideal welding generator.

Measurement of Noise From Power Transformers

From the results of an investigation on a typical large electric power system, it is concluded that the specification of tolerable noise in transformers by means of measurements with commercially available noise meters is entirely practicable. The problems involved in this investigation and the principal results obtained are presented and discussed in this paper.

By
A. P. FUGILL
MEMBER A.I.E.E.

The Detroit (Mich.) Edison Company

FOR SEVERAL YEARS the residents in the vicinity of transformer substations have been becoming increasingly noise-conscious. As a result, the need for quiet transformers for service on electric power systems has been growing constantly. In attempting to satisfy this need, however, both the manufacturer and the purchaser have been handicapped by the lack of any suitable standards for the tolerable amount of noise. In most cases, the purchaser could determine the permissible degree of noise by reference to existing installations of similar nature, but to state those requirements in definite terms that would be interpreted correctly by all concerned was well-nigh impossible. During the past 2 years, The Detroit Edison Company has been investigating the feasibility of using noise meter measurements as a dependable and definite means of specifying transformer noise.

From the results of this investigation to date, as presented in detail in this paper, it is concluded that the specification of tolerable noise in transformers by means of measurements with commercially available noise meters is entirely practicable. In fact, sufficient information is now available for 2 ratings of transformers to warrant the inclusion of actual values for permissible noise in future purchase specifications issued by this company, and similar values will be available shortly for other ratings. This paper will be limited to an explanation of the method, together with a presentation of the supporting experimental data, with no attempt to recommend values to be used in actual specifications as such values depend too much upon the judgment of the purchaser and the service for which the transformer is intended.

Full text of a paper recommended for publication by the A.I.E.E. committees on electrical machinery and power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 29–25, 1935. Manuscript submitted Oct. 1, 1934; released for publication Oct. 18, 1934. *Not published in pamphlet form.*

Measuring Equipment and Unit of Measurement

The type of noise meter used was that which measures the pressure level of the total noise with inherent compensation for the equivalent loudness of the component notes according to a predetermined weighting curve. Measurements were made with commercially available noise meters, one manufactured by the Westinghouse Electric and Manufacturing Company and one by the General Electric Company. Since both meters have been described previously in the technical press, no detailed description is needed here. (See "An Electrical Ear," by K. A. Oplinger, *The Electric Journal*, August 1931; "The Measurement of Machinery Noise," by H. B. Marvin, A.I.E.E. TRANSACTIONS, volume 50, 1931, pages 1048–51.) It is sufficient to state that this type of meter consists essentially of a microphone placed at the point at which the noise is to be measured, and the amplifying, weighting, and measuring equipment necessary to convert the output of the microphone to a reading on a properly calibrated milliammeter.

The unit in which the pressure level is expressed throughout this paper is the decibel, which is defined according to the latest proposed standards of the American Standards Association by the formula $db = 20 \log \frac{p}{0.0002}$, where p is the acoustic pressure of the sound wave in dynes per square centimeter. It should be noted that the reference pressure used, 0.0002 dynes per square centimeter, corresponds to a reference intensity of 10^{-16} watts per square centimeter as specified in the proposed standards. As a rough guide for those not familiar with this unit of measurement, it might be stated that a transformer having a total noise of 50 decibels could barely be heard 300 feet away on a quiet night while a transformer having a total noise of 70 decibels could be heard easily at twice that distance. For the range of values in this paper, a change in total noise of less than 0.5 to 1.0 decibel probably would not be noticed by the average listener.

Summary of Conclusions

Although the investigation as originally planned has not been entirely completed, sufficient information has been obtained to warrant definite conclusions on that phase of the problem dealing with the development of a method to be used in the specification of noise. Based upon the results of more than 2,500 separate noise meter measurements on about 60 transformers in actual service at 20 city and suburban substations, the following conclusions are drawn:

1. The tolerable noise in a transformer can be specified satisfactorily as the average total noise for at least 25 microphone positions located according to the general plan shown in figure 1. The transformer must be so located that the meter reads inherent noise unaffected by external conditions. The make of the noise meter to be used in the measurements must be stated.

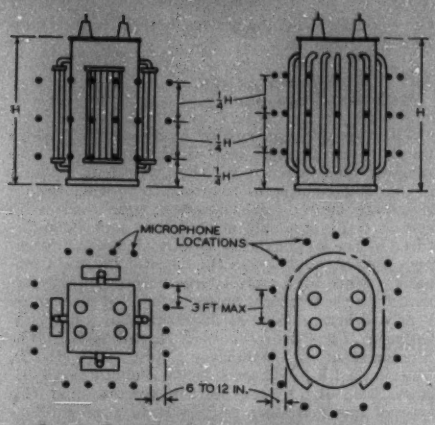


Fig. 1. Typical positions of microphone for use in measuring total noise for specification of tolerable noise in transformers

2. At the present time, noise meters of different makes do not give the same results, even when compensation for dissimilar weighting networks is included. In the 2 meters compared, a difference of at least 8 decibels was found. To facilitate the general acceptance of noise specifications, some standard of reference should be established against which different meters can be calibrated. Preferably, the manufacturers of noise meters should include similar weighting networks and calibrate their instruments for equal readings. Obviously, this should not be difficult as the difference is not due to fundamental differences in the design of the meters. It is to be hoped that the subcommittee of the American Standards Association that is now working on the development of meter standards and calibration methods, together with the manufacturers of noise meters, will be able to solve this problem in the near future.

3. So long as the same meter, or probably a meter of the same make, is used, the results of measurements of the total noise of transformers taken under conditions readily obtained in practice can be depended upon for purposes of comparison if the method suggested in the first conclusion is followed. On the average, measurements could be repeated the same day within 0.5 decibel. Using the average of 8 repeated measurements over a period of $2^1/_2$ months as the reference, individual measurements during this period averaged within 1.0 decibel of this reference. The maximum differences were about double these values, 1.2 and 2.1 decibels, respectively.

4. The results of noise meter measurements clearly differentiate between quiet units and others. Individual transformers measured within about 3 decibels of the average for each group of duplicate units, while the difference between the average noise for transformers considered quiet and the average for any other group was about 8 to 10 decibels.

General Plan of the Investigation

Until a few years ago, the measurement of noise was a highly specialized problem requiring trained experimenters with delicate equipment which could hardly be used outside the laboratory. With the introduction of modern noise measuring equipment, however, noise measurement no longer was reserved for the research scientist, but became a useful tool in the solution of practical noise problems. It seemed reasonable, therefore, that measurements with a noise meter could be used to specify permissible noise in transformers. It was obvious that the result for a single position of the microphone was not adequate because of the nonuniform character of the sound pattern around the transformer. Not only does a slight change in the position of the microphone sometimes change the reading on the meter by several decibels, but also the noise at one point is not a true indication of the noise from the complete transformer. It seemed probable, however, that the average of measurements of total noise for a series of microphone positions forming an envelope around the transformer as shown in figure 1 might be a true criterion of the acceptability of a transformer. Before such a method of noise specification could be accepted, experience had to be accumulated to answer 3 questions:

1. Can such an average value be checked on repeated measurements on a given transformer under practical conditions of measurement?

2. Are the values obtained on different transformers about the same for transformers considered about equal in noise characteristics, and, for transformers considered unequal, is there sufficient difference to insure proper discrimination?

3. Are the requirements as to extraneous noise and the relative positions of surrounding reflecting surfaces so stringent as to make such measurements prohibitive?

Considered theoretically, there were many reasons why all the questions might be answered in the negative. For instance, since noise meters were somewhat untried, there was some doubt about their accuracy when used under the practical conditions of field testing. It was evident even to a casual observer that the readings were affected by such factors as air movement against the diaphragm of the microphone, mechanical vibration of the microphone support, temperature of the instrument, and extraneous magnetic fields. Furthermore, it was not certain that the inherent noise of the transformer bore a

Table I—Comparison of Repeated Measurements of Total Noise With the Same Meter

Group / Date of Test	1	2	3	4	5	6
	Average Total Noise in Decibels					
June 19	61.6	58.6	58.8	53.6	55.9	55.7
June 19	60.8	58.2	59.8	58.0	54.7	54.8
June 20	59.3	56.5	58.5	57.0	53.9	52.9
June 20	59.3	57.1	58.1	56.6	53.9	52.8
Aug. 21	60.8	58.0	58.0	55.8	54.1	53.7
Aug. 21	59.7	57.8	57.8	56.1	53.8	53.3
Sept. 5	58.4	56.8	56.7	55.2		
Sept. 5	60.3	59.3	58.3	57.1	55.5	54.1
Average	59.9	57.8	58.3	56.8	54.5	53.6
	Difference Between Measurements Taken on Same Day					
June 19	0.8	0.4	1.0	0.6	1.2	0.9
June 20	0.0	0.6	0.4	0.4	0.0	0.1
Aug. 21	0.1	0.2	0.2	0.3	0.3	0.4
Average	0.3	0.4	0.5	0.4	0.5	0.5
Sept. 5	1.9	2.5	1.6	1.9		
	Difference Between Each Result and the Average					
June 19	1.7	0.8	0.5	1.8	1.4	2.1
June 19	0.9	0.4	1.5	1.2	0.2	1.2
June 20	0.6	1.3	0.2	0.2	0.6	0.7
June 20	0.6	0.7	0.2	0.2	0.6	0.8
Aug. 21	0.1	0.2	0.3	1.0	0.4	0.9
Aug. 21	0.2	0.0	0.5	0.7	0.7	1.3
Sept. 5	1.5	1.0	1.6	1.6		
Sept. 5	0.4	1.5	0.0	0.3	1.0	0.5
Average	0.75	0.74	0.60	0.87	0.70	1.07

direct relationship to its design and type of construction, or that it remained constant from day to day even with the same load and voltage. Again, there was no complete data to indicate the magnitude of the effect on the measured noise of the extraneous noise level and the relative character and position of surrounding reflecting surfaces. As in all noise problems of a complicated nature, the simplest and most positive method to obtain information on these factors was by experiment. In this case, it seemed best to check their combined effect by taking a comprehensive series of measurements in the field on transformers in actual service under a range of conditions, using men regularly employed for such test work to make the measurements. Such an experiment would indicate whether laboratory accuracy in the control of extraneous conditions or the constant supervision of highly trained experimenters was necessary to obtain reasonably accurate results. If so, such a method would not be accepted generally by the electric power industry and must be discarded in favor of some more practicable scheme.

The general plan of the investigation to answer the 3 questions stated may be outlined by grouping the measurements according to their purposes:

1. The first group was made to determine the consistency of repeated measurements for 3 conditions: with the same meter, with different meters of the same make, and with meters of different makes. In all tests, measurements of total noise were made for a given set of microphone positions around a given transformer. This procedure was repeated on the same transformer several times under such different extraneous conditions as prevail during actual operation, and the results were compared.

2. The second group was made to indicate the comparison between the measured results and the noise characteristics of a transformer. Representative readings of total noise were taken on a large number of different transformers and the average results were compared. The classification of transformers according to these results then was checked against the opinions of listeners as to the noise characteristics of these same units.

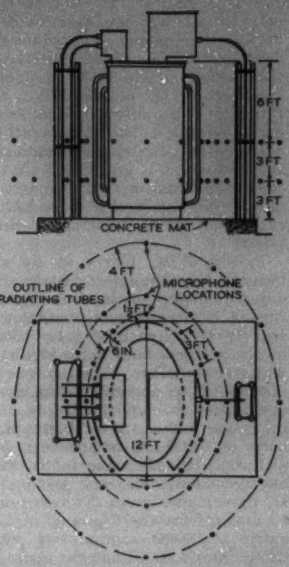
3. The third group, which was not complete at the time this paper was written, is intended to show the effects of extraneous noise and surrounding reflecting surfaces. To do this, the total noise of a given transformer will be measured with these factors varied, and the results will be compared.

Consistency of Repeated Measurements

The first group of measurements may be subdivided further, as suggested, to show results with the same meter, with different meters of the same make, and with meters of different makes.

Results With the Same Meter. To determine the comparison using the same meter, a 6,000 kva transformer installation was selected at a substation in a well-developed residential district close to a heavily traveled highway. Using the same meter, a reading of total noise was taken at each of the microphone positions shown in figure 2 several times during a period of $2^1/_2$ months. Each time, the readings for the 12 microphone positions equally distant from the transformer and at the same height were combined to obtain the 6 groups of average values tabulated in table I according to the date of measurement. The readings for the same day were taken from 1 to 3 hours apart. No changes were made in the meter during this period except that the

Fig. 2. Positions of microphone for checking consistency of measurements on 6,000-kva 3-phase transformers



batteries were renewed between the 2 readings taken on September 5. The differences between comparable results of measurements taken within a few hours of each other, as shown in the center of the table, show a maximum difference for this condition of measurement of 1.2 decibels with an average of less than 0.5 decibel for the first 3 days. The comparison for September 5 shows that an average difference of about 2.0 decibels may be expected between readings with new batteries and those at the minimum values set by the manufacturer. The comparison of the 8 readings taken over the $2^1/_2$ month period shows a greater difference than those taken the same day, as would be expected because of the possibility for wider variation in external conditions. Since the average of the 8 results for each group tends to be the correct value, the difference between any reading and this average is a measure of the accuracy to be expected in repeated measurements. As indicated in the tabulation at the end of table I, the maximum difference obtained was 2.1 decibels and the average of all these differences was less than 1.0 decibel.

In view of the fact that an average listener would have considerable difficulty in differentiating between 2 transformers 1.0 decibel different in total noise, even by comparing them directly, it is believed that the accuracy of this check is well within that required for practical measurements. It should be remembered, moreover, that some of these readings were taken at night under quiet conditions while others were taken during periods of heavy traffic, that the transformer was in regular service so that its load and voltage varied to some extent, that the

noise meter was not calibrated at the laboratory during that period, that different operators were used to read the meter, that the battery voltage in the meter varied over the complete range considered allowable by the manufacturer, that the meter was transported by automobile at least 2,500 miles during that period, and that weather conditions were not constant, although all readings were taken in the late summer. It is believed that with more careful control of some of these factors, particularly meter battery voltage, transformer load and voltage, and extraneous noise, even closer checks could be obtained.

Results With Meters of the Same Make. The measurements to determine the comparison between different meters of the same make were not so conclusive because 2 such meters were not available. During the period of test, however, one of the meters was sent back to the factory for minor changes and recalibration. When it was returned, the correction factors and calibration curves were all different so that it corresponded to a different meter of the same make. Several groups of readings were made on 6,000 kva transformers before recalibration and repeated after the meter was returned. The average results for each group, tabulated in table II, show a maximum difference of 2.4 decibels with an average for the 6 groups of 1.3 decibels. Inasmuch as these comparative measurements were taken from 6 to 18 months apart, this close check is considered reasonable proof that similar meters made by the same company can be used for obtaining comparative values for purposes of noise specification.

Results With Meters of Different Makes. Measurements made to check the difference between results obtained with 2 meters of different makes fall into 2 classes. For the first class, measurements were made on 2 different banks of 1,000-kva single-phase transformers with microphone positions as shown in figure

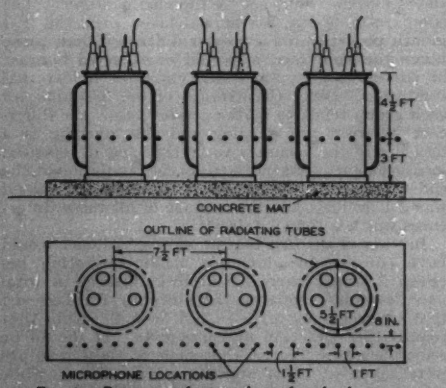


Fig. 3. Positions of microphone for checking consistency of measurements on 500-kva single-phase transformers

Table II—Comparison of Repeated Measurements of Total Noise With One Noise Meter Before and After Factory Recalibration

Group	1	2	3	4	5	6
Before recalibration, db	60.9	57.4	61.1	59.3	62.1	58.4
After recalibration, db	60.1	57.9	62.1	61.2	63.1	60.8
Difference	0.8	0.5	1.0	1.9	1.0	2.4
Average difference						1.3 decibels

Table III—Comparison of Repeated Measurements of Total Noise With 2 Noise Meters of Different Makes

Group	1	2	Avg.	3	4	5	6	7	Avg
Meter *A*, db	64.0	62.8		62.3	59.7	59.6	66.0	64.4	62.8
Meter *B*, db	60.3	58.0		58.3	54.2	54.2	60.9	57.4	57.8
Difference*	3.7	4.8	4.3	6.0	5.5	5.4	5.1	7.0	5.0	5.8

* Correction for weighting network adds about 4.0 decibels to these values.

3. Readings for all positions of the microphone were made with one meter, and immediately thereafter repeated with the other meter. Not more than 15 minutes elapsed between readings with different meters, so there was little chance for conditions to change. For the second class of measurements, readings were taken on 2 6,000-kva 3-phase transformers with microphone positions similar to the 6 inch groups in figure 2, with additional readings at a height of 9 feet. In these tests, however, several days elapsed between the measurements with one meter and those with the other. As indicated by the maximum difference of 2.1 decibels in the results obtained under similar conditions when the same meter was used, any greater difference than this can rightfully be charged to dissimilarity between the meters. The first 2 columns of table III give the results of this comparison for the first class of measurements and the remaining 6 columns give the results for the second class. As indicated, an average difference between meter readings of 4.2 decibels was obtained for the readings taken practically simultaneously, and 5.8 decibels for those taken on different days. Unfortunately, these 2 meters were not designed for equal weighting of the component notes. Since the dissimilar results might be accounted for on this basis, correction should be made for this factor. Applying this correction on the basis of the analysis of total noise which was made at the time the total noise was measured, it was found that the correction of about 4.0 decibels added to the difference already found making the corrected difference between meter readings at least 8.0 decibels.

From this series of measurements, it may be concluded that measurements of total noise with a noise meter of this type, taken under practical conditions of measurement can be relied upon for purposes of comparison so long as the same meter is used, and probably so long as meters of the same make are used. Measurements with meters of different makes, however, cannot be compared directly unless the proper correction is obtained and applied. Until such time as the industry establishes a standard reference against which different meters can be cali-

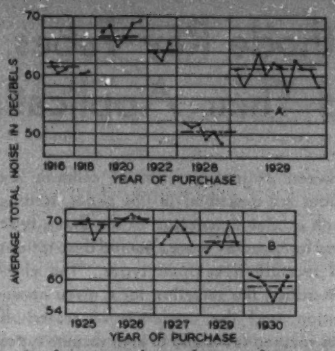


Fig. 4. Average total noise from transformers in service on The Detroit Edison Company system

A. 500-kva 24,000/4,800-volt single-phase transformers
B. 6,000 - kva 24,000/4,800 - volt 3-phase transformers
—·—Average for group

brated, or the manufacturers of noise meters recalibrate their meters to read alike, it will be necessary to indicate the make of meter in specifying noise.

Correspondence Between Meter Readings and Transformer Noise

As previously stated, the second series of readings was taken to determine whether the result of such a total-noise measurement is a proper criterion of the acceptability of a transformer from the standpoint of noise. According to the procedure previously outlined, measurements of total noise were made on 57 transformers which had been in actual service from 5 to 18 years. This number included 2 ratings, 500-kva single-phase, and 6,000-kva 3-phase, some purchased as duplicate units, and some obviously different as to construction of tank and inherent design. It was apparent that the noise characteristics varied over a wide range; some units, particularly in the smaller rating, were so noisy that they would not be considered acceptable today, and others were about as quiet as any that have been built for these ratings.

The average results of total-noise measurements on all these transformers are plotted according to the year of purchase in figure 4. The dots connected by the solid lines are the values for units purchased at the same time as duplicates. It is quite probable that some of the units purchased at different times may be essentially duplicates as far as all factors affecting noise are concerned; this point was not checked, however, because of insufficient information regarding the design of the transformers.

An analysis of the values plotted in figure 4 clearly shows a correspondence between the design of a unit and its measured total noise. For units of duplicate design, which were built according to the same design specifications and under the same manufacturing conditions but with no special emphasis on their noise characteristics, the maximum difference between the value for any unit and the average for the group was 3 decibels. However, the difference between the average values for transformers that were obviously different in design was at least 8 decibels. This indicates that once the fundamental factors causing noise in transformers are determined, it should be possible to build quiet transformers consistently according to a given design. Furthermore, assuming that only transformers of the lowest group for each rating were considered acceptable, there would be no difficulty in differentiating between those units and the rest of the transformers tested, depending solely on the results of total noise measurements.

There still may be some question, however, as to whether the classification of these transformers according to noise meter measurements corresponds to a similar classification by ear, which, after all, is the basis upon which a unit is judged after installation. The transformers covered by these measurements were in actual service at different stations so that it was impossible to judge the comparative noise by listening alternately to one transformer after another. It is exceedingly difficult to differentiate by ear between transformers that do not differ greatly in noise characteristics when those units are several miles apart. In this case, however, there was sufficient difference to permit dividing the transformers roughly into 3 groups, those considered quiet, those considered normal, and those definitely noisy. Of the 500 kva transformers, there was no doubt that the units purchased in 1928 were very quiet, and those purchased in 1920 were exceptionally noisy; the ones purchased in 1916, 1918, and 1929 were somewhere between these 2 extremes, and were considered about normal for this class of transformer. Of the 6,000 kva transformers, there were no exceptionally noisy units and the only ones that appeared other than normal were those purchased in 1930. These were definitely quieter than any others of the same rating on the system. From this correspondence between the logical classification of these transformers by meter measurements and the rough grouping according to the opinions of listeners, it seems safe to conclude that the results of total-noise measurements on such meters can be depended upon in purchasing transformers according to noise specifications.

It is of interest to note that the 500 kva units that measured about 70 decibels were considered noisy, while the 6,000 kva units that measured about the same were considered normal. This is probably because it is customary to expect less noise from smaller units, and indicates that different values for acceptable noise probably should be used for different sizes of transformers. It is interesting to note also that the 500 kva units purchased in 1916 and 1918 are practically equal in noise to those purchased in 1929. Apparently during that period, there was no pronounced trend toward quieter transformers.

Effect of Extraneous Conditions

The information so far obtained is believed to furnish reasonable proof that it is practicable to

specify the inherent noise of a transformer, provided only that the unit under test is so located that the measurements are not seriously affected by extraneous noise and by the proximity of major reflecting surfaces. In any specification for transformer noise, definite requirements as to these 2 factors should be included. It is the present plan to continue this investigation to obtain more comprehensive data on the effects of these factors. From the limited information now available, the requirements do not appear to be particularly stringent so long as the transformer can be located outdoors for measurement. Apparently, any open space corresponding in size and noise conditions to an average lot in the residential section of a large city probably would be suitable, particularly if the readings were taken at night. Whether or not such measurements could be made inside the manufacturer's factory buildings without serious error is problematical. It is believed that additional investigation will show that this is entirely possible, although the measurements may have to be made at night. At any rate, the difficulties of such measurements are not insurmountable and some solution can be found with a little study.

Analysis of Transformer Noise

It may be contended that an analysis of the transformer noise into its component notes, as well as the total noise, should be used for specification purposes. At the start of this investigation, it was thought that it might be necessary to specify the maximum value for the largest component note, but now it appears that in the majority of cases, the specification of total noise will be sufficient. However, in view of the fact that there may be a few instances where the values of the component notes are important, several analyses of transformer noise already have been made and more will be made as time permits.

Admittedly there are still several factors in the general problem of specifying noise in transformers that remain to be studied, but it seems that sufficient data have been collected to prove that the method of specifying noise outlined in this paper is satisfactory. In view of the increasing interest in noise being displayed by the general public, the noise of a transformer has become an important factor which must be considered in purchasing such equipment. Therefore in any future purchase specifications on major transformers issued by The Detroit Edison Company, it is intended that some such specification will be included. Other electric power companies confronted with this same problem have, no doubt, their own ideas on methods of noise specification. It is hoped that as such information is presented, these companies will find it possible to specify transformer noise using, of course, values for permissible noise suitable to their own requirements. Only by actual experience with such promising methods can the present confusion be removed and eventual standards of noise specification be evolved that can be accepted by all concerned.

Cathode Ray Tubes and Their Application

Several distinctive types of cathode ray tubes are described in this paper, starting with a brief description of the Braun type and followed by more detailed descriptions of recently developed types. The characteristics, the selection for a given application, and the operation of sealed-off gas-focused types and of high vacuum types are discussed. Also auxiliary apparatus is considered; and applications of cathode ray tubes are suggested briefly.

By
J. M. STINCHFIELD
ASSOCIATE A.I.E.E.
R.C.A. Radiotron Co., Inc.
Harrison, N. J.

FOR many years, the cathode ray tube has been known to possess unique properties making it indispensable for certain research investigations. Although its usefulness and versatility were recognized at an early date, the cathode ray tube has not acquired extensive use in the fields of applied engineering. This slow utilization by engineers of a device having such excellent theoretical possibilities has undoubtedly been due in part to the lack of rugged, reliable, low cost, and readily available tubes.

Today, cathode ray tubes have reached a state of development such that the user can depend upon them for information previously obtainable only by more costly and more delicate apparatus. A cathode ray tube operated at relatively low voltages shows a clear, sharp trace in a well-lighted room and is readily calibrated so that quantitative measurements can be made. It is easily applied to a wide variety of practical engineering uses.

The principle on which the cathode ray tube operates is illustrated by figures 1 to 5. These show schematically the essential elements of certain distinctive types of cathode ray tubes. It will be seen that all of these have the following attributes: A containing envelope E of either glass or metal for the purpose of maintaining in the tube either a low pressure of gas or a vacuum; a cathode C for the production of free electrons; an anode A for accelerating the electrons; a method for concentrating the electrons into a beam by means of apertures O,

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 22–25, 1935. Manuscript submitted Sept. 20, 1934; released for publication Oct. 18, 1934. *Not published in pamphlet form.*

or through focusing fields applied by means of electrodes F, or by externally mounted electromagnets M, or by a combination of these. The electrons are concentrated into a beam and focused to a point on a screen S made of a material which will show a fluorescent glow at the point of impact by the electron beam. Since the electron beam consists of rapidly moving electrons, it constitutes a current having both electromagnetic and electrostatic properties, but without the mass ordinarily accompanying a conductor of current. Hence, the electron beam can be deflected easily and rapidly by electromagnetic and electrostatic fields. The deflecting fields produced by the phenomenon under investigation take the form either of electrostatic fields usually produced by voltages applied across the deflecting plates, illustrated by D in some of the figures, or electromagnetic fields usually produced by current in coils illustrated by T in figure 5. The deflected electron beam traces on the screen a fluorescent path which can be viewed, measured, and photographed.

Types of Tubes

Brief descriptions of several distinctive types of cathode ray tubes follow.

The Braun Type. The Braun type of cathode ray tube, illustrated in figure 1, is enclosed in a glass bulb about 50 centimeters in length. A small metal disk, the cathode, is mounted at the end of the bulb neck. The anode is a small metal rod projecting into the bulb from the side. Beyond the anode is a diaphragm separating the cathode-anode section from the deflecting field and the fluorescent screen section. The diaphragm has a centrally located aperture of about one millimeter in diameter. The gas pressure in the tube ranges from 4 to 8 microns of mercury. A voltage of 12,000 to 30,000 volts is usually applied between anode and cathode. When the tube is in operation, the ionized gas molecules bombard the cathode plate causing impact emission of electrons which are accelerated by the high positive potential toward the anode. Because the anode is small and on one side of the bulb, many of the electrons travel on past it through the aperture in the diaphragm. This constitutes the cathode ray or electron beam which is deflected by electric or magnetic fields and produces the fluorescent pattern on the screen at the enlarged end of the tube. A magnetic solenoid is sometimes placed concentrically over the small end of the tube to assist in focusing the electron beam on the screen.

The Dufour Type. The Dufour type, shown diagrammatically in figure 3, usually employs a cold cathode source of electrons similar to that of the Braun type but also provides for inserting photographic plates or film inside of the tube. The screen end of the tube is usually made of metal with a removable compartment for holding the photographic plates. A vacuum pump and pressure gauge are part of the operating equipment. About 12 minutes are needed to produce the required vacuum which in one type is equivalent to a pressure of 10 microns for a potential of 50,000 to 60,000 volts between cathode and anode. The electrons record by acting directly on the photographic emulsion. A good trace is recorded even when the electron stream sweeps across the film as rapidly as 100 miles per second. The Dufour type, due to the high recording speeds attainable, has proved most useful for the investigation of very high speed transient phenomena. However, the elaborate equipment and its high cost have limited the use of this type.

The Lenard Type. The Lenard type is similar to the Braun type except that the former has a window of some thin material, usually metal foil or glass, on the screen end of the tube. Since the window must withstand atmospheric pressure, it requires support and is limited in size by practical considerations. The photographic plate for recording high speed transient phenomena is located outside the tube close to the window section. The electron beam is accelerated with about 75,000 volts. As a result of the high velocity of the electrons, the beam passes through the window and is recorded directly on the photographic plate. The difficulties of producing a satisfactory window which will not unduly limit the sweep of the electron beam have prevented extensive practical use of this type.

The Wehnelt Type. The Wehnelt type using an oxide-coated thermionic cathode as the source of electrons was suggested by Wehnelt shortly after the advent of the Braun type. Figure 2 illustrates schematically a tube of this type. It is inherently a low voltage type, since the electrons are released at the cathode by an oxide-coated thermionic emitter in the presence of gas. Due to the effect produced on the cathode by the gas present in this type, the operating life is limited to a few hours.

The Low-Voltage Gas-Focused Type. The low-voltage gas-focused type is in some respects like the Wehnelt type. An oxide-coated thermionic cathode is used but the tube is sealed off with a definite gas pressure. The electron beam is produced by a tubular anode mounted at the end of a protecting shield located around the filamentary cathode. Anode voltages from 250 to 400 volts can be used. The anode current is approximately 0.5 milliampere. The adjustment of the focus of the electron beam is

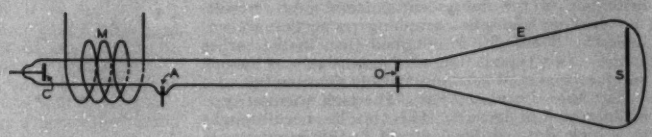


Fig. 1. The Braun cathode ray tube

controlled by the filament current. D-c filament supply must be used. The pattern on the fluorescent screen is viewed best in subdued light. Recurrent wave forms may be photographed by focusing an ordinary camera on the fluorescent pattern on the screen. By careful operation of the filament at the lowest current which will focus the electron beam to a suitable fluorescent spot, the life of this type is extended appreciably beyond that of the earlier Wehnelt type. The low-voltage gas-focused type is useful for recurrent wave forms where low voltage operation is desired.

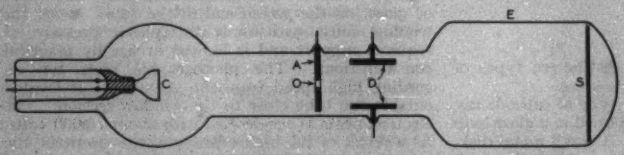
The Medium-Voltage Gas-Focused Type. The medium-voltage gas-focused type is shown in figure 4. It operates with anode voltages from 400 volts to 2,500 volts. The cathode consists of an oxide coating applied to a small section at the tip of the filament. The filament is operated at a voltage less than one volt in order to permit a-c operation. The filament current is controlled by means of a rheostat with an ammeter in series and is kept at the lowest value consistent with a sharply focused spot on the screen. A Wehnelt-cylinder electrode around the cathode is operated at a negative voltage to control the beam focus and reduce the positive ion bombardment of the cathode. The tube is sealed off at a gas pressure corresponding to the operating conditions and the dimensions of the tube. The higher operating voltages of this type improve the brilliancy of the fluorescent pattern. As a result, the viewing and photographing properties are enhanced. Better life is obtained than in the earlier types. This type is now used extensively in Europe and has been used to some extent in this country.

The High Vacuum Type. The high vacuum type is illustrated in figure 5. This type has been brought to a high state of development in this country. It operates on principles similar to those of the high-vacuum amplifier tube. The focusing of the electron beam on the fluorescent screen is accomplished by means of electrostatic fields produced by the electrodes in the tube. In order to control the brilliancy of the fluorescent pattern, a control electrode is introduced. The beam current is controlled independently of focusing and of beam acceleration. This permits a definite control of the brilliancy of the fluorescent pattern. An indirectly heated cathode is used in this type so that it can be operated on a-c voltage. Rated filament voltage is supplied by a transformer. This type is like usual receiving tubes, not especially critical to line voltage fluctuations.

The electrodes constituting the electron gun are: Cathode, control electrode, accelerating electrode, focusing electrode (anode 1), and high voltage electrode (anode 2). The accelerating electrode is omitted in some types. Beyond anode 2 is the deflecting plate system or a narrow section of the bulb across which may be mounted electromagnetic deflecting coils. The fluorescent screen material is coated directly on the inner surface of the large end of the bulb. A conductive coating is sometimes applied to the inner surfaces of the sides of the bulb. The coating is conductively connected to the anode terminal and provides a well-defined anode potential free from the influence of stray charges over the entire region between the electron gun and the fluorescent screen. In some cases, the anode terminal is mounted on the side of the bulb. This arrangement provides spacing for the use of high voltages on the anode.

High vacuum type tubes for operation at anode voltages from 600 volts to 10,000 volts are available. Operation much below 1,000 volts does not, in general, give as sharp a focus as does the low-voltage gas-focused type. A brilliant and well defined trace on the fluorescent screen of a high vacuum type is obtained with an anode voltage of 1,000 volts. Inherently, there is no limitation to the range of anode voltages, either low or high, over which high vacuum tubes can be made to operate.

Since the life of the high vacuum tube depends



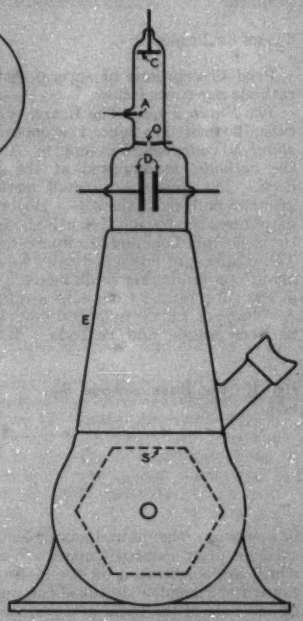


Fig. 2 (above). The Wehnelt cathode ray tube

Fig. 3 (right). The Dufour cathode ray tube

upon the same factors that determine the life of high-vacuum amplifier tubes, the same operating life can be expected. The screen is generally very stable so that only excessive electron bombardment or heating impairs its usefulness. Inherently, therefore, the life of the high vacuum type should be good. Practically, results confirm this statement.

The improved cathode ray tubes now available are useful not only for viewing and recording recurrent wave forms, as were the earlier low voltage types, but can be used over a greater range of transient phenomena. For example, velocities of the fluorescent spot of 16 miles per second have been recorded with an ordinary camera and a high-vacuum cathode-ray tube operating at 10,000 volts.

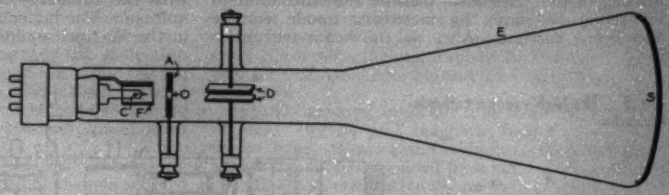


Fig. 4. The gas-focused cathode-ray tube

Factors Influencing the Selection of a Cathode Ray Tube for a Given Application

Some of the characteristics influencing the choice of a cathode ray tube type for a certain application are as follows:

The Effect of Anode Voltage. Below 1,000 volts on the anode, the deflection sensitivity of the cathode ray tube is high; however, the luminous brilliancy of the pattern is low. The focus is liable to be poor, although in some tubes, particularly of the gas-filled low-voltage type, it is fairly good. The deflection of the beam is more easily influenced by stray fields, and distortion of the pattern is more likely to occur than at higher voltages.

Voltages ranging from 1,000 volts to 2,000 volts produce a sharply focused spot and well defined line. The pattern is clearly visible in a normally lighted room. Periodic phenomena can be viewed, traced, and photographed satisfactorily. When a non-recurrent phenomenon is photographed, the velocity of the spot on the screen must be low enough to give sufficient illumination to record. The effect of stray fields on the movement of the beam can usually be eliminated by proper location and shielding of the tube.

Anode voltages ranging from 2,000 volts to 10,000 volts contribute toward a sharply focused spot and greater luminous brilliancy. This voltage range is useful in recording transient phenomena. The high voltage decreases the deflection sensitivity so that the deflecting voltage or current must be increased.

Anode voltages ranging from 10,000 volts to 75,000 volts have been used extensively in the Braun tube and later in the Dufour and similar types of tubes for the recording of lightning surges and other high speed transient phenomena. The complete pattern in some instances is traced in from 1 to 10 microseconds.

Means of Deflecting Beam. One arrangement for deflection of the beam consists of 4 electrostatic deflection plates with the terminals connected through the tube base. Two of the plates may have a common connection. This type is useful in many applications where an inexpensive and compact tube is required. The deflector plate capacitance of this design is low enough and the impedance high enough for most applications.

Another arrangement has 4 electrostatic deflection plates with separate terminals mounted on the sides of the bulb. The separate terminals permit a greater latitude in circuit connections. A mid-point ground connection can be used to secure a balanced impedance to ground. The capacitance between the deflector plates is low. The deflector plate impedance for this design can be made higher than with the design where connections are made through the base.

An arrangement with one pair of electrostatic deflection plates with the terminals on the side of the bulb is useful when magnetic deflection can be used on one axis or when deflection in only one direction is to be used, as in recording on moving film. The use of combined electrostatic and electromagnetic deflection is of advantage when it is necessary to reduce interaction of the 2 deflecting fields to a minimum.

An arrangement without electrostatic deflection plates obtains deflection entirely by magnetic fields from externally mounted coils. Where electromagnets can be used, this method permits obtaining a considerable range in sensitivities by the design of suitable coils.

Choice of Size of Viewing Screen. A large sized screen permits showing a large pattern and good detail. In general, the accuracy of measurements may be increased by the use of a large screen, but often a large pattern may be examined "piece by piece" on a smaller-sized screen with the aid of biasing voltages. A large screen requires greater deflection voltage to utilize the full screen. The large sized screen also means an increase in the over-all dimensions of the equipment assembly. A tube with a medium or small sized screen requires less space and can be used conveniently in portable equipment. Less deflecting voltage is needed than

for larger screens. Accuracy corresponding to good engineering practice is obtained readily with moderate sized tubes.

Effects of Properties of Luminescent Screens. An efficient screen is one giving a high luminous brilliancy for a given wattage input per unit of screen area. Since the power that can be dissipated per unit area of the screen is limited by heating or disintegrating of the screen material and by local heating of the glass bulb, there is a definite limit to increasing brilliancy by increasing anode voltage and beam current. Also, as the beam current is increased, the size of the spot on the screen tends to become larger. It is evident then that a screen delivering high candlepower per watt input can, for example, record higher-speed transients than a similar screen with a lower efficiency.

The persistence characteristic of the screen shows the brilliancy of the phosphorescent after-glow as a function of time relative to the initially excited fluorescent glow. A medium or long persistence screen aids in viewing transient phenomena. The trace on a long persistence screen may be seen for several seconds when viewed in subdued light. A short persistence screen is useful for recording on moving film where the time in which the relative brilliancy falls to a low value determines the speed at which the film can be operated without causing blurring of the trace on the film.

The spectral characteristic of the screen shows the radiant energy versus wave length or the color distribution of the excited fluorescence. A green-colored light corresponds most nearly to the maximum sensitivity of the eye; a blue light corresponds to maximum photographic effect on ordinary blue-sensitive and verichrome emulsions. The green color in addition to its good viewing properties may have sufficient spectral energy in the blue region to be good for verichrome emulsion and gives additional photographic sensitivity when supersensitive panchromatic film and plates are used.

Effect of Conductive Coating on Bulb. A conductive coating on the inner surface of the bulb is effective in bringing the anode potential close to the screen. This produces greater freedom from stray fields, better ability to respond to high speed transient phenomena when the beam current is switched on and off rapidly, and less current pick-up by the deflector plates. For example, when a very high deflector-plate resistance is desired, a tube with inner coating and separately mounted deflector terminals on the bulb should be used. Conductive coating is sometimes applied to the outer surface of the bulb to serve as an electrostatic shield.

Means of Focus and Brilliancy Control. The adjustment of focus and brilliancy of the trace on the screen may be made by separate controls such as are used on typical high vacuum types, or these adjustments may be limited to the control of focusing with the brilliancy being determined by the anode voltage. The latter arrangement is commonly used in the Wehnelt-cylinder gas-focused type. The use of a separate brilliancy control permits an increase above normal for short periods while photographic records are being made. It also permits the use of low voltages to control the beam current.

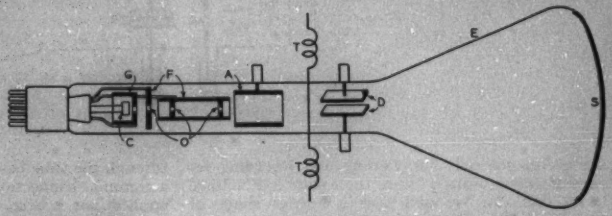


Fig. 5. The high-vacuum cathode-ray tube

High Vacuum and Gas Types of Cathode Ray Tubes. The high vacuum type is independent of frequency from zero up to high radio frequencies where the electron velocity due to deflecting fields approaches the electron velocity due to anode voltages.

The gas type is independent of frequency until the deflection velocity becomes great enough to interfere with the ionization of the gas by the electrons in the beam. Since the focusing depends upon the ionization of the gas along the path of the beam, the focus becomes poor at high radio frequencies.

The deflector plate resistance is in general lower for the gas type than for the high vacuum type. This is especially noticeable for small deflecting voltages, or when the source of driving power is limited. The deflector plate resistance of the high vacuum type depends upon the electron current collected by the deflector plates. This can be made as low as desired by reducing the beam current or by the use of a tube with an internally coated bulb.

When tubes are operated at anode voltages below 1,000 volts, sharper focus is generally obtained with gas type tubes designed for low voltage.

In general, there is less background light on the screen in a high vacuum than in a gas type.

The operating life of the gas type may be limited by cathode bombardment or change in gas pressure. The life of the high vacuum type is inherently good.

Effects of Deflector Plate Capacitance and Impedance. A deflector plate capacitance of a few micro-microfarads and a deflector plate resistance in excess of a megohm will have a negligible effect when connected to most circuits. When the circuit requires

low capacitance, the spacing and mounting of the deflector plates should be considered. The deflector plate resistance in a high vacuum type may be increased by the use of lower beam current. However, brilliancy of the pattern need not be sacrificed if higher anode voltage is available. An internal coating on the bulb also increases deflector plate resistance of the high vacuum type.

Linearity of Deflection. Distortionless electromagnetic deflection requires a uniform distribution of magnetic field across the path of the beam. The stray magnetic field should not concentrate in the focusing region. With this method of deflection control, it is advantageous to use a tube having provision for properly located and closely spaced electromagnets. With correctly designed tubes using electrostatic control, the deflection is linear with voltage.

Response to High Speed Transient Phenomena. The high-speed transient response of the gas focused type is determined by the time required for ionization, which is of the order of 10^{-6} seconds.

When the high vacuum type is used for viewing or recording high speed transients, where the beam current is switched rapidly on and off, a momentary accumulation of charge may occur on parts of the bulb before sufficient time to obtain equilibrium has been reached. The use of a tube with an internally coated bulb eliminates the possibility of any such difficulty.

There is no inherent time or frequency limitation in the case of the high vacuum type, although with conventional tubes, at frequencies of about 10^8 cycles per second or a wave length of about 3 meters, a limitation begins to appear due to the finite velocity of the electrons. This limitation also exists in other types of high vacuum tubes; the limiting frequency being determined by the physical dimensions of the tube and the accelerating voltage.

Installation and Operation of the Gas Focused Type

The hot-cathode gas-focused cathode-ray tube can be compared with a gas filled detector tube. As in the case of other gas filled tubes, particular care should be taken to see that rated voltages are never exceeded. It is essential to long filament life that the tube should be used at the lowest filament voltage and lowest anode voltage which will give a sharp focus and sufficient brilliancy on the fluorescent screen for the particular application. It is always advisable to use a meter to show the filament current and to have the filament current continuously adjustable between the maximum rated value and approximately $^1/_2$ this value.

Some of these types can be operated on d-c filament voltage only. Other types may be operated with a-c filament supply. The a-c types usually operate with less than one volt on the filament to avoid the effects of a-c ripple. The filament current should be adjustable and kept as low as consistent with obtaining a sharply focused spot. The filament current may be lowered slightly after the tube has heated. During the life of the tube, a gradual increase in filament current is usually required to produce a sharp spot on the screen. The focusing voltage on the Wehnelt-cylinder electrode is kept as negative as possible consistent with a sharply focused spot. The brilliancy of the pattern may be increased by using higher anode voltage, but the maximum rated anode voltage should not be exceeded. In general, the 3 operating parameters of the tube are anode voltage, filament current, and Wehnelt-cylinder voltage. For a fixed value of one of these, there may be several combinations of the other 2 which will give an approximately focused spot. Generally, the first 2 should be kept at as low a positive voltage as possible and the latter, as negative as possible.

It is advisable to shield the tube from the influence of stray electric and magnetic fields. The stray fields from transformers, chokes, and auxiliary apparatus may be avoided by a suitable disposition, spacing, and orientation of parts. Likewise, stray fields from equipment external to the cathode ray apparatus can be minimized.

Installation and Operation of the High Vacuum Type

The high vacuum cathode-ray tube is in many respects like a high vacuum amplifier tube. No special technique is required in installing and operating the tube other than that normally used in the handling of high vacuum amplifier tubes. The cathode is indirectly heated, like an a-c amplifier tube, from the winding of a transformer and is operated at rated voltage without any adjustments. The currents to the electrodes of the electron gun usually total 0.1 or 0.2 milliampere or less so that the current in the voltage divider may be as low as about one milliampere. Under these conditions, the ripple in the rectified voltage is small and a condenser of 0.5 to 2.0 microfarads supplies adequate filtering. The d-c power required is low so that a small transformer with proper insulation for the high voltage can be used. A few one watt carbon resistors and potentiometers serve as the voltage divider. A half-wave rectifier or a voltage-doubler rectifier circuit is suitable. The rectified d-c voltage is approximately equal to the peak of the a-c voltage for the half-wave circuit or twice this value for the voltage doubler circuit. The rectifier tube carries only a small current but must withstand a peak inverse voltage of twice the peak a-c voltage of the transformer.

The control electrode is normally operated with a bias voltage negative with respect to the cathode. It is used for controlling the beam current and hence the brilliancy of the fluorescent pattern. Usually, the control electrode voltage is made adjustable by means of a potentiometer tap in the voltage divider in order to permit a range of voltage from zero to a voltage sufficiently negative to cut off the beam current completely.

When the tube has an accelerating electrode, it is normally connected to a fixed tap on the voltage divider corresponding to rated voltage.

The focusing electrode (anode 1) is used to focus

the beam current to a sharply defined spot on the screen. The voltage of this electrode is usually equal to approximately $^1/_4$ of the voltage on anode 2. A range of adjustment upward to about $^1/_3$ of the voltage on anode 2 is usually allowed.

When the brilliancy of the fluorescent pattern is adjusted, considerable defocusing sometimes results due to the regulation of the high-resistance voltage divider. This is readily corrected by adjusting the focusing voltage, or it may be eliminated, if desired, by increasing the current in the voltage divider.

If a range of anode voltages is required, a potentiometer on the line voltage side of the high voltage transformer will change the voltage on all electrodes simultaneously. This method will keep the pattern approximately in focus. Proper location or shielding of the tube is advisable in order to avoid the influence of stray electric and magnetic fields.

Sweep Circuits and Auxiliary Apparatus

In order that the wave form of phenomena producing a vertical deflection may be viewed, a horizontal deflection is applied to sweep across the screen at a uniform rate. The linear time sweep may traverse the screen only once when observing a nonrecurrent wave form or it may be arranged to be returned rapidly to its starting position and to repeat the linear time sweep.

When the frequency of the wave form being observed is a multiple of the repetition frequency of the linear time sweep, the wave form remains stationary on the screen. The number of cycles of the wave form appearing throughout the sweep on the screen shows the ratio of the frequency of the wave form to the frequency of the linear sweep voltage. Thus, a sweep frequency of 3,000 cycles per second shows 4 cycles of a 12,000 cycles per second wave form.

A linear time-sweep generator with good linearity, short-return sweep time, good frequency stability, and adjustable in frequency from very low frequencies to the upper audio frequency range, is available with present tubes. The type *RCA-885* gas filled triode tube was especially designed for this service. With suitable circuits, a sweep of 200 volts amplitude (or by special arrangements, 400 volts amplitude) can be obtained. The linear time sweep is generated by charging a condenser at a constant current rate. The constant current characteristic of the plate circuit of a pentode amplifier tube is used preferably as the constant-current controlling device. A diode operated at low filament voltage to produce saturation may also be used for this purpose. Another means consists in using only a small portion of the initial charging curve of the condenser. Since the exponential charging characteristic of a condenser is initially linear, the use of a high resistance in series with the condenser and a high charging voltage will permit an appreciable amount of voltage across the condenser before it departs appreciably from linearity. Either the charging or the discharging voltage of the condenser may be arranged to produce the linear time sweep. The return sweep occurs on discharge or charge according to the circuit arrangement. The time constant of the circuit causing the return sweep should be low with respect to the time of the sweep. Generally, the arrangement is used in which the condenser charging produces the linear time sweep and the discharge the return sweep. Any one of these methods properly employed is capable of a high degree of linearity.

The return sweep occurring on the discharge of the condenser may be accomplished electrically by a gas filled triode or in certain applications it may be done mechanically by a rotating contact, a tuning fork, or other means. The gas filled triode permits a large frequency range and locked synchronization with the wave form being observed. Synchronization is locked by means of a small amount of wave form voltage coupled to the grid circuit of the gas filled triode. The mechanical method either controls the phenomena being observed and is, therefore, self-synchronized, or it provides a standard with which the frequency of the wave form can be compared.

Other time bases are used for various applications. A 60 cycle per second wave of approximately sine-shape voltage from the power line is often useful as a sweep voltage. When the amplitude is made large enough to cause the end portions to sweep beyond the limits of the screen, the central portion is nearly linear. If the frequency of the wave form being observed is a multiple of 60 cycles per second, the wave form will appear stationary on the screen and will have an approximately linear time distribution. Since the sweep and the return sweep of the 60 cycle per second voltage are the same, the wave form is spread twice across the screen. One method for preventing confusion of the wave form pattern consists in applying some of the 60 cycle per second voltage with a 90 degree phase shift to the deflection in the vertical direction. The result is that the sweep and the return sweep appear as 2 separate lines on the screen, since the 60 cycle per second voltages sweep out an elongated ellipse instead of a line. Another method consists in making the return sweep invisible by applying some of the 60 cycles per second voltage with a 90 degree phase shift to the brilliancy control electrode. The beam current is cut off during the return sweep by the negative half of the 60 cycles per second voltage. Where exact linearity is not necessary, this 60-cycle sweep method is convenient. Since there are a large number of 60 cycle intervals over the audio frequency range, a stationary wave form is readily obtained. The wave forms of different frequencies can be spread to convenient proportions by increasing the 60 cycles per second sweep voltage within the limits permissible in the deflecting circuits of the cathode ray tube.

A circular time base is often useful for frequency comparisons. In general, an ellipse results with axes parallel to the deflecting directions when voltages of the same frequency but with a 90 degree phase relation are applied to the deflecting plates. When the deflection amplitudes in the 2 directions are equal, the ellipse becomes a circle. The voltage with a 90 degree phase relation is readily obtained by means of a condenser and resistance. If the voltage source supplying the circular time base is changed

rapidly from zero to a maximum, the successive circles produced by each cycle are swept into a spiral. The spiral affords a convenient time sweep of known variable velocity and of considerable length on the screen.

Other auxiliary apparatus used frequently are amplifiers and current transformers. Resistance coupled amplifiers are most useful when uniform response over a wide frequency range is needed. For extremely low frequencies and d-c voltages, directly coupled amplifiers are used. For high frequencies where a wide range is needed, resistance coupled amplifiers having screen grid or pentode tubes and low plate-load resistances are used. The resistance coupled amplifier is used to amplify voltages to the proper level for applying them to electrostatic deflecting plates or electromagnetic deflecting coils. If a low resistance is introduced into a circuit where current is to be observed, a small voltage drop in the resistance is produced which may be amplified to a level suitable for deflecting the cathode ray beam.

Current transformers provide a means for converting current into voltage suitable for direct connection to the electrostatic deflection plates. When a uniform response over a frequency range is desired, the primary of the current transformer is connected across a low resistance in the circuit in which the current to be observed flows. The inductance of the primary is made high so that its reactance in the frequency range used will be large with respect to the resistance. The voltage developed across the primary is stepped up by the turn ratio of the transformer, the secondary of which is connected to the deflection plates. For example, with a turn ratio of 100 to 1 and the primary shunted with 10 ohms, a current of 10 milliamperes will produce 10 volts on the secondary or a peak-to-peak amplitude of about 0.5 inch on the screen of a cathode ray tube operated at 1,000 volts.

Applications of Cathode Ray Tubes

It is impractical in a discussion of this length to more than hint at some of the possible applications for cathode ray tubes. Fundamentally, the cathode ray tube may be regarded as an electron pointer or the movement of an uncalibrated electrical indicating device. The calibrating scales and circuit are provided by the user to suit his particular type of measuring or indicating apparatus.

One of the simplest uses of the cathode ray tube is the measurement of voltage. This is most conveniently done with the electrostatic deflection type of tube. The displacement of the spot on the screen is directly proportional to the applied voltage. When a d-c voltage is applied, the polarity as well as the magnitude is indicated by the displacement of the spot. When an alternating voltage is applied, the spot sweeps back and forth with an amplitude proportional to the peak-to-peak value of the applied voltage. For example, a 10-volt root-mean-square sine wave produces a sweep with an amplitude equal to 28 volts. At frequencies above 8 cycles per second, the sweep of the spot appears as a line, due to the persistence of vision. There is no error due to frequency until extremely high radio frequencies are reached. Overvoltage on the deflecting plates, which is not excessive, merely sweeps the spot off the screen. Thus, the cathode ray tube, being rugged, having a high impedance, and being independent of frequency, is useful as a peak voltmeter.

Since the electron beam can respond to several deflecting fields simultaneously or in rapid succession, the cathode ray tube can be used for time or frequency comparisons. The feature of being able to combine in the cathode ray tube the effects of 2 or even more factors makes it possible to obtain graphical results directly on the screen; as, for example, the tracing of the hysteresis characteristics of samples of iron and the tracing of resonance characteristics of tuned circuits. The inertialess characteristic of the electron beam makes it particularly applicable for high frequencies, although it responds equally to all frequencies usually encountered. It is, therefore, well suited for the viewing and recording of transient phenomena. Wave form is shown when the deflection is spread with a linear time-sweep voltage. A direct indication of phase between components of the same frequency is obtainable readily. Power ranging from low to high values and over an extreme range of frequencies can be determined either by amplitude and power-factor measurements or directly from an elliptical figure, the area of which is proportional to the power. Fluctuating pressures can be recorded, direction can be indicated, and many other engineering problems too numerous to mention here can be expeditiously solved with the aid of the cathode ray tube.

In conclusion, it may be said that present-day cathode ray tubes are simple to use, are flexible in application, and can be used to advantage in the solution of many engineering problems.

References

A complete bibliography on cathode ray tubes would be extensive. The following are a few references which will serve to guide the reader to other references.

Periodicals

Improved Cathode-Ray Tube Method for the Harmonic Comparison of Frequency, D. W. Dye. Physical Society *Proc.*, London, v. 37 (1925), p. 158.

A Low Voltage Cathode Ray Oscillograph, J. B. Johnson. Am. Opt. Soc. *Jl.*, v. 6, 1922, p. 701; and *Phys. Rev.*, v. 17, 1921, p. 430.

A Low Voltage Cathode-Ray Oscillograph With Fluorescent Viewing Screen, H. P. Kuehni. *Gen. Elec. Rev.*, v. 37, Sept. 1934, p. 429.

Measurements in Electrical Engineering by Means of Cathode Rays, J. T. MacGregor-Morris and R. Mines. I. E. E. *Jl.*, London, v. 63, 1925, p. 1056.

A New Cathode Ray Oscilloscope, W. O. Osbon. *Elec. Jl.*, v. 28, 1931, p. 329.

A Braun Tube for Direct Photographic Recording, M. von Ardenne. *Experimental Wireless*, London, v. 7, 1930, p. 66.

Improvements in Cathode-Ray Tube Design, V. K. Zworykin. *Electronics*, Nov. 1931, p. 188.

Text Books

Braunsche Kathodenstrahlröhren und ihre Anwendung, E. Alberti, Julius Springer Co., Berlin, 1932.

High-Frequency Measurements, August Hund. McGraw-Hill Book Co., Inc., New York.

Die Kathodenstrahlröhren, M. von Ardenne. Julius Springer Co., Berlin, 1934.

The Cathode-Ray Oscillograph in Radio Research, R. A. Watson Watt. His Majesty's Stationery Office, London.

Effect of Overloads on Transformer Life

Effects of overloading on the life of oil-immersed self-cooled power transformers are discussed in this paper. Experience has shown that under average loads and ambient temperatures, a transformer rated for a temperature rise of 55 degrees C, has a very long life, and can be overloaded considerably for short periods with little loss in life.

By
L. C. NICHOLS
FELLOW A.I.E.E.

Allis-Chalmers Mfg. Co., Milwaukee, Wis.

THERE is very little published information for telling the user of a transformer what the effect on the life of the transformer is, when it is operated at either high or low ambient temperatures, or when it is operated at high overloads for relatively long periods resulting in temperatures too high to operate continuously with safety. Any operation of the transformer consumes some of its life. Manufacturers of transformers are asked questions of the following nature:

1. What overload will a transformer carry without injury?
2. What overload will a transformer carry if the ambient temperature is 0 degree C, 10 degrees C, 20 degrees C, etc.?
3. What overload will a transformer carry for 1 or 2 hours following full load or following a load less than normal?
4. How long will a transformer carry an overload without injury if the temperature rise is greater than 55 degrees C?
5. What is the life of a transformer?
6. How often can these overloads be repeated?

Some of these questions already have been answered in A.I.E.E. publications.

Present A.I.E.E. rules allowing overloads at low ambient temperatures, and overloads allowed as given in the paper entitled "Overloading of Power Transformers," by V. M. Montsinger and W. M. Dann, published in the October issue of ELECTRICAL ENGINEERING, p. 1353–5, are very satisfactory from many standpoints, and yet they still leave something to be desired. What effect on the life of the transformer do these overloads have? If the transformer is operated within its rating, what is the life of the transformer? These questions cannot be answered definitely because it is practically impossible to gather exact data. However, on the basis of data presented in this paper, the following conclusions seem justified:

1. A transformer rated for a temperature rise of 55 degrees C has a very long life when operated under average loads and ambient temperatures.
2. A transformer can be overloaded considerably for short periods with very little loss in life.
3. Under the new proposed recommendations, emergency loads would consume less than $^1/_4$ of 1 per cent and recurrent overloads less than $^1/_{1000}$ of 1 per cent of the life of the transformer for each overload.
4. If a transformer is loaded at a constant load 24 hours a day in a 40-degree ambient temperature, then a transformer rated $^1/_3$ larger than the load should be used.

OPERATION AT LOADS GREATER THAN RATED LOAD

Any insulating material deteriorates, and the deterioration is a function of both temperature and time. The higher the temperature the greater the rate of deterioration; experience indicates that the rate of deterioration doubles with every 8-degree C increase in temperature.

Most transformers are single rated, 55-degree C rise, and good for operation at an ambient temperature of 40 degrees C. This means that the hot spot temperature in the transformer is 105 degrees C. Present rules of the A.I.E.E. might indicate that a reasonably long life of 15 to 20 years could be obtained if the transformer were operated continuously at this temperature. This is not correct. Tests made by placing different kinds of insulating material in oil for a period of 5 years at a temperature of 90 degrees C show that the material at the end of that time has aged to such an extent that it is exceedingly brittle; a transformer with insulation in this condition would fail from mechanical injury of the insulation, if there was any movement of the insulation. Tests also have been made on insulation for very short periods of time and at much higher temperatures.

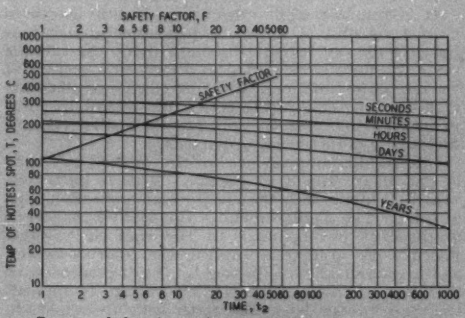


Fig. 1. Life of transformer insulation versus hot spot temperature

Per cent of life used, $L = 100(t_1/t_2)F$, where t_1 = time operated at hot spot temperature T, t_2 = life of insulation at temperature T, and F = safety factor

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Oct. 30, 1933; released for publication Oct. 16, 1934. *Not published in pamphlet form.*

Experience of actual operation in the field with transformers steadily loaded at 100 per cent load at ambient temperatures approaching approximately 40 degrees C has shown that failures in these transformers have been due to deterioration of the insulation after comparatively short periods of time.

The curves of figure 1 show the life that can be expected from transformer insulation when operated continuously at any given hot spot temperature; data collected from various sources indicate that they are reasonably accurate and sufficiently conservative for practical use. These curves show that if a transformer were operated continuously at a hot spot temperature of 105 degrees C, the insulation would have a life of only $1^1/_2$ years. In order to be reasonably safe, if the temperature exceeds 105 degrees C, the expected life is divided by a factor varying from 1 at 105 degrees to 10 at 250 degrees. As an example of the use of figure 1, suppose a transformer is operated with a hot spot temperature of 150 degrees for 4 hours. The figure shows a life of 240 hours, but a factor of safety of 2.6 must be used. Therefore when operated for 4 hours at 150 degrees, one operation has consumed $100(^4/_{240})2.6$ or 4.3 per cent of the life. By means of this chart, if the time of operation at a given temperature is known, then the per cent life consumed can be calculated.

The first reaction of most people in looking at this chart will be that $1^1/_2$ years' life at a hot spot temperature of 105 degrees C is entirely too short, as this represents 100 per cent load continuously of a transformer rated for a 55-degree rise in a 40-degree ambient temperature, with an allowance of 10 degrees for hot spot. As an actual fact, a transformer is

Table I—Loss in Life of an Oil-Immersed Self-Cooled Transformer† When It Is Overloaded Under Various Conditions

Load Conditions	Overload in Per Cent of Rated Load	Loss in Life in Per Cent of Total Life When Duration of Overload Is: 5 sec	1 min	5 min	15 min	30 min	1 hr	2 hr	4 hr	10 hr	24 hr
40° C ambient, 50% load followed by:	125	0.000	0.000	0.000	0.002	0.005	0.016	0.054	0.217	1.870	6.000
	150	0.000	0.000	0.000	0.006	0.023	0.075	0.420	2.000	20.800	85.000
	200	0.000	0.000	0.006	0.140	0.630	3.100	26.000	*	*	*
	250	0.000	0.000	0.076	5.000	30.000	*	*	*	*	*
	500	0.000	0.057	*	*	*	*	*	*	*	*
	1,000	0.000	*	*	*	*	*	*	*	*	*
	2,000	53.500	*	*	*	*	*	*	*	*	*
40° C ambient, full load followed by:	125	0.000	0.000	0.003	0.016	0.034	0.075	0.230	0.580	2.290	6.000
	150	0.000	0.000	0.008	0.057	0.150	0.370	1.300	4.330	25.000	85.000
	200	0.000	0.000	0.069	0.890	3.000	12.000	78.000	*	*	*
	250	0.000	0.003	0.750	30.000	*	*	*	*	*	*
	500	0.000	0.880	*	*	*	*	*	*	*	*
	1,000	0.000	*	*	*	*	*	*	*	*	*
	2,000	*	*	*	*	*	*	*	*	*	*
30° C ambient, 50% load followed by:	125	0.000	0.000	0.000	0.000	0.000	0.002	0.009	0.030	0.188	0.600
	150	0.000	0.000	0.000	0.001	0.003	0.009	0.042	0.200	2.500	10.500
	200	0.000	0.000	0.000	0.018	0.073	0.370	3.800	24.000	*	*
	250	0.000	0.000	0.009	0.680	4.000	27.500	*	*	*	*
	500	0.000	0.009	*	*	*	*	*	*	*	*
	1,000	0.000	*	*	*	*	*	*	*	*	*
	2,000	6.750	*	*	*	*	*	*	*	*	*
30° C ambient, full load followed by:	125	0.000	0.000	0.000	0.002	0.004	0.009	0.025	0.063	0.229	0.600
	150	0.000	0.000	0.000	0.006	0.014	0.040	0.150	0.500	2.710	10.500
	200	0.000	0.000	0.008	0.110	0.430	1.700	10.000	68.000	*	*
	250	0.000	0.000	0.104	4.600	22.000	*	*	*	*	*
	500	0.000	0.117	*	*	*	*	*	*	*	*
	1,000	0.000	*	*	*	*	*	*	*	*	*
	2,000	26.800	*	*	*	*	*	*	*	*	*
10° C ambient, 50% load followed by:	125	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.012	0.075	0.220
	150	0.000	0.000	0.000	0.000	0.001	0.004	0.016	0.068	0.750	3.500
	200	0.000	0.000	0.000	0.008	0.023	0.130	1.200	10.000	*	*
	250	0.000	0.000	0.003	0.200	1.600	10.000	*	*	*	*
	500	0.000	0.003	*	*	*	*	*	*	*	*
	1,000	0.000	*	*	*	*	*	*	*	*	*
	2,000	3.000	*	*	*	*	*	*	*	*	*
10° C ambient, full load followed by:	125	0.000	0.000	0.000	0.000	0.002	0.004	0.011	0.007	0.087	0.220
	150	0.000	0.000	0.000	0.002	0.005	0.014	0.050	0.158	0.920	3.500
	200	0.000	0.000	0.003	0.036	0.140	0.540	4.200	22.000	*	*
	250	0.000	0.000	0.037	1.500	8.500	44.000	*	*	*	*
	500	0.000	0.049	*	*	*	*	*	*	*	*
	1,000	0.000	*	*	*	*	*	*	*	*	*
	2,000	9.500	*	*	*	*	*	*	*	*	*
0° C ambient, 50% load followed by:	125	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.031	0.096
	150	0.000	0.000	0.000	0.000	0.000	0.002	0.006	0.028	0.250	1.100
	200	0.000	0.000	0.000	0.002	0.008	0.040	0.460	3.340	*	*
	250	0.000	0.000	0.001	0.078	0.540	4.000	78.000	*	*	*
	500	0.000	0.000	*	*	*	*	*	*	*	*
	1,000	0.000	*	*	*	*	*	*	*	*	*
	2,000	1.100	*	*	*	*	*	*	*	*	*
0° C ambient, full load followed by:	125	0.000	0.000	0.000	0.000	0.000	0.002	0.004	0.010	0.037	0.096
	150	0.000	0.000	0.000	0.000	0.002	0.006	0.018	0.057	0.304	1.100
	200	0.000	0.000	0.000	0.012	0.046	0.210	1.300	9.180	*	*
	250	0.000	0.000	0.012	0.630	2.700	17.000	*	*	*	*
	500	0.000	0.015	*	*	*	*	*	*	*	*
	1,000	0.000	*	*	*	*	*	*	*	*	*
	2,000	3.850	*	*	*	*	*	*	*	*	*

* Over 100 per cent; transformer probably would fail.

† Data in this table are for a transformer rated as follows: copper temperature rise, 55 deg C; oil temperature rise, 40 deg C; ratio of losses, 2.75.

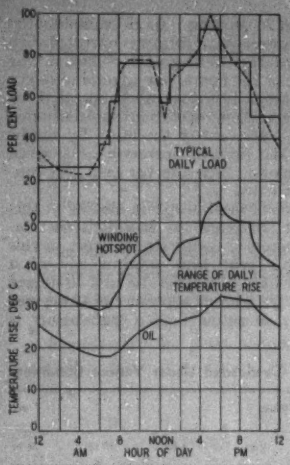


Fig. 2. Typical daily load cycle of a transformer in service on a large electric power company system, and curves showing hot spot temperature of winding and oil

practically never operated continuously at either a 40-degree ambient temperature or 100-per cent load.

A typical daily load on a transformer is indicated in figure 2 by a dotted line. This load cycle was obtained from a large electric power company, and represents the daily load cycle of that company's system. This is approximated by the heavy line for easy calculation. The hot-spot temperature rise of a typical transformer is shown in the lower part of this chart.

A transformer operated in the City of Pittsburgh, Pa., loaded as shown in figure 2 and with ambient temperatures equal to the monthly mean maximum temperature will have a life of 47 years as calculated from figure 1. If operated with ambient temperatures 8 degrees higher than that of Pittsburgh, the life would be 23 years.

Overloads

Table I shows what loss in life in per cent may be expected when a transformer is overloaded under various ambient temperatures and when various overloads are applied for various times following full load and following 50-per cent load. As the temperature rise of the transformer is not much greater at 50-per cent load than at no load, these charts can be used for any load following no load. It is to be noted that with 125-per cent load and a 40-degree ambient temperature following 50-per cent load, practically none of the life is consumed until after a 15-min period, and in 24 hours 6 per cent of the life would be consumed. However, with 150 per cent load for 24 hours, 85 per cent of the life would be consumed. If, however, the ambient temperature is zero, only 1.1 per cent of the life would be consumed in 24 hours at 150-per cent load. In calculating this loss in life from resultant temperatures for various times, a transformer was selected that had 40-degree oil temperature rise and 55-degree copper temperature rise with a ratio of losses of 2.75. If the transformer had a greater ratio of losses than this, it could not be overloaded so much, but this data represents fairly accurately and conservatively what may be expected of practically any modern transformer. This table should be very valuable to operators, especially when emergency conditions necessitate overloading a transformer. For instance, a transformer operated in a 20-degree ambient temperature will carry 25 per cent overload for 24 hours and only 0.6 of 1 per cent of the life will be consumed, or it will carry much greater overloads for shorter periods with only a small percentage of the life consumed, as shown by the table.

Calculation of Transformer Temperature Rise

Several charts have been prepared showing how the temperature rise of a transformer may be estimated when carrying various overloads for different times, provided certain information is available. What must be known are the iron loss and the copper loss at full load, temperature rise of the oil at full load, temperature rise of copper over the oil at full load, and weights of transformer core, copper, case, and oil. The temperature rise at practically any load can be determined from these figures. The ultimate temperature rise of the oil varies as the 0.8 power of the total loss. The ultimate temperature rise of the copper over the oil varies directly as the copper loss.

In figure 3 are shown heating and cooling curves for a typical transformer. Curves *A* represent what the

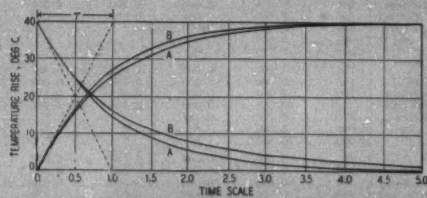


Fig. 3. Heating and cooling curves for a typical transformer

Curves A. Energy dissipation assumed to be directly proportional to temperature rise

Curves B. Energy dissipation assumed to be proportional to 1.25 power of temperature rise, but radiating surface reduced to give same final temperature as for curves A

heating and cooling would be if the temperature rise varied directly as the loss, which is how the temperature rise of copper over oil varies; curves *B* show what the heating and cooling would be if the temperature rise varied as the 0.8 power of the loss, which is how the oil temperature varies. In other words, the heat dissipation varies as the 1.25 power of the temperature. It may be noted by comparing curve *B* with curve *A* that while the initial rate of temperature rise and the final temperature rise is the

same for both, in curve B the temperature rise is more rapid than in curve A. Also the cooling is at a less rapid rate, although they both start at the same initial rate.

If these heating and cooling curves were converted into straight lines, they could be drawn more easily, especially when it is desired to draw heating curves for many different loads.

If a transformer heats up according to a known law, say with heat dissipation varying as the 1.25 power of the temperature rise as in curve B, it starts at an initial rate that can be determined from the losses, weights, and specific heat of the material in the transformer, and finally reaches an ultimate temperature after continuous operation at a given load. There is only one curve that can be drawn following this law with the same initial rate and the same ultimate temperature rise.

Figure 4 shows how the time scale can be changed to convert the curve into a straight line. Where this straight line crosses the ultimate temperature the time must be infinity, and where the temperature rise is zero, the time also must be zero. Any convenient length may be chosen for this time scale that will be marked zero to infinity. The unit of time chosen is that time required for the temperature to reach the ultimate value, if the rise continued at the initial rate. In this length of time the temperature rise, following the 1.25-power law, reaches 68 per cent of the ultimate value; therefore, unit time on the time scale will be at a point 68 per cent of its total length from the zero point. Other points on the time scale are easily laid off as indicated.

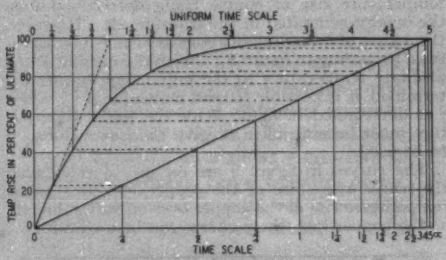


Fig. 4. Graphical method of laying off scale to convert transformer heating curve to a straight line

Time unit = time to reach ultimate temperature rise at initial rate

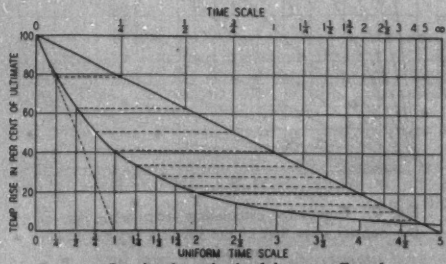


Fig. 5. Graphical method of laying off scale to convert transformer cooling curve to a straight line

Time unit = time to reach ultimate temperature drop at initial rate

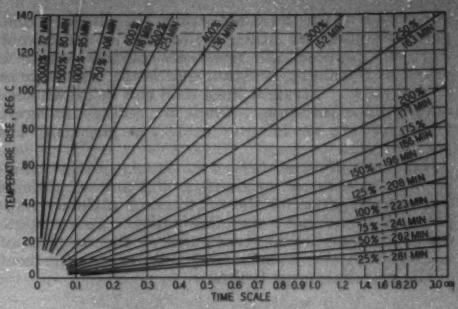


Fig. 6. Straight-line transformer heating curves drawn as shown in Fig. 4

Energy dissipation proportional to 1.25 power of temperature rise

Time unit = ultimate temperature rise ÷ initial rate of rise

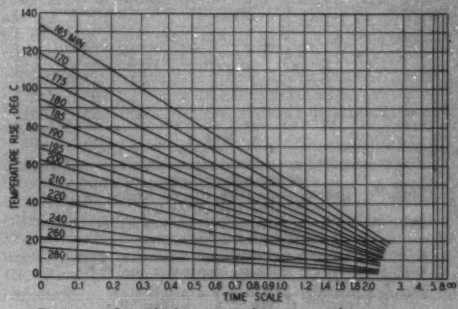


Fig. 7. Straight-line transformer cooling curves drawn as shown in Fig. 5

Energy dissipation proportional to 1.25 power of temperature rise

Time unit = initial temperature rise ÷ initial rate of fall

Similarly, figure 5 shows how a cooling curve can be made into a straight line.

A family of heating curves drawn as just outlined is shown in figure 6. These curves represent temperature rise of the oil under various loads and for various times for the particular transformer mentioned previously, but are fairly typical and may be used with fair accuracy for any transformer. At 100 per cent load the ultimate temperature rise is 40 degrees C. A straight line then can be drawn between zero and 40. If the temperature rise of the oil varies as the

0.8 power of the total loss, then the ultimate temperature rises for other loads can be calculated. For this purpose the resistance of the copper is taken as remaining constant and is the resistance at 75 degrees C. Straight lines then can be drawn very readily for other loads. These are marked in figure 6 in per cent as 125 per cent, 150 per cent, 175 per cent, etc.

The unit of time, however, remains to be calculated. As defined previously, this unit of time is the time required for the oil to reach ultimate temperature if no heat was dissipated. To calculate this, the loss in the transformer, the weights of materials in the transformer, and the specific heat of the materials must be known.

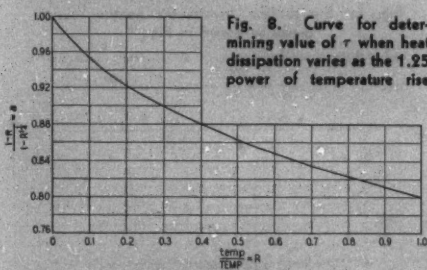


Fig. 8. Curve for determining value of τ when heat dissipation varies as the 1.25 power of temperature rise

τ = time required to reach ultimate temperature at initial rate of temperature change

Temp. = ultimate temperature rise on heating or initial temperature rise on cooling

temp. = initial temperature rise on heating or ultimate temperature rise on cooling

K = heat capacity of body (watt-minutes per degree C)

k = watts loss ÷ (ultimate temperature rise)$^{1.25}$

$$\tau = \frac{K}{k}\left(\frac{\text{Temp.} - \text{temp.}}{\text{Temp.}^{1.25} - \text{temp.}^{1.25}}\right) = \frac{aK}{k\ \text{Temp.}^{0.25}}$$

$$\text{If temp.} = 0,\ \tau = \frac{K}{k\ \text{Temp.}^{0.25}}$$

As all the material in the transformer does not come up to the same temperature as the hottest oil, only $^2/_3$ of the weight of the case and $^3/_4$ of the weight of the oil are used in these calculations. This unit of time, τ, is equal to $A(C + D + E) + G$, where A is the ultimate temperature rise of the oil, C equals 3.64 times pounds of core plus $^2/_3$ of the pounds of the case, D equals 2.93 times pounds of copper, E equals 14.23 times $^3/_4$ of the pounds of oil, and G is the total loss.

As the ultimate rise A does not vary directly as the loss but as the 0.8 power of the loss, the unit of time is different actual time for each load. This unit of time has been calculated for the various loads and indicated on the curves of figure 6 immediately adjacent to the per cent load. With these straight lines drawn, the temperature rise of the oil for any load for any time can be read. For instance, suppose a transformer starts cold and 100-per cent load is applied for 8 hours, or 480 minutes. As the unit of time is 223 minutes, 8 hours is represented by 2.15 on the time scale, and the temperature rise of the oil is 36.5 degrees C. Suppose 50-per cent overload is applied for 2 hours. The 150-per cent curve at 36.5 degrees C is 0.7 on the time scale. Two hours from that time is 120 minutes, and as τ for this curve is 196 minutes, add 0.61 in time, making a total of 1.31; this gives an oil temperature of 52.5 degrees C. Similarly, the temperatures for any successive loads that would cause an increase in temperature can be calculated.

The cooling that can be expected from any temperature with the transformer disconnected from the line is shown by the curves of figure 7. The value of τ to be used depends upon the initial temperature and is the same value as would be used on the heating curve (figure 6) according to the ultimate temperature rise. At 40 degrees C, τ would be 223 minutes, the same as shown in figure 6 for 100-per cent load which gave an ultimate temperature rise of 40 degrees. With a transformer having an initial oil temperature of 51 degrees C, τ is 210 minutes, or in 210 minutes the oil would cool off to 20 degrees C.

If a transformer, however, is operated at a load that would cause the oil to cool off from its initial temperature, then figure 7 must be used, but a straight line must be drawn from the initial temperature rise on the left side of the chart to the ultimate temperature rise on the right side of the chart, this ultimate temperature rise of course being determined from the energy generated in the transformer. However, the value of τ under this condition must be calculated according to figure 8. With the ratio R of the ultimate temperature to the initial temperature determined, it is possible to read multiplier A by which τ as determined in figure 7 for the initial temperature must be multiplied to give the new value of τ to be used.

The curves in figure 9 are for use in calculating the temperature rise of the copper over oil. As the temperature rise of the copper over oil varies directly as the copper loss, these curves can be used both for

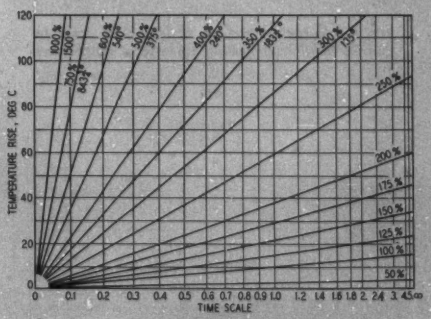


Fig. 9. Curves for calculating temperature rise of the copper over that of the oil in a typical power transformer

Copper loss of transformer at 100 per cent rated load = 27 kw, weight of copper = 2,610 lb, time unit = 4.25 min, unit time (in minutes) = 2.93 × temperature differential ÷ watts loss per pound

Temperature differential varies as square of load

heating and cooling. The unit of time in minutes is equal to 2.93 times the pounds of copper times the ultimate temperature rise of the copper over the oil divided by the copper loss, or is equal to 2.93 times the temperature rise of the copper over oil divided by the watts loss per pound. In this particular example these curves are drawn with 15-degree differential between copper and oil for 100-per cent load, this temperature rise of copper and oil varying as the square of the load for other loads. For this particular transformer the unit of time is 4.25 minutes; by referring to the curve it may be seen that in 4.25 minutes the temperature of the copper would be 10 degrees C higher than that of the oil at 100-per cent load. These curves show that if the load is applied for 20 minutes the copper will reach its ultimate temperature rise over the oil, and therefore these curves need not be used unless the overloads are for less than 20 minutes. If now 200-per cent load is applied for $4^1/_4$ minutes following full load, the 200-per cent load curve should be used; 15-degree C rise is at 0.29 on the time scale, and $4^1/_4$ minutes more would be 1.29 and the oil rise 43 degrees C. Similarly temperatures during cooling can be found by using this same chart, the value of the time scale remaining the same. It is only necessary to draw a straight line from the initial temperature on the left-hand scale to the ultimate temperature for the load in question on the right-hand scale and read directly the temperature for any intermediate time as indicated by the time scale.

A Thermionic-Tube Measuring Instrument

A universal measuring instrument for communication circuits has been developed which has a number of advantages over previous methods of obtaining measurements in such circuits. This thermionic-tube instrument gives direct measurements of current, voltage, power factor, or power in communication circuits and is accurate over a wide range of frequencies.

By
TOM B. WAGNER Portland, Ore.

THE A-C power taken by communication apparatus is seldom measured directly. This is due primarily to the lack of a satisfactory direct reading power instrument such as the wattmeters used in commercial power circuits. The power taken in communication circuits is usually only a fraction of a watt and sensitive instruments are accordingly required. Then, too, communication frequencies cover the wide band from about 50 cycles to millions of cycles per second. This prevents the use of ordinary commercial power instruments.

Power measurements in communication circuits are determined from I^2R values; the current is read with a thermocouple instrument and the effective resistance is measured with a bridge. The resistance R is, however, sometimes difficult to measure; for example, the resistance offered by a loud speaker varies with the current used. Also, this method is slow and laborious, and while it can be employed, it does not offer the same flexibility that can be obtained with direct reading devices such as ordinary wattmeters.

With the appearance of the Wunderlich thermionic tube, having 2 symmetrical and hence equally-effective control grids, the possibility was recognized of utilizing this tube as a basis for a vacuum tube wattmeter. By impressing a voltage proportional to the current taken by the load being measured on one grid and the voltage across the load on the other grid, it seemed possible that the alternating current in the plate circuit of the tube would be proportional to the product of the load voltage E, the load current I, and the cosine of the angle between E and I. As a result of this investigation it was found that the device not only operated as a wattmeter, but it could readily be used to give voltage, current, or power factor separately, thus supplying a means of measuring the 4 fundamental electrical quantities.

Theoretical Considerations

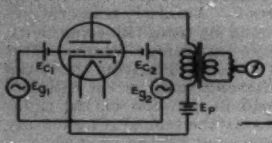
The Wunderlich tube has an indirectly heated cathode and is not unlike the common type 27 tube except for 2 control grids instead of the conventional single control grid. In Fig. 1 the arrangement of the electrodes in the Wunderlich tube is shown.

In the instrument here described, the tube was biased to operate essentially as a linear amplifier. That is, when an a-c voltage E_s is superimposed on the d-c bias E_c of one of the control grids of the tube, this a-c voltage affects the electron flow to the plate of the tube in the same relation as the polarity and magnitude of the a-c impressed on the grid. This process is shown graphically in Fig. 2. This pulsating plate current is passed through a transformer to separate the d-c from the a-c component. The

Full text of a paper presented at a joint meeting of the Institute's Portland Section and Oregon State College Branch, May 20, 1933, and subsequently awarded the Institute's 1933 Branch paper prize. Manuscript submitted May 31, 1933; released for publication July 2, 1934. *Not published in pamphlet form.*

alternating voltage appears on the secondary side of the transformer and operates a suitable indicator.

If an a-c voltage of the same frequency is simultaneously impressed on the other control grid of the tube the electron flow to the plate will depend upon the magnitudes and phase relations of these 2 a-c



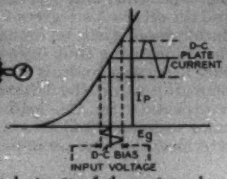


Fig. 1 (left). Fundamental circuit of the universal measuring instrument for communication circuits

Fig. 2 (right). Grid characteristics of the Wunderlich tube

voltages. That is, if in-phase a-c voltages of 3 volts are placed on each grid of the tube, the indicator will give a certain reading. After changing the grid voltages to 2 volts on one grid and 4 volts on the other grid the total grid input voltage is still 6 volts, and the indicator reads the same as before. It was found by tests that this was about the greatest difference in the a-c grid voltages that could be employed to give the same indicator reading as for equal a-c grid voltages (the sum of the a-c voltages being the same in either case).

Description of the Instrument

One of the most important features of this instrument (shown in Fig. 3) is the possibility of inserting it in a circuit without disturbing the circuit. In Fig. 4 a complete diagram of the instrument is shown and the photograph shows the parts and their arrangement as used in the experimental study. The resistance of the potentiometer R_1 was 4 ohms. It was found necessary to use a low value of resistance for this series resistor in order to keep the power losses and IR voltage drop in the instrument as low as possible.

A 3-stage resistance-coupled vacuum-tube amplifier was used to increase the voltage drop across R_1 sufficiently to excite one of the grids of the Wunderlich tube. This is the current measuring part of the circuit. It might appear that the amplifier would cause a phase distortion or change in wave shape, but this is not true. Observation with an oscillograph showed no phase or wave form distortion between the input and output circuits of the amplifier.

The resistor R_3 is connected in parallel with the output circuit and is of high resistance to keep the power losses low. This is the voltage measuring part of the instrument.

If the a-c voltages across R_1 and R_2 are substituted for the a-c generators in the grid circuits of the tube in Fig. 1 the device is complete, and the thermocouple current will depend upon the magnitudes and

Fig. 3. Equipment of the universal measuring instrument for communication circuits

phase relations of these voltages. To have satisfactory coupling between the plate circuit of the tube and the low resistance thermocouple used in the indicator circuit a high ratio step-down transformer giving suitable transfer impedance was used.

Operation as an Ammeter

For use as an ammeter R_2 is set at zero and R_1 and R_3 are set at predetermined points, depending upon the magnitude of current to be measured. The microammeter connected to the thermocouple is the indicator, and from an over-all calibration curve (Fig. 5) the current through R_1 is read.

Operation as a Voltmeter

For use as a voltmeter R_1 and R_3 are set at zero and R_2 is set at some predetermined point, depending upon the magnitude of voltage to be measured. The voltage is read from an over-all calibration curve (Fig. 6) plotted against readings of the microammeter.

Operation as a Wattmeter

For power measurements R_1 and R_3 are set at given points, depending upon the current and voltage magnitudes. The microammeter then gives

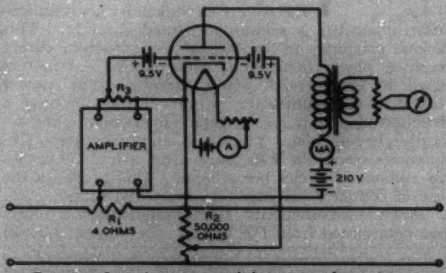


Fig. 4. Complete circuit of the universal instrument used in securing calibration curves

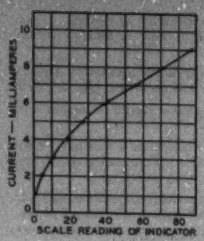


Fig. 5. Current calibration for universal instrument

$E_d = -9.5$ volts $E_s = 210$ volts

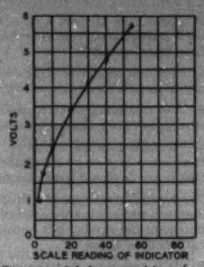


Fig. 6. Voltage calibration for universal instrument

$E_d = -9.5$ volts $E_p = 210$ volts

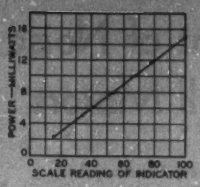


Fig. 7. Power calibration for universal instrument

$E_d = -9.5$ volts $E_p = 210$ volts

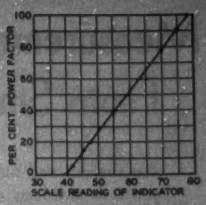


Fig. 8. Power factor calibration for universal instrument

Each grid set to cause indicator to read 20

$E_d = -9.5$ volts $E_p = 210$ volts

an indication of the power being consumed by the load. As for the ammeter and voltmeter, the power values are read from an over-all calibration curve (Fig. 7). In using the instrument care should be exercised that the maximum a-c voltage does not exceed the d-c bias voltage on the control grids of the tube.

Operation as a Power Factor Meter

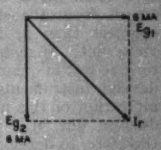
For operation as a power factor instrument R_1 and R_2 are first set at zero. Resistor R_3 is then varied until the microammeter connected to the thermocouple reads an arbitrary scale (in these tests) of 20, corresponding to 6 ma of thermocouple current. The dial reading of R_2 is recorded. Then R_2 is brought back to zero. The resistor R_1 is then set at some convenient point, and R_3 is varied until the microammeter again reads 20.

With R_1 and R_3 left at these points, R_2 is set on the dial reading previously obtained. The magnitude of the voltages on each grid is now the same, although these voltages do not necessarily have the same phase relations. If they have the same phase relations the microammeter will read 78 (12 ma thermocouple current) as shown on the calibration curve (Fig. 8) for 100 per cent power factor. If there is a phase difference between these 2 voltages the microammeter will read less than 78 as shown by the curve (Fig. 8), giving an indication of the power factor of the load.

The calibration was obtained at various power factors with a load composed of pure capacitance and resistance in series. Knowing the IR drop from the product of the load current and resistance, and dividing this IR drop by the total load voltage measured with a voltmeter, the per cent power factor was obtained. While the curve is plotted from experimental data, it is possible to check each end of the curve by simple calculations.

When the load has unity power factor the current reading of the microammeter should be double that produced when setting either grid from equal a-c potentials. Under typical operating conditions a scale reading of 20 indicates 6 ma of thermocouple current. Doubling this value of 6 ma gives 12 ma, and the scale reading on the microammeter for 12 ma is 78, which is the correct reading for 100 per cent power factor. For zero power factor the a-c grid voltages are 90 deg out of phase and can be represented by current vectors as in Fig. 9. The current I_r is the vector sum of the 2 equal currents, or 1.414×6 ma $= 8.5$ ma. This 8.5 ma corresponds to a scale reading on the microammeter of 39.5. Therefore, a scale reading of 78 will give unity power factor, and 39.5 gives zero power factor. This checks very well with the experimental calibration curve of Fig. 8. In a similar manner, using either trigonometric or graphic solution, other points on this curve can be checked.

Fig. 9. Vector diagram of grid voltages at zero power factor



Conclusions

1. The error of the instrument as used in this investigation is approximately 2 per cent for frequencies ranging from 100 cycles to 3,000 cycles.

2. The instrument would undoubtedly work very well at much higher frequencies if proper shielding and other construction refinements were employed.

3. The instrument consumes negligible power from the source, and does not affect circuit conditions materially.

4. The calibration curve for power factor can be checked mathematically.

5. Four measuring instruments can be included in one, namely, a voltmeter, an ammeter, a wattmeter, and a power factor instrument.

6. The chief objection to the instrument is the indirect method of measuring power factor, requiring several adjustments to make a reading, thus increasing the chances for errors.

7. Although exhaustive tests were not made to determine the error due to poor wave form, it does not appear that the error would be greater than with other measuring instruments. Moreover, in most laboratory tests for which this instrument is particularly adapted, sine waves are used.

Measurement of Noise From Small Motors

An analysis and summary of some of the concrete problems and considerations involved in the measurement of noise caused by fractional horse power motors are presented in this paper. Some experimental data and several important conclusions are given, but much remains to be done before standardization is possible. Desirable characteristics of a noise meter for this application are pointed out.

By
C. G. VEINOTT
ASSOCIATE A.I.E.E.

Westinghouse Elec. & Mfg. Co., Springfield, Mass.

MEASUREMENT of the total noise of a small motor undoubtedly presents a different aspect from the standpoint of a practical motor engineer than it does from an abstract physical viewpoint. If motor noise is to be measured as a routine test in quantity production, it is necessary to develop instruments and a technique whereby some indication of this noise can be made near the production line in a noisy factory. It is necessary, therefore, to develop means for measuring or obtaining an indication of the motor noise in noisy surroundings, where the noise is likely to vary considerably and where there are likely to be all sorts of intermittent noises, such as hammering, that would affect a noise meter considerably. The quietness of the modern fractional horse power motor renders this problem the more difficult. At this immature stage of the art, it is unwise to attempt to recommend any instrument or technique for purposes of standardization. It is hoped, however, that this presentation of some of the aspects of the problem will prove of value to future investigators and will stimulate other papers on this subject.

The principal points brought out in this paper and the conclusions reached may be summarized as follows:

1. Motor noise should be classified into 2 groups: (a) air-borne noise, and (b) transmittable noise, or potential noise that may be transmitted through the mounting structure.

2. A "sound proof" box for measuring air-borne noise should have sound insulation that reduces the noise level at least 40 decibels. (This is based upon a factory noise level of 70 to 80 decibels.)

3. The interior of this box should be acoustically dead, that is, it should have as short a time of reverberation as possible. Also, no 2 interior walls should be parallel, in order to minimise errors from standing waves.

4. The box should be large enough so that a reasonable spacing, say a foot, between the microphone and the motor can be used.

5. For measuring air-borne noise, the motor should be mounted on an effective noise insulating base.

6. While it is desirable to have the microphone a foot away from the motor, the microphone should be of such a type and construction that it can be placed nearer the motor when necessary.

7. A satisfactory type of microphone remains to be developed. It does not appear that the condenser microphone, the crystal microphone, or the moving coil microphone as at present developed are entirely satisfactory.

8. It is important that the meter should be able to read both an unweighted and a weighted total noise.

9. In a practical noise meter, provision should be made so that the signal indicated on the output meter can be listened to by means of high quality headphones. A pair of headphones, and a little judgment as to the quality of the sound, are often of great assistance in determining whether or not a reading is of any value. When using the headphones, the signals should be unweighted.

10. The question of pitch, in connection with motor noise, often is raised. A quantitative measurable indication as to whether the noise is composed mainly of low or high frequency components is highly desirable. For this purpose, the author proposes the term "quality index," abbreviated QI, which is defined as the difference between the weighted and unweighted intensities, expressed in decibels.

Measuring Motor Noise in a Large Room

Before plunging deeper into the subject, it may be well to mention the type of noise meter used for the greater part of the experiments discussed in this paper. The meter used was described fully by Osbon and Oplinger (see "A New Portable Meter for Noise Measurement and Analysis," *Journal* of Acoustical Society of America, July 1933, pages 39–45). The sound pick-up is a standard high quality condenser microphone of the type extensively used in broadcasting and sound recording. It has a 3-stage amplifier included in the microphone housing. The electrical output from this microphone is fed into a high-quality 3-stage transformer-coupled amplifier with a calibrated attenuator in the input circuit and a calibrated meter to measure the output. The system is arranged to give a flat frequency response from 100 to 6,000 cycles per second. A weighting network that gives an over-all response approximating the 50 decibel loudness contour of the standards proposed by the American Standards Association can be switched into the circuit at will. (See "Proposed Standards for Noise Measurements," by Harvey Fletcher,

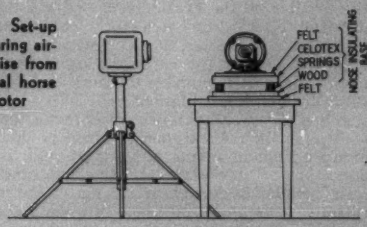


Fig. 1. Set-up for measuring air-borne noise from a frectional horse power motor

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for presentation at the A.I.E.E. winter convention, New York, N. Y., Jan. 29–25, 1935. Manuscript submitted Oct. 1, 1934; released for publication Oct. 17, 1934. *Not published in pamphlet form.*

ELECTRICAL ENGINEERING, volume 52, November 1933, pages 744–6.) A jack is provided so that it is possible to listen, by means of headphones, to the signal being picked up by the microphone for measurement.

To form an idea of the sound field surrounding a small motor, a typical motor was chosen and mounted on a noise insulating base, as shown in figure 1. The base and motor were placed on a small table in the center of a noise proof room which was approximately 12 feet square. Figure 2 shows the measured weighted intensity levels at various distances from the motor in various directions. Figure 3 represents a similar test on another typical motor.

Note: *All decibel figures given in this paper are based upon a reference level of 10^{-16} watts per square centimeter.*

The general tendency seems to be for the motor noise to become the more independent of direction of motor, the farther the microphone is placed from the motor. At 2 inches from the motor the sound in different directions may vary by 10 decibels or more, but at a distance of 1 foot this variation is reduced to 2 or 3 decibels.

How far the microphone should be placed from the motor merits consideration. It should be far enough from the motor to obtain an over-all indication of the average noise emitted by the motor. It should be placed near enough, however, so that reflected waves at the microphone will be negligible in intensity compared with the direct sound from the motor, and also near enough that the intensity of the signal in the microphone due to the motor noise will be substantially greater than that of the general noise of the room, say 10 decibels greater, as recommended by P. L. Alger. (See "Progress in Noise Measurements," ELECTRICAL ENGINEERING, volume 52, November 1933, pages 741–4.) Care should be taken that air currents from the ventilating fan do not impinge directly upon the microphone diaphragm. Care also should be taken to avoid errors due to localization of sound in the motor, such as in ball bearings or in noisy brushes. The motors on which data were given in figures 2 and 3, did not have strongly localized sources of sound.

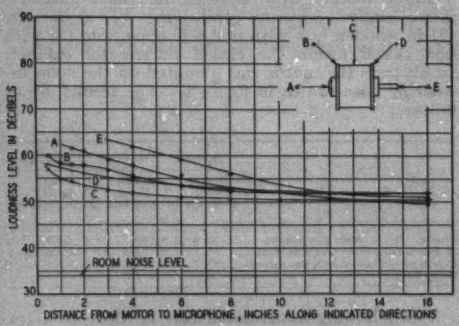


Fig. 2. Exploration of the sound field surrounding a typical small motor in free air

Most of the subsequent measurements on motors discussed in this paper were taken in the *C* direction, that is, with the motor shaft perpendicular to an imaginary line drawn from the microphone to the motor. Where possible this distance was 1 foot, but it was often necessary to shorten this distance to $2^1/_4$ inches.

The preceding paragraphs were concerned with the measurement of the inherent or air-borne noise. In many motor installations, the transmitted noise, that is, the noise radiated by the base upon which the motor is mounted, is of more importance than the air-borne noise. The noise of 3 motors was measured, with the microphone 1 foot from the motors, first on a noise insulating base, as shown in figure 1, and second on a small pine table the top of which was approximately 18 inches square. The following results were obtained:

	On Noise Insulating Base	On Pine Table
Motor 1	48 decibels	50 decibels
Motor 2	54 decibels	61 decibels
Motor 5	55 decibels	68 decibels

These results show strikingly the effect of the motor mounting. Motor 1 was provided with steel mounting springs which transmitted but little of the inherent torsional vibration of the motor to the base; motors 2 and 5 were mounted rigidly.

Any appraisal of small-motor noise must take into account transmittable as well as air-borne noise. One method proposed for measuring the transmittable noise is to mount the motor on top of a box and measure the noise intensity inside the box, with the motor running. This method is fraught with certain difficulties, however. An alternative method tried by the author for comparing relative transmittable noises of motors was to place a wooden board on top of the noise insulating base shown in figure 1, and allow the motor to run on this board. This method was partially successful, but not entirely satisfactory, because any slight warping of the board would cause the motor to rattle and render the readings useless.

NOISE MEASUREMENT IN A SMALL CHAMBER

Theory. The preceding considerations apply to the measurement of motor noise in a very quiet room. In a noisy factory, it is expensive and difficult, if not impractical, to construct a "noise proof" room sufficiently quiet so that the noise of quiet fractional horse power motors can be measured with a noise meter. The most logical idea, then, would be to place motor and microphone in a small "sound proof" box. One way of constructing such a box would be with the following ends in view:

1. To have sound-insulating walls to keep out room noise.

2. To intensify the motor noise to raise it above the noise level inside the box; this can be done by making the box (1) small in volume, and (2) with hard reflecting interior walls, or (3) what amounts to the same thing, with the longest possible time of reverberation.

Problems involved are:

1. Intensification without distortion.

2. Minimization of errors from standing waves. Probably the most practical way of doing this is by constructing the box so that no 2 sides are parallel.

An alternative to the construction with no 2 sides parallel would be to construct the box with an interior of sound-absorbing walls, making the box as nearly accoustically dead as possible. Because of its apparent advantages, it was decided to conduct an experimental investigation on the first mentioned type of box.

Experimental Data. As a measure of the quality of a sound, the author suggests the term "quality index," abbreviated QI, and this is defined as the difference, in decibels, between the unweighted and weighted measurements of intensity. For a 1,000 cycle pure tone, the quality index is zero. For a pure tone of 120 cycles, using the 50 decibel contour, the quality index is approximately 15. In general, a large quality index indicates a relatively large proportion of low frequency components in the noise.

A box with no 2 sides parallel and with outside dimensions as given in figure 4 was constructed of mahogany $^5/_8$ inch thick, and the interior walls were left hard and smooth. Tests were made to determine the amount of sound insulation that could be obtained. For these tests, the box was suspended in a noise proof room from a spring fastened to the ceiling; the spring was deflected about a foot by the weight of the box and microphone inside. The following results were obtained:

	Cover Off		Cover On		Reduction in Noise Level Due to Box
	Noise Level, Decibels	QI	Noise Level, Decibels	QI	
No machines running	42	11	41	6	1
Vacuum cleaner	69	1	52	6	17
Electric drill	82	0	63	0	19

It is disturbing, but very important, to note at low levels an almost negligible apparent reduction of surrounding noise. This is probably because of the residual microphone and tube noises of the meter.

It is observed also, that high frequency noises are reduced more effectively by the box than are low frequency noises. Further experiments made to check this point demonstrated that the walls of the box would reduce a 60 cycle tone by 7 decibels, a 250 cycle tone by 11.5 decibels, and a 1,000 cycle tone by 23.6 decibels.

Attempting to obtain a further reduction in noise level inside this wooden box, the latter was placed inside a refrigerator cabinet and the space between

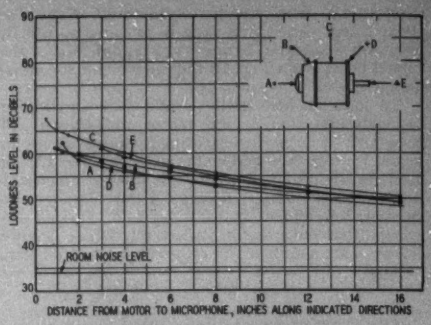


Fig. 3. Exploration of the sound field surrounding a typical small motor in free air

the outside of the box and the inside of the refrigerator filled with jute. A refrigerator cabinet, with hard steel walls, separated by jute or good sound absorbing material, makes excellent sound insulation except that the steel is so thin that it easily can vibrate like a diaphragm. The whole assembly of refrigerator, wooden box, and microphone was mounted on springs so as to be isolated from floor vibrations. Tests were made to determine the reduction in noise level obtainable from the sound insulation. At high external noise levels the following results were obtained:

1. Average reduction from wooden box only, 22.5 decibels.
2. Average reduction from refrigerator only, 21.7 decibels.
3. Average measured reduction from both, 42.3 decibels.

In spite of the fact that this combination should reduce the interior noise 40 decibels below the external noise, it was found impossible to get a reading below 34 decibels inside the box, even with an external noise intensity of only 40 decibels. Again, this is probably because of the residual noise of the microphone and tubes.

Three motors were selected for noise measurements under 3 separate conditions: (1) in free air, (2) in wooden box with one side open, and (3) in wooden box closed inside the closed refrigerator cabinet. In all tests the motor was mounted on the noise insulating base shown in figure 1. The results are as follows:

	Motor 1		Motor 2		Motor 3	
	Noise Level, Decibels	QI	Noise Level, Decibels	QI	Noise Level, Decibels	QI
Free air, $2^1/_4$ in. from microphone	55.8	3.3	60	..	7.5	61.3	2.0
In non-parallel-sided box, box open	58.7	7.0	64.5	11.4	65.6	10.9
In non-parallel-sided box, box closed	61.7	4.7	62.6	5.8	65.5	4.1
Intensification due to box	5.9		2.6		4.2	

The following conclusions can be deduced from these results:

1. Intensification of signal is too small, only about 4 decibels, to

be of practical assistance. It is doubtful if any more intensification than this can be obtained.

2. Intensification is accompanied by an erratic and unpredictable distortion of the quality.

3. It is interesting to note that, for 2 of the 3 motors, the measured noise was louder with one side of the box open than it was with the box totally closed.

4. It is also interesting to note that with the box open, the low frequencies were much more prominent than they were with the box closed or with the motors in free air.

Since intensification was the primary reason for constructing the box, small in size, and with hard sound-reflecting interior walls, the author, as a result of these experiments, is led to the conclusion that a noise testing box for small motors should have an acoustically dead interior and as short a time of reverberation as possible. Inasmuch as perfect sound-absorbing interior walls are impossible to obtain, errors due to standing waves should be minimized by constructing the interior so that no 2 sides are parallel.

Noise Meters

The Microphone. The condenser microphone is recognized generally as a high quality microphone, with the desirable characteristic of a flat frequency-response curve. It is used extensively in radio broadcast work, and in high-fidelity sound recording. It has been used extensively and successfully as the sound pick-up for noise meters. Under ideal conditions it can be used successfully for measuring noise from fractional horse power motors. All the data in figures 2 and 3 were taken with a condenser microphone, and it may be noted that the room noise level was too low to cause any measurable error in the readings. However, while under ideal conditions, the residual noise level is low enough, this level seems to be disproportionately raised in the presence of large low frequency components of noise at, or near, the threshold of hearing. In a manufacturing plant, such noises apparently will penetrate the best sound insulation that can be devised and will affect the microphone. The noise thus picked up in a "sound proof" room surrounded by machinery sounds not like machinery noise, but like "air rush" against the microphone diaphragm. A motor running in this room at some distance from the microphone causes no change in the reading of the output meter, yet it can be heard distinctly in head phones connected in the output circuit of the noise meter. In general, the output meter needle dances around erratically with little apparent reference to the noises the ear detects faintly filtering into the room. The author seriously questions the suitability of the condenser microphone for measuring the noise from quiet fractional horse power motors in a noisy factory, no matter by how much "sound proof" insulation the microphone is surrounded.

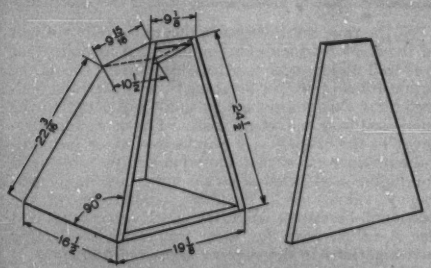


Fig. 4. Box with no 2 sides parallel used for measuring motor noise, all dimensions in inches

A crystal microphone was tried by inserting a microphone head of that type in place of the regular condenser head. The crystal microphone was 14 decibels more sensitive than the condenser microphone at 1,000 cycles, but only 8 decibels more sensitive at 120 cycles. The effect of this difference in sensitivity at different frequencies was to give the over-all response of the meter an equivalent weighting network corresponding to the 40 decibel contour instead of the 50 decibel contour. The results obtained with the crystal microphone were, in general, somewhat the same as with the condenser microphone, and but little more encouraging. Its performance at low noise levels was quite unsatisfactory. In general, it gave the same results as the condenser microphone so far as total-noise measurements were concerned, except of course, slightly lower readings for noises containing prominent low frequency components. Perhaps if less amplification had been used with the crystal microphone, it would have been more satisfactory. Less amplification could have been used because of its greater sensitivity.

The moving coil microphone offers another possibility. Comparative noise tests were made with a Western Electric noise meter which used a moving coil microphone. The moving coil microphone gave a reading at a lower noise level than did the condenser microphone and the needle of the output meter seemed to follow more closely feeble intermittent sounds that were barely audible. It was thought that a part of this difference in performance may have been ascribable to a different weighting network in this meter. Laboratory precision apparatus was not available, but as nearly as could be determined with a beat frequency oscillator and a "photophone" loud speaker, the over-all weighted response of the 2 meters was practically the same at all frequencies. The more plausible explanation, therefore, seems to be that the inherent residual noise of the moving coil microphone is less than that of the condenser microphone, and this, if true, is probably ascribable to its greater sensitivity and consequent less need of amplification. In general the agreement between the noise meters was within 1 or 2 decibels for several different motors, a vacuum cleaner, and an electric drill, provided the microphones were not nearer than 1 foot to the source of noise.

A most serious objection to this moving coil microphone, however, was its sensitivity to stray magnetic fields. With the microphone as far as 2 inches away from a motor, the stray fields of which were negligible from the standpoint of motor performance, the stray fields caused the microphone to indicate 15

to 20 decibels too high, an obviously intolerable error. If the moving coil microphone can be shielded successfully from stray magnetic fields without affecting its acoustic properties, it might be very successful for this application.

The Weighting Network. The high noise levels observed with the condenser and crystal types of microphones might have been charged to an improper weighting network for measuring low intensity sounds. The fact that the crystal microphone weighted out the low frequency tones more than did the condenser microphone, but had approximately the same noise level as the latter, and also the fact that the meter with the moving coil microphone apparently had about the same weighting network as the meter with the condenser microphone, would appear to rule out this deduction.

Choice of a suitable weighting network is an important problem. The ideal sought is to select the one that gives, for the largest number of motors, a response most nearly approaching the loudness level that would be determined by the average of a large number of observers by direct aural comparison with a 1,000 cycle reference tone. One way of deciding upon such a network would be to take an acoustic spectrum and select that contour that was most closely approached by the largest number of components of the spectrum.

Efficiency Tests of Induction Machines

Several different types of tests for the efficiency of induction machines are discussed in this paper, and results obtained by the different methods are compared. The procedure involved in making the different types of tests is given in detail. In the determination of losses, special attention is given to the stray load loss, which, in most previous tests, has not been considered.

By
C. C. LEADER
Membership Application Pending

F. D. PHILLIPS
ASSOCIATE A.I.E.E.

Both of General Elec. Co., Schenectady, N. Y.

THE determination of efficiencies for induction machines has been a debated subject in the A.I.E.E. since its organization. Papers (see references at end of this paper) have been presented and discussed from time to time, but the Institute has not considered the measurement of stray load loss of sufficient importance, or the means available for their measurement sufficiently accurate, to warrant the inclusion of these losses in the calculation of efficiencies. Thus the rules of the Institute have for many years read as follows:

9–301. Methods of Determining Efficiency Recognized.* The following methods of determining efficiency are recognized as standard:

(*a*) Directly Measured Efficiency: The efficiency is obtained from simultaneous measurements of input and output.

(*b*) Conventional Efficiency: The efficiency is obtained from the component losses, most of which are accurately determinable and the remainder of which are assigned conventional values; or all of the losses may be determined by conventional methods of test. The efficiency determined in this way is the ratio of the output to the output plus the losses, or of the input minus the losses to the input.

* In other than small machines determinations of efficiencies by (*a*) are impractical unless resort is made to expensive measurements.
The use of the conventional efficiency is recommended. Most of the losses are accurately measurable. Those to which conventional values are assigned are so closely approximated that the percentage of error in the determined efficiency is small. The high efficiency generally attained in electrical machines renders an error in the measurement or estimation of one or more of the losses of much less effect on the efficiency as obtained by the conventional method than would an error of like magnitude in the measurement of the total input or output.

9–308. Losses to Be Considered. Conventional efficiencies shall be based upon the following losses:

(*a*) I^2R losses in windings (See 9–310)

(*b*) Friction, windage, and core losses, including brush friction (when present). (See 9–311)

(*c*) Brush contact loss. (See 9–312)

(*d*) Stray load losses. (See 9–313)

(*e*) Miscellaneous losses. (See 9–314)

9–313. Stray Load Losses.* In induction machines no allowance for stray load losses shall be included.

* Stray load losses are inconsiderable in machines of modern design having primary conductors of small section. If the primary windings contain conductors more than $^3/_8$ inch in depth in a 60 cycle machine, eddy current losses may be appreciable. See A.I.E.E. TRANSACTIONS, volume 32, 1913, pages 423–37.

At the time this note was written, the only element of the stray load losses in an induction machine that was well understood was the eddy current loss in the armature copper, but for some time it has been realized that this component is small compared to the increased iron loss under load. The great improvement in the efficiency of pumps and other mechanical equipment in recent years has created a demand for higher and more accurate induction motor efficiency values, and, therefore, committees of the National Electrical Manufacturers' Association and the A.I.E.E. have for some time been conducting investigations to develop an improved technique.

This paper is written to present the results of a series of comparative efficiency tests by different

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 22–25, 1935. Manuscript submitted Oct. 15, 1934; released for publication Oct. 30, 1934. *Not published in pamphlet form.*

methods on induction machines made with the specific purpose of demonstrating the improved technique of testing mentioned.

Nature of the Stray Load Loss

Although the existence of stray load losses has been recognized, the equipment, instruments, and especially the technique necessary to determine these losses have not been sufficiently accurate until the last few years. There are now available the results of the researches of a number of engineers, and the development of new methods of accurate measurement of these losses, which are zero at no load but increase with the load.

The stray load loss is defined as the difference between the actual total power losses under load conditions and the sum of the load I^2R and the no load losses. The elements of the stray load loss (see "Power Losses in Induction Machines," by P. M. Narbutovskih, Electrical Engineering, volume 53, Nov. 1934, p. 1,466–71) may be classified as follows:

a. Changed core loss and high frequency rotor I^2R loss due to changed magnetic fields.

b. Increased eddy losses in conductors.

c. Increased eddy losses in structural parts.

Item *a* is the only important factor in moderate sized motors in common use.

Methods of Measuring Efficiency

Five methods have been proposed for the measurement of efficiencies:

a. By accurate dynamometers especially designed for this purpose.

b. By loading one machine on a directly coupled duplicate machine, accurately measuring the electrical input and electrical output. This pump back test can also be made on duplicate machines connected by belts, but the difficulty of determining the belt loss makes the directly coupled method preferable.

c. By separately measuring the various losses and adding them to the output to obtain the input or subtracting them from the input to obtain the output.

d. By loading on a calibrated load machine.

e. By the calorimetric method of measuring the heat carried away by the cooling medium.

Methods *d* and *e* will not be considered further in this discussion due to their special character.

Table I—Dynamometer Test

	Test Reading	Corrected Readings
Watts input	610	610.5 × (40 × 0.997)
Pounds torque	76	76.35
Rpm slip	21.3	21.3
Frequency	60	59.90
Amperes	3.63	3.63 × (30 × 0.997)
Volts	220	220
Input running light coupled		1,288
Input running light uncoupled		684
Actual load supplied by dynamometer running light		604 watts
Actual scale reading running light, 1.79 pounds =		534 watts
Dynamometer error		70 watts
Motor output = $\frac{76.35 \text{ pounds} \times 1.75 \text{ feet} \times 1{,}178.7 \text{ rpm}}{7.04}$ + 70 =		22,440.6
Total input = 610.5 × (40 × 0.997)		= 24,346.7
Total losses		1,906.1
Meter losses		21.5
Motor losses		1,884.6
Efficiency		92.25%
Horsepower		30.08
Segregation of Losses		
Core loss	465	
Windage and friction	125	
Stator I^2R (W_1)	630	
Rotor I^2R (W_2)	410	
Total known losses	1,630	
Stray load losses = 1,884.6 − 1,630 = 254.6		

Table II—Proposed Dynamometer Test

	Test Reading	Corrected
Input (motor)	612	617 × (40 × 0.997)
Output (generator)	520	522.5 × (40 × 0.997)
Total losses	92	93.5 × (40 × 0.997)
Volts	220	220
Amperes (motor)	3.65	3.65 × (30 × 0.997)
Amperes (generator)	3.27	3.27 × (30 × 0.997
Slip (motor)	1.83%	
Slip (generator)	1.54%	
Total measured losses = 93.5 × (40 × 0.997) =	3,729	
Meter losses =	43	
2 × (dynamometer error) =	140	
Total motor and generator losses	3,546	
Segregation of Losses	Motor	Generator
Core loss	465	465
Windage and friction	125	125
Stator I^2R (W_1)	640	515
Rotor I^2R (W_2)	431	338
Total known losses	1,661	1,443 = 3,104
Total measured losses	3,546	
Total known losses	3,104	
Total motor and generator load loss	442	
Motor load loss	248	
Motor known loss	1,661	
Motor total losses	1,909	
Efficiency	92.25	
Horsepower	30.4	

Procedure Followed in Making Tests

For purposes of comparison, motors rated 30 horsepower, 1,200 rpm, 3 phase, 60 cycles, 220 volts, were selected and were tested in succession by methods *a*, *b*, and *c*.

Method (*a*). For method *a* the dynamometer was rated 100 horsepower, 1,050 to 3,500 rpm. The dynamometer pull was measured by means of a standard lever and weight system scale connected to a lever arm of 1.75 feet. The motor was directly coupled to the dynamometer and loaded to 30 horsepower at rated voltage and frequency. When temperature conditions became constant, readings were taken of watts input, slip in revolutions per minute, pounds torque as indicated on dynamometer scale, frequency, volts, and amperes. In order to obtain the amount of load supplied by the dynamometer but not indicated on the scale—sometimes referred to as the dynamometer error—readings were made of the following:

1. Dynamometer scale and watts input to the motor with the dynamometer armature and field open.

2. Watts input to motor uncoupled from the dynamometer.

With no dynamometer error the scale reading converted to watts would exactly equal the difference in input readings noted under 1 and 2.

All the meters, instrument transformers, and dynamometer scale used in making the above observations were then checked against laboratory standards to determine correction factors. The results are indicated in table I.

Table III—Pump Back Test (Coupled)

	Test Reading (Avg. 2 Directions)	Corrected
Input	613 × (40 × 0.997)	24,446
Output	523.6 × (40 × 0.997)	20,881
Total losses	89.4 × (40 × 0.997)	3,565
Motor slip	1.83%	1.83%
Generator slip	1.54%	1.54%
Motor amperes	3.65 × (20 × 0.997)	72.8
Generator amperes	3.28 × (20 × 0.997)	65.4
Motor resistance, hot	0.08	0.08
Generator resistance, hot	0.08	0.08

Segregation of Losses

	Motor	Generator
Core loss	465	465
Windage and friction	135	125
Stator I^2R (W_1)	640	515
Rotor I^2R (W_2)	428	338
Total known losses	1,658	1,443 = 3,101
Total measured losses	= 3,565	
Meter losses	43	
Total motor and generator losses	3,522	
Total known losses	3,101	
Total stray load loss	421	
Motor stray load loss	235*	
Motor known losses	1,658	
Motor total losses	1,893	
Efficiency	92.25	
Horsepower	20.2	

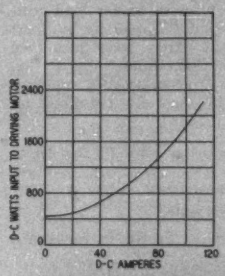
$$* \frac{W_2 \text{ Motor} \times \text{Total Stray Load Loss}}{W_2 \text{ Motor} + W_2 \text{ generator}}$$

Modification of Method (*a*). The above procedure conforms to the proposed "Test Code for Polyphase Induction Machines" of the A.I.E.E. For reasons which will be made obvious in the discussion given later in the paper, the following procedure is recommended for the dynamometer test:

At conditions of constant temperature rise and desired horsepower output, make readings of watts input, voltage, current, slip, and speed. Then without disturbing the setting of dynamometer scale, and holding constant speed and voltage, reduce the frequency of the motor power supply until the dynamometer scale again becomes balanced, and read watts output, amperes, and slip. Determine dynamometer error as outlined above. Results of this method are given in table II.

Method (*b*). For method *b*, 2 exactly duplicate motors were coupled together. The machine run as a motor was excited with rated voltage and frequency, and the generator at rated voltage and a frequency sufficiently below rated frequency to give full load input to the motor. When constant temperature conditions were reached, readings were made of watts input and output, motor and generator amperes, and slip. These readings were then repeated with the power flow reversed—that is, the machine that was first a motor became a generator and *vice versa*. The machines were then shut down and hot resistance readings taken. Finally, an excitation curve was taken on each motor coupled to the other. See table III for results obtained with this method.

Method (*c*). For method *c* the motor was directly coupled to a small d-c motor rated 8.5 horsepower, 14.5 amperes, 230 volts, 600/1800 rpm. (See table IV.) Two lines of the stator winding were excited with d-c and the motor driven at synchronous speed. Readings were taken of driving motor armature volts and amperes, holding constant field current, for values of d-c excitation from zero to 150 per cent equivalent, full load a-c current. (See figure 1.)



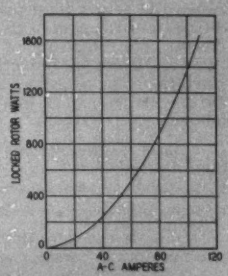


Fig. 1 (left). D-c rotational watts input to the driving motor used in the direct measurement of losses in an induction motor

Fig. 2 (right). Locked rotor synchronous watts as determined in the method of direct measurement of losses in an induction motor

To determine the 60 cycle rotor loss, starting torque was measured over these current ranges. (See figure 2.)

A comparison of the results obtained in other tests conducted by methods *a*, *b*, and *c* is given in table V.

General Discussion

Method (*a*). The dynamometer method has usually been considered the most convenient for machines of about 100 horsepower or less where suitable dynamometers and instruments have been available. It has been favored by many users because only one machine to be tested is necessary as well as a single source of controlled power, and a minimum of measuring instruments. It also gives the most directly calculated measurement of efficiency. However, there are a number of details involved in power measurement that are not generally appreciated. To begin with, a wattmeter connected *directly* in a power circuit will read the power consumed by either its voltage or current coil (depending upon the method of connection) in addition to the power it is desired to meter. A General Electric type P_2 polyphase wattmeter voltage coil at 220 volts consumes

about 7 watts, so that in the common hook-up for measuring power there will be at least 21 watts instrument losses. If current and potential transformers are used, the wattmeters will read the losses on *one* set of these also. When instrument transformers are used, calibrations must be available for both ratio and phase angle displacement. All of these points must be considered in addition to the calibration of the wattmeter scale itself. Furthermore, the accuracy to which an instrument can be read is dependent upon the scale deflection, the steadiness of the needle, and the ability of the observer to read what the instrument indicates. This last point is quite important, for it is not uncommon to find observers who consistently read instruments higher or lower than their true indicated values.

The measurement of mechanical power is equally difficult. There are 2 measurements, torque and speed, each bearing directly on the power. The pounds pull exerted by the dynamometer is usually measured by means of either a spring or link scale, the pull being exerted through a lever arm of definite length. In conjunction with the calibration of the scale, the dynamometer sensitivity is important. This is the amount of weight required to give a readable deflection of the dynamometer scale; that is, the weight required to overcome the static friction of the trunnion bearings. Dynamometers (see "Modern Equipment for the Precise Testing of Motors," by A. A. Emmerling, *General Electric Review*, volume 37, Oct. 1934, p. 471–6) may be equipped with a mechanism which continually oscillates the intermediate races of specially designed trunnion bearings, which has the effect of increasing the sensitivity about 50 times. The recommended method of determining speed involves the measurement of both frequency and slip. Slip may be measured quite accurately and easily by means of a differential slip meter. Frequency, however, must be determined to less than 0.1 per cent, requiring at least a specially calibrated device capable of indicating this closely.

The dynamometer also must be checked for failure of its scale to indicate all the load applied. Finally, readings of input and output must be made simultaneously. The limiting features of this method are: (1) the number of readings, pertaining directly to the efficiency, which must be determined with almost perfect accuracy; (2) the restriction of size and rating of the motors that may be tested on a given dynamometer, and the resulting large investment in dynamometers necessary if the method is to be given wide use.

Modification of Method (*a*). The modified procedure suggested for conducting the dynamometer test overcomes most of these objections. Although the same accuracy is required of the instruments measuring electrical power, by reversing the power flow certain of the contributing sources of error may be eliminated. If the observer tends to read an instrument high, his observations will be high for both motor and generator readings, thereby minimizing the error in the difference. Similarly, if a current or potential transformer ratio is in error, both the input and output readings will be high or low by the same percentage. Exact frequency measurement is not necessary as neither the input nor output is a direct function of speed. Variations up to about one per cent in frequency have little effect on efficiency. There are only 2 measurements bearing directly on the efficiency.

The only measurement of mechanical power necessary is in the determination of the "dynamometer error." The difference between the watts input and output by this method will be the losses of the machine as a motor and generator plus 2 times the dynamometer error:

Motor input − motor losses = dynamometer scale + dynamometer error

Generator output + generator losses = dynamometer scale − dynamometer error

Input − output = losses (motor + generator) + 2 × (dynamometer error)

Since the dynamometer error is always a very small percentage of the total power, inaccuracies in determining the mechanical power used in finding this error will produce little effect on the results obtained by this method.

There may be a minor source of error in the segregation of losses. From investigation of numerous tests, it has been shown conclusively that the stray load loss is a direct function of the load current squared, or slip loss; so it is reasonable to assume that this holds between motoring and generating action.

It has long been felt that, when a dynamometer test is made on a motor, it is very desirable to make a check test as a generator, in order to check the measurement of mechanical power against electrical power. This proposed procedure provides for that test, while at the same time reducing the effect of error in the measurement of mechanical power to one of the second order magnitude.

Method (*b*). The procedure for the directly coupled pump back test is analogous to the proposed dynamometer test, so that the pump back test has all the advantages thus noted. It does not have any limitation as to size or rating, however, as exactly duplicate machines must be available. It should be noted that the pump back method does not give the efficiency for one machine, but rather the average of 2 machines running as a motor. A major point in favor of testing by this method is the minimum amount of investment in testing equip-

Table IV—Direct Method

Full load current = 73 amperes.....Running light current = 23.2 amperes
Equivalent direct current:
Full load = 1.225 × 73 = 89.3
Running light = 1.225 × 23.2 = 28.4
Net d-c watts:
Full load = 1,540 − 440 = 1,100 } figure 1
Running light = 540 − 440 = 100 }
Load loss + rotor I^2R = 1,000
Rotor I^2R:
Full load = 740 } figure 2
Running light = 74* }
666
Stray load loss = 1,000 − 666 = 334

* Since the value of torque on figure 2 at running light current is inaccurate, the value for this point is obtained by multiplying the torque for full load current by the ratio $(I_{RL}/I_{FL})^2$.

Table V—Comparison of Results of Other Tests by the 3 Methods

Motor	HP	Speed	Type	Full Load Efficiency by Method (a)	(b)	(c)
A	10	1,200	S.C.	84.6	84.6	
B	10	1,200	S.C.	87.2	87.3	
C	10	1,200	S.C.	82.3	82.4	
D	30	1,200	W.R.		88.1	88.1
E	50	1,800	S.C.	91.9		91.7
F	25	1,200	S.C.	89.73		89.7
G	125	1,200	W.R.		92.7	93.1
H	15	1,200	S.C.	89		88.35
I	15	1,200	S.C.	86.07		86.2
J	50	1,800	W.R.	89.3		88.3

Note: S.C. = squirrel cage
W.R. = wound rotor

ment since, in most cases, adequate sources of power and instruments are available.

Method (c). The d-c method presents the one advantage that it may be applied to any single motor irrespective of size or rating. The d-c rotational watts may be determined accurately by the method outlined. In the case of squirrel cage machines, however, the determination of rotor I^2R loss presents a rather difficult problem, especially if the motor bearings have high static friction. In this case, it may be necessary to measure the starting torque at current values considerably higher than normal. There should be no limit to the value at which this may be taken other than heating. On some machines, if the rotor heating is excessive the value of starting torque watts may be considerably higher than those existing in the machine under the d-c test. As there is no absolutely positive way to determine when these losses are the same for the 2 conditions, the decision must be left solely to judgment. Tests indicate that errors resulting from heating may be considerably less than those arising from the situations in which the static friction torque is equal to or greater than the losses to be measured.

The d-c method similates load conditions in so far as they affect stray load loss without actually producing full load torque on the shaft. In the case of wound rotor induction motors, the test is a parallel of the synchronous motor short-circuit test, which has long been approved as a standard.

General Recommendations

The results of tests as given in this paper, and the information obtained from a large number of other tests made during the past few years indicate that first 2 of the test methods considered give the same results, if proper equipment is available, and due care is taken in testing, calibration, and calculation. It is concluded that both methods are satisfactory for use in the standards for determining efficiency guarantees. Which method is to be preferred, therefore, depends upon the accuracy expected with the available equipment, and the cost of making the test, rather than upon any differences in the inherent accuracy of the method.

For small or moderate sized machines up to about 100 horsepower rating, and particularly when only one machine is available for test, the dynamometer method may be the most convenient and is to be recommended. However, too great stress cannot be laid on the necessity for extreme care in making test readings, calibrations, and calculations; and the desirability of making check generator and motor tests should be remembered.

Where 2 duplicate machines are available, the electrical pump back method is most convenient, and affords greater accuracy with less probability of error than the other methods. Check tests with the power flow reversed are assumed to be a standard procedure in this test. With proper power supply and equipment available, this method is to be preferred to the other methods for all sizes of machines of ratings of above about 10 horsepower.

For single machines of larger sizes, the separate loss method, determining the stray load loss with d-c excitation, is often the only method practical, as large dynamometers are not available, and in unusual cases, adequate power supply may not be obtainable. This method does not exactly duplicate actual load conditions, but tests have shown that results obtained are a measure of the actual stray load loss. In other words, while these values are not exactly the same as those obtained by methods *a* and *b*, they are of the same order of magnitude. There is not enough comparative data available to draw definite conclusions as to its relative accuracy, therefore it should be preferred only when the other methods are not available.

References

1. Note Sur L'Essai Des Moteurs Asychronus, P. Mennier. *L'Eclairage Electrique*, v. 34, 1903, p. 228–31.

2. The Distribution of Magnetic Induction and Hysteresis Loss in Armatures, W. M. Thornton. I.E.E. *Jl.*, v. 37, 1906, p. 125–37.

3. Pole Face Losses, C. A. Adams, A. C. Lanier, C. C. Pope, and C. O. Schooley. A.I.E.E. Trans., v. 28, 1909, p. 1133–56.

4. Induction Motor Load Losses, H. G. Reist and A. E. Averrett. A.I.E.E. Trans., v. 32, 1913, p. 423–8.

5. Stray Losses in Induction Motors, A. M. Dudley. A.I.E.E. Trans., v. 32, 1913, p. 429–34.

6. Notes on Induction Motor Losses, R. W. Davis. A.I.E.E. Trans., v. 32, 1913, p. 435–7.

7. The Unsymmetrical Hysteresis Loop, J. D. Ball. A.I.E.E. Trans., v. 34, 1915, p. 2.693–715.

8. A Method of Separating No-Load Losses in Electrical Machinery, C. J. Fechheimer. A.I.E.E. Trans., v. 39, 1920, p. 291–9.

9. Induction Motor Core Losses, P. L. Alger and R. Hisergian. A.I.E.E. *Jl.*, v. 39, 1920, p. 906–20.

10. Tooth Frequency Iron Losses in Slip Ring Induction Motors, D. B. Hosseson. *The Electrician*, v. 91, 1923, p. 240–2.

11. Tooth Pulsation in Rotating Machinery, T. Spooner. A.I.E.E. Trans., v. 43, 1924, p. 252–61.

12. Surface Iron Losses With Reference to Laminated Materials, T. Spooner and I. F. Kinnard. A.I.E.E. Trans., v. 43, 1924, p. 262–81.

13. Squirrel Cage Induction Motor Core Losses, T. Spooner. A.I.E.E. Trans., v. 44, 1925, p. 155–63.

14. No-Load Copper Eddy-Current Losses, T. Spooner. A.I.E.E. Trans., v. 45, 1926, p. 231–9.

15. Induction Motors and Induction Machines in General, A.I.E.E. Standard No. 9, 1927.

16. Measurement of Stray Load Loss in Polyphase Induction Motors, C. J. Koch. A.I.E.E. Trans., v. 51, 1932, p. 756–63.

17. Determination of the Additional Losses in Three-Phase Asynchronous Motors, H. E. Lincks. *Archiv fur Elektrotechnik*, v. 23, 1929, p. 19–39.

18. Stray Load Loss Test on Induction Machines, T. H. Morgan and P. M. Narbutovskih. Elec. Engg., v. 53, Feb. 1934, p. 386–90.

19. Modern Equipment for the Precise Testing of Motors, A. A. Emmerling. *Gen. Elec. Rev.*, v. 37, 1934, p. 471–6.

Multiple Lightning Strokes

Multiple lightning strokes have long been known to exist, but so far instruments for recording the successive discharges on electric power lines have not been available. The application of expulsion protective gaps to 3 typical transmission lines, however, has made a partial investigation possible, with the aid of the automatic oscillograph. The results of this investigation are presented herewith. As many as 12 successive discharges have been recorded in a single stroke; these discharges have been as close together as 1 cycle (on a 60 cycle system) and as far apart as 9.5 cycles.

By
K. B. McEACHRON
MEMBER A.I.E.E.

General Electric Co.
Pittsfield, Mass.

LIGHTNING itself still remains the major unknown in the problem of protecting electric power lines from lightning. Sufficient information is available to make what are believed to be reasonable assumptions, but the wave shapes of lightning itself, magnitudes, and frequency of occurrence of each form still are unknown. The existence of multiple strokes has long been known, but no record of their occurrence has been obtained from the instruments in use during the lightning investigations of recent years.

The operation of expulsion protective gaps on 3 typical transmission lines, together with oscillographic means of registering the follow currents over a period of approximately 1 second have shown about 20 per cent of the lightning strokes on 2 of the lines to consist of successive discharges. The maximum number recorded was 12, occurring in about $^2/_3$ of a second. The effect of successive discharges on insulation, gaps, and protective apparatus must be determined before the importance of the multiple stroke can be evaluated.

Data obtained on these 3 lines show that successive discharges may occur as close together as 1 cycle of a 60-cycle system, and as far apart as 9.5 cycles. Additional data no doubt will extend these values. The data show also that many more expulsion gaps flashed over when the conductor was positive than when negative. It is suggested that the power frequency potential plays an important rôle in determining which conductor will be flashed. Tests simulating a direct stroke to a tower show that the polarity of the line conductor exhibits a marked effect on which conductor is to flash over. If the lightning is severe enough, of course, all conductors will flash.

Full text of a paper recommended for publication by the A.I.E.E. committee on transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

Review of Previous Work

Much progress has been made in recent years in the determination of the effects of lightning on transmission lines and apparatus. Field studies[1,2,3,4,5] have yielded much information concerning the magnitude of voltages appearing on transmission lines, and the frequency of their occurrence. The propagation of impulses over lines[6,7,8,9] has been studied by the use of the portable cathode ray oscillograph and impulse generator. From these studies, coupled with other field tests with natural lightning, the decrease in crest potential and change in wave shape with travel now are known reasonably well. Calculations[10] now may be made with confidence concerning the effect of various terminal impedances on the shape of traveling waves of known shape.

Field tests[11] have been made with applied impulses showing the effect of lightning arresters under various conditions, both on high potential circuits and on low potential distribution circuits. The necessity of adequately grounding transmission line towers to prevent insulator flashover when a tower or ground wire is struck has been recognized, and field[12,13] tests have been made to determine the effect of various factors entering into this problem. The foregoing is but a very brief résumé of some of the accomplishments of recent years; but, it is clear to one who has followed technical literature on this subject that the major variable, still largely unknown, is the lightning discharge itself. Once the characteristics of lightning are known, including voltage, current, and time relations, and frequency of occurrence, it will be possible to put the problem of protection from lightning on a better basis than is now possible.

Field investigations have been conducted during recent years, having as their object the determination of the wave shape of the potential of the lightning discharge. Data on wave shape were obtained through the use of cathode ray oscillographs coupled to transmission lines. These have yielded valuable information but in only one instance[14] reported in the United States was the lightning discharge close to the oscillograph. In every other instance the discharge traveled for considerable distances over the line wires, suffering changes in magnitude and wave shape. In addition, the record frequently is complicated by flashovers, which allow unknown amounts of current to pass to the earth. Thus, it can be seen that much still remains to be done, as there is not available a cathode ray oscillogram that shows the form of the lightning discharge itself without accompanying flashover.

Much valuable field work has been done, and is still in progress, having for its object the determina-

tion of currents associated with direct strokes of lightning. Measurements have been made by various means, but probably the most reliable data have been obtained recently through the use of the surge crest ammeter.[8] The results thus obtained will be most helpful, since the data give both magnitude and frequency of occurrence as between storms, if the magnets of the instrument are checked after each storm. No information, however, is obtained concerning the number and magnitude of discharges during a given storm, except that a record is obtained of the maximum current if all the polarities are the same. The magnets do not give any indication of wave shape.

Records Obtained With Rotating Camera

It has been known for many years[16] that many lightning discharges are multiple in character—each succeeding discharge following closely the path of the preceding discharge. As many as 40 discharges in 0.624 second have been recorded by the use of the rotating camera.[16,17]

Recently, Dr. B. F. J. Schonland and H. Collens[18] of South Africa, using a modified Boys camera, have shown that each of the multiple strokes is preceded by a leader stroke that proceeds from the cloud to the earth, to be followed by the main flash building up from the earth to the cloud. The leader, which precedes the first flash, has been called a stepped leader, and appears to travel in the form of a dart toward the earth in a series of steps. The rate of travel is relatively slow, perhaps of the order of $^1/_{10}$ of the speed of the subsequent leaders which apparently travel at about 0.1 to 0.01 of the speed of light. These results have been confirmed in Pittsfield by Lloyd and McMorris.[19] The path of the main flash and subsequent flashes is determined by the stepped leader.

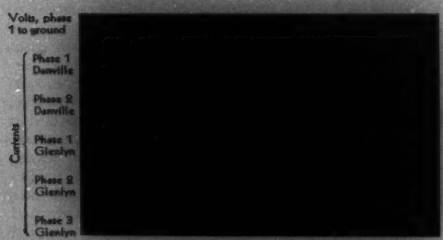


Fig. 1. Typical crater lamp oscillogram taken on the Roanoke-Danville and -Glenlyn (Va.) lines showing operation of expulsion protective gap on successive lightning discharges (first half cycle retouched)

It is important to understand the mechanism of lightning in order that its action may be understood. There seems to be considerable evidence that lightning does not always strike the highest object. In fact, there is evidence to show that steel buildings have been struck part way down the vertical surface, and occasionally steel masts have been struck below the top. Apparently, local ionization may have considerable influence in directing lightning strokes, and it is with this thought in mind that investigators[20] have been trying to determine the relation between sources of ionization on the earth's surface and the location of lightning strokes. The evidence of protection[21] obtained from large numbers of lightning rods indicate that the highest object usually is struck, perhaps 95 or more per cent of the time; but if perfect protection is to be obtained, the Faraday cage must be resorted to rather than depending upon a cone of protection. For many uses the Faraday cage is not practical.

Multiple Strokes

Heretofore, it has not been possible to secure data concerning the existence of multiple strokes on transmission lines. The maximum time scale of the cathode ray oscillograms taken did not exceed 1,000 microseconds, which was much too short to record the multiple stroke, and, so far as the writer is aware, none ever were recorded. The other devices used in the field investigations of natural lightning could not show clearly the presence of multiple strokes.

The application of expulsion gaps to the 132 kv Glenlyn-Roanoke (Va.) and Roanoke-Danville (Va.) lines of the American Gas and Electric Company, and to the Laurinburg-Wilmington (N. C.) 110 kv line of the Carolina Power and Light Company, made a partial investigation of direct strokes possible. Heretofore, when a line flashed over, the follow current to ground obscured the effect of any subsequent multiple flash, and thus no evidence was obtained. However, here was an opportunity to secure some valuable data, since the expulsion gap allows power current to flow for only $^1/_2$ cycle, and a subsequent multiple flash occurring at a greater time interval than $^1/_2$ cycle would leave a record of its existence on the ordinary automatic magnetic oscillograph. Fortunately, automatic oscillographs were available to indicate fault current on each system.

However, the record would be incomplete without the first half cycle, and since most of the discharges might be single and not multiple strokes, it became apparent that means must be found to record the first half cycle of fault current. This was accomplished at Roanoke through the use of the crater lamp oscillograph[22] built especially for this use. With this oscillograph, the film is kept running continuously during the lightning storm, the light source being a crater lamp which is initiated in about 20 microseconds through "thyratron" control ("thyratron" is a trade name of the General Electric Company and indicates a 3-electrode gas- or mercury-vapor filled electronic tube). In many cases, it is possible with this equipment to get a "kick" on the oscillograph vibrator due to the transient before follow current starts. The oscillograph was connected, as described in a paper by Sporn and Gross (scheduled for publication in the January 1935 issue)

so as to read fault current in phases 1 and 2 of the Roanoke-Danville line, and in all 3 phases of the number 1 circuit of the Roanoke-Glenlyn line. The sixth vibrator was used to record potential to ground of phase 1 at Roanoke. The automatic type *PM*-13 oscillograph at Glenlyn recorded the fault currents in both circuits of the line to Roanoke. The Roanoke-Glenlyn line is a double circuit line, number 1 circuit being equipped with expulsion protective gaps.

On the Laurinburg-Wilmington line the automatic type *PM*-13 oscillograph was installed at Laurinburg. With this oscillograph, the 110 kv expulsion protective gaps do not leave any record of follow current during normal operation, unless multiple discharges occur, but in 2 cases records were obtained showing the presence of multiple discharges. The data obtained have been included with that from Roanoke, but is identified in each case.

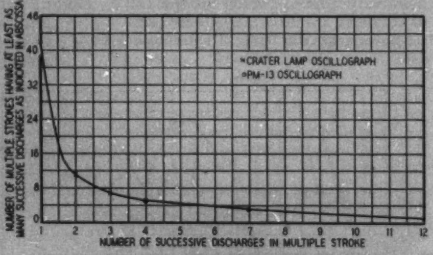


Fig. 2. Number of successive discharges in multiple lightning strokes

Data taken with type PM-13 oscillograph from Carolina Power and Light Company system

Record 73 from the Roanoke-Danville line, showing successive discharges, is reproduced in figure 1. This record from the crater lamp oscillograph shows the first tube operation.

Frequency of Occurrence

Out of a total of 39 recorded strokes obtained on the crater lamp oscillograph at Roanoke (counting multiple strokes as one) 8 or 20 per cent were multiple. These data were obtained from 123 miles of line. On the Carolina system, the total number of strokes is unknown, since only automatic oscillograph records are available. However, on this system 2 records were obtained from 92¼ miles of line.

There seems to be a definite tendency for some storms to produce more multiple strokes than others. For instance, the records at Roanoke show that on the first 10 days during which strokes occurred a total of 16 strokes was recorded during the time from June 11 to July 19, but none of these were multiple although 5 occurred on one day. However, on July 21 a storm beginning at 3:06 p.m. and continuing for 5 hours yielded 4 multiple strokes and 2 single strokes. Of these 4, 2 consisted of 2 successive discharges each, 1 of 4, and 1 of 3 discharges. Four days later a 2 hour storm beginning at 3:12 p.m. delivered to the lines under observation 9 single strokes, 1 of 2, and 1 of 3 successive discharges. Three single strokes were recorded during the storm of July 26, while on July 28 only 2 strokes were recorded, both multiple, 1 consisting of 2, and the other of 7 successive discharges. Nearly a month later, on August 24, the next and last record was obtained, being a single stroke.

Thus, in a total of 15 days on which expulsion gaps functioned due to lightning, multiple strokes were measured on only 3 days, but during these 3 days, 8

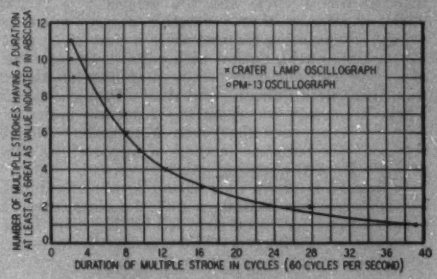


Fig. 3. Total duration of multiple lightning strokes

Data taken with type PM-13 oscillograph from Carolina Power and Light Company system

out of 19 or 42 per cent were multiple. During these 3 days, a total of 36 discharges occurred, of which 25 were successive and 11 were single discharges.

In the foregoing, no effort has been made to include records of direct strokes where follow current through the expulsion gap did not take place. No doubt some of the oscillograph operations were due to lightning discharges that did not cause tube operations. Such records are, however, too uncertain to be included, and therefore the results given may be in error to that degree.

Number and Times of Successive Discharges

Combining all of the data from the 2 systems being studied together, figure 2 shows the relation between the number of successive discharges and the number of times at least that many discharges occurred. Although all of the multiple discharge points are known for the Carolina data, yet the number of single strokes is unknown. Adding these would increase the total number of discharges by an unknown amount. It would not affect the shape of the curve materially. This curve indicates that, as would be expected, the larger the number of successive discharges, the less frequently they occur.

The total time occupied by successive discharge of the multiple strokes is given in figure 3 showing that the longest time was 40 cycles or about ⅔ second.

This compares with 0.624 second obtained photographically by Larsen.

Time Interval Between Successive Discharges

The time interval between successive discharges is important, as it will determine the characteristics protective devices must have to be always in a condition to offer the same protection for successive discharges as for a single stroke. The time interval also will have an important bearing on the strength of insulation, whether solid or otherwise, required for such conditions as compared with the strength required to withstand a single impulse.

The curve in figure 4 shows that the shortest time interval was 1 cycle and the longest $9^1/_2$ cycles. Thus, it appears that protective devices must be capable of restoring themselves in a time of 1 cycle. Tests made on insulation with equal time intervals of 1 cycle represent a frequency of application higher than these data indicate, and thus would lead to an insulation design incorporating a certain factor of safety. It appears that such a procedure would represent the simplest method of approaching this problem from the testing point of view.

In figure 5 is shown the relation between the number of successive discharges and the time interval between them for those recorded having more than 2 successive discharges. There seems to be some tendency for the time interval to become greater

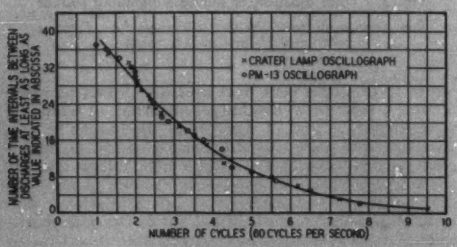


Fig. 4. Time between discharges in multiple lightning strokes

after the second discharge, but there is no well defined relationship, the 2 7 discharge strokes showing a decreasing interval after the fifth discharge. Of course these values are confined to strokes causing operations of the expulsion gap, and may not represent all the multiple strokes, which might have been obtained with a moving film camera.

Effect of Conductor Polarity

On all 3 phases of both circuits there appears to be a definite tendency for expulsion gap operation when the phase potential is positive. Table I shows the results tabulated with respect to polarity. Including all of the successive discharges as separate discharges, follow current began 54 times when one of the phase conductors involved was positive, and 22 times when one of the conductors involved was negative; 7 times the potential was substantially zero. The data show that follow current occurred 32 times with conductors of positive polarity only involved, and 4 times with conductors of negative polarity only involved. This is without respect to whether the conductor is the top, middle, or bottom conductor.

It is suggested that the reason for the expulsion gap operation when the conductor is positive, may well be accounted for largely when it is remembered that the records show most direct strokes to be negative; therefore, the flashover potential of the conductor having the highest positive potential will be reached first, assuming that lightning strikes the tower or ground wire. If after this flashover, sufficient potential still remains, other conductors will flash over, the most positive one tending to flash first. This tendency would be greatest at maximum positive potential, which for the 132 kv circuits out of Roanoke would equal 107 kv crest. This value is somewhat greater than 10 per cent of the 1x5 mi-

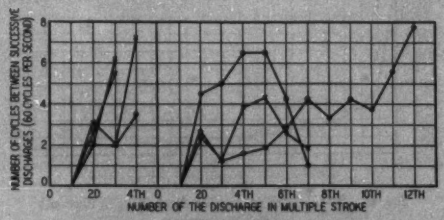


Fig. 5. Time between successive discharges of multiple strokes having 3 or more discharges

Curves on left are for strokes having 3 and 4 successive discharges; those on right are for strokes having 7 and 12 successive discharges
x—crater lamp oscillograph; o—type PM-13 oscillograph

crosecond flashover voltage of the insulator string, and often would be sufficient to determine which phase would flash over. The fact that 7 times as many expulsion gap operations occurred when only positive conductors were involved as when only negative conductors were involved seems to give weight to this suggestion.

Laboratory tests made recently in Pittsfield (Mass.) to simulate a positive conductor and negative stroke to the tower indicate clearly that the foregoing explanation offered is plausible. In making the test, 3 suspension insulators were suspended, the ground end being connected to earth through a resistance of several thousand ohms. A potential of 20 kv from a power transformer was applied between the line conductor and the earth. The circuit was so arranged that a negative impulse could be applied to the ground end of the insulator string at either 90 or 270 degrees with respect to the potential on the line conductor. Without power voltage on the string, the impulse flashover was found to be

Table I—Polarity of Phase Potential When Follow Current Begins

Multiple Strokes to Danville Circuit

Record No.	40	43	49	49	51	57	72	73	Total per Phase	
No. of Discharges	2	2	4	3	2	3	2	7		
Phase 1	− +	0 −	+ + +		+ −	+ +	+	0 0	8 +	3 − 3 zeros
Phase 2	+	+ +	+	+ +	− +	−		+ + +	12 +	3 −
Phase 3				+ +	−	−	+	+ + +	6 +	2 −

Single Strokes to Danville Circuit

Record No.	1	2	4	7	14	30	31	46	50	53	54	55	56	58	59	60	61	67	70			
Phase 1	+	+	+	0	−			+	+	+	+		+	−	−	+	+	−	+	10 +	4 −	1 zero
Phase 2				+	−	+	+	−		+			−	+	−			+		6 +	4 −	
Phase 3								+	−	−		+					−			2 +	3 −	

Single Strokes to Glenlyn Circuit

Record No.	3	8	10	12	13	25	27	28	38	44	62	64			
Phase 1	+			0		0					+		2 +		2 zeros
Phase 2		−			+			0	+	−	+		3 +	2 −	1 zero
Phase 3	+		+		+		+	−			+		3 +	1 −	
Total													54 +	23 −	7 zeros

about 350 kv. With a positive potential on the string, flashover took place with 16 per cent reduction in impulse potential, and with the conductor negative it was necessary to increase the impulse potential 13 per cent. Similar results were obtained with a higher power voltage on the insulator string.

It may be argued that negative lightning would be more likely to strike a conductor when positive than when negative. While this may account for some of the records, it would seem as though with this hypothesis the top conductor should have received a larger share of the discharges than it did. The total number of discharges when the conductor was positive was 20, 21, and 13 for the top, middle, and bottom conductors, respectively. No test data are available to show just how important a factor this effect may be. There is nothing in the data to show conclusively whether the line conductors or ground wire were struck; but, based upon general consideration, one would expect the ground wire to receive the majority of discharges because of its more exposed position.

Summary

1. Multiple strokes occur to transmission lines, and create a series of impulses that may be as close together as 1 cycle or as far apart as 9.5 cycles (on a 60 cycle system). As many as 12 successive discharges were recorded, although photographically 40 discharges have been recorded in a time of 0.624 second.

2. There seems to be a tendency for multiple strokes to be somewhat confined to certain storms, although more data must be obtained before any definite conclusions can be drawn.

3. There seems to be little consistency between multiple strokes as to the time interval between successive discharges.

4. The polarity of the power frequency potential appears to have considerable influence upon determining which conductor flashes to ground. This has been shown experimentally to be expected when lightning of opposite polarity strikes the tower or ground wire. It also may have some influence in determining which line conductor is struck.

5. Since the data obtained show that 20 per cent of the recorded strokes consisted of more than one discharge, the effect of multiple discharges must be considered in any protective scheme. This is true both with regard to the apparatus to be protected and the protective apparatus itself.

6. More data is needed concerning the multiple stroke so that good engineering estimates of its importance and effects can be made. It is expected that this investigation will be continued.

References

1. Lightning Investigation on Transmission Lines—IV, W. W. Lewis and C. M. Foust. Elec. Engg., v. 53, Aug. 1934, p. 1180–6. See also list of references.

2. Lightning Investigation on a 220-Kv System, Edgar Bell. Elec. Engg., v. 53, Aug. 1934, p. 1188–94. See also list of references.

3. Lightning Performance of 132-Kv Lines, Philip Sporn and I. W. Gross. Elec. Engg., v. 53, Aug. 1934, p. 1195–1200. See also list of references.

4. Lightning Discharges and Line Protective Measures, C. L. Fortescue and R. N. Conwell. A.I.E.E. Trans., v. 50, 1931, p. 1090. See also list of references.

5. Surge Crest Ammeter, C. M. Foust & H. P. Kuehni. *G. E. Review*, 1933, p. 644–8.

6. Field Tests on Thyrite Lightning Arresters, K. B. McEachron and R. J. Wade. A.I.E.E. Trans., v. 50, 1931, p. 479.

7. Traveling Waves on Transmission Lines With Artificial Lightning Surges, K. B. McEachron, J. G. Hemstreet, and W. J. Rudge. A.I.E.E. Trans., v. 49, 1930, p. 885. See also list of references.

8. Experimental Studies in the Propogation of Lightning Surges on Transmission Lines, O. Brune and J. R. Eaton. A.I.E.E. Trans., v. 50, 1931, p. 1132. See also list of references.

9. Impulse Tests on Substations, R. N. Southgate, A. S. Brooks, E. R. Whitehead, and W. C. Roman. A.I.E.E. Trans., v. 50, 1931, p. 561. See also list of references.

10. Attentuation and Distortion of Waves, L. V. Bewley. Elec. Engg., v. 52, Dec. 1933, p. 876–84.

11. Lightning Protection for Distribution Transformers, K. B. McEachron and L. Saxon. A.I.E.E. Trans., v. 51, 1932, p. 239.

12. Counterpoises for Transmission Lines, C. L. Fortescue. Elec. Engg., v. 52, Dec. 1933, p. 908–17.

13. Theory and Tests of the Counterpoise, L. V. Bewley. Elec. Engg., v. 53, Aug. 1934, p. 1163–72.

14. Lightning Investigation on the 220 Kv System of the Pennsylvania Power and Light Co., Edgar Bell and A. L. Price. A.I.E.E. Trans., v. 50, 1931, p. 1101.

15. Ueber Blitzphotographien, H. Kayser. Konigl. Akad., Berlin, Berichte, v. 2, 1894, p. 1119.

16. Photographing Lightning With Moving Camera, Alex Larson. Smithsonian Inst. *Annual Report*, 1905, p. 119.

17. Ueber die Entstehungsweise der Blitzes, B. Walter. *Annalen der Physik*, v. 10, 1903, p. 393.

18. Progressive Lightning, B. F. J. Schonland and H. Collens. *Proc.* of the Royal Society, Series A, v. 143, p. 654.

19. New England Lightning Checks African Studies, K. B. McEachron. *Elec. World*, July 7, 1934, p. 15.

20. Influence of the Geological Constitution of the Ground at Spots Where Lightning Strikes, Damiate and Bonget. *R.G.E.*, v. 34, No. 1, p. 27.

21. Lightning—Its Origin and Control, George F. Lewis, Deputy Fire Marshal of Ontario. Presented 15th Annual Convention of Fire Marshals Association of North America, New York, N. Y., Dec. 8, 9, and 10, 1920.

22. Crater Lamp Oscillograph, W. A. McMorris, M. A. Rusher, and J. H. Hagenguth. *G. E. Review*, Nov. 1934, p. 514.

Impulse and 60 Cycle Strength of Air

The effect that the shape of electrodes has on the dielectric strength of air when subjected to impulse and 60 cycle voltage waves is considered in this paper. Principal attention is given to rod and plate electrodes and to sphere and plate electrodes, comparative data on the different types being given. Among other factors, the effect of polarity on breakdown voltage is brought out. These data on strength of air between various electrode shapes are correlated into working principles and presented from the standpoint of the design engineer interested in their application.

By
P. L. BELLASCHI
MEMBER A.I.E.E.

W. L. TEAGUE
ASSOCIATE A.I.E.E.

Both of
Westinghouse Elec. and
Mfg. Co., Sharon, Pa.

AIR is universally used in high voltage engineering, such as for the insulation of transmission lines, substation structures, coördination and protective apparatus, bushings, and in fact even for the insulation of complete electrical apparatus. Hence the paramount importance of air as a dielectric is manifest; this accounts for the many endeavors in the past to establish the strength of air on a reliable basis. The inconsistencies and variations between the results of various investigators is another reason for the repeated efforts in the past to obtain reliable data on the strength of air. The following considerations account for the incomplete reliability of a great deal of the past data for application to design work in high voltage engineering: First, the technique of voltage testing[1,2,3] and measurement[4–7], particularly with impulses, had not been established on a reliable and practical basis until in recent years. Second, the effect of such factors as air density, pressure, humidity, etc., on the strength of air to impulse[8,9] and 60 cycle[10–12] voltages have been formulated lately to a degree of accuracy that better comparison of data obtained in various laboratories is now possible.

Many investigators have studied the strength of air,[13–19] particularly from a fundamental standpoint.[13–16] Some of the published data is limited to relatively short gaps. Of these data, a great deal is difficult to interpret and consequently to apply to design, simply because testing conditions, air density (temperature and atmospheric pressure), humidity, etc., are either not fully specified or more often not mentioned at all. Nevertheless some data particularly for 60 cycle strength for wide gap openings is found in the literature which are useful for design application, though the desired detail information of test and atmospheric conditions may be lacking. A systematic effort has been made lately[20–22] to standardize the technique of testing and measurement and to establish reliable correction factors which, all combined, will aid in making published data in the future of greater usefulness.

In the investigation reported here full advantage was taken of the latest technique in testing and measurement, as well as in the application of correction factors wherever it was deemed essential to refer the experimental data to unity air density (25 degrees centigrade temperature and 760 millimeters barometric pressure) and standard humidity (6.5 grains per cubic foot). Impulse and 60 cycle voltages ranging up to 2,000 kv have been investigated as these comprise the voltages which are commonly encountered in present everyday practice. Thus data on strength of air between various electrode shapes and arrangements that are of fundamental importance in high voltage engineering are presented in this paper. To render the experimental results more useful, the data are correlated into working principles, thus aiming to show that the

Fig. 1. Rod-to-plate gap

0.5 inch square cut, square rod; 0.25 × 120 × 170 inch plate

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–25, 1935. Manuscript submitted Oct. 18, 1934; released for publication Nov. 1, 1934. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

fundamentals of high voltage engineering are susceptible of being established on a more systematic basis.

The results of this investigation are therefore presented from the standpoint of the design engineer whose particular concern is the immediate application of working principles to the economical development of electrical apparatus which must perform according to required characteristics. However, the writers realize that the data on the strength of air now made available offer great opportunities for studies on the mechanism of breakdown in gases to account for, explain, and, if possible, even to formulate the phenomena observed. Such a study is, however, beyond the practical realm of the present paper.

The first part of this paper deals with the impulse and 60 cycle strength of air for rod and plate electrodes whereas in the second part the impulse and

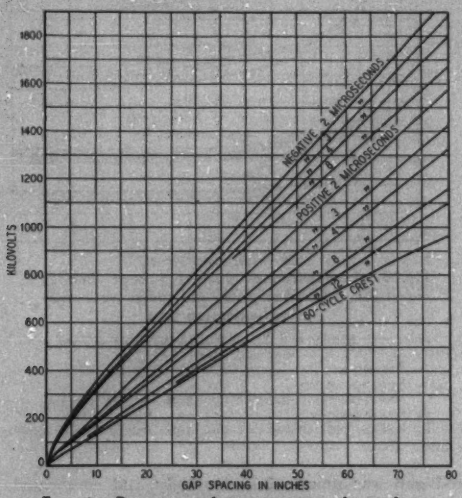


Fig. 2. Positive and negative impulse voltage characteristics of rod-to-plate gap

Relative air density = 1.00, absolute humidity = 6.5 grains per cubic foot

60 cycle strength of air between sphere and plate electrodes is given. The following conclusions summarize the pertinent facts on the strength of air as affected by shapes of electrodes.

Conclusions

1. The effect of polarity on the impulse flashover of air gaps corresponds in amount to the degree of departure from symmetry in the arrangement and shape of the electrodes. The flashover voltage is lowest when the positive polarity is applied to the electrode where the electric field is most intense and highest when the negative polarity is applied to that electrode.

The quantitative amount of the polarity effect on the impulse flashover of rod and plate electrodes in various arrangements is given in tables I and II and figures 5 and 6.

For the sphere-to-plate gap at spacings greater than 3 diameters the electric field becomes dissymmetrical to a degree which results in essentially the same negative and positive impulse flashover as for an equal spacing of the rod-to-plate gap.

2. The transition in the impulse voltage characteristics from a dissymmetrical to a symmetrical gap, whether the electric field is relatively uniform or not uniform, is rather abrupt particularly for the negative polarity. This transition is markedly evident for the

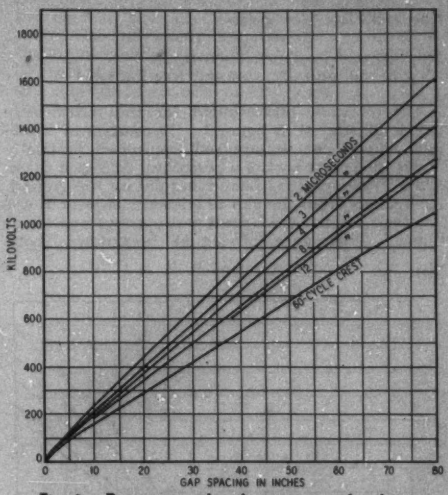


Fig. 3. Positive impulse characteristics of rod gap

Relative air density = 1.00, absolute humidity = 6.5 grains per cubic foot

sphere-to-plate gap as the spacing is increased above 2 diameters (figure 13) and also for the rod-to-plate-with-rod-extension gap (figures 5 and 6).

3. In contrast with the polarity effect where the negative impulse flashover exceeds the positive flashover as is the case for dissymetrical gaps with the field concentrated at one electrode, the negative impulse flashover for relatively uniform fields is less than the positive flashover voltage. This effect is revealed in the case of the sphere-to-sphere gap in figure 14, and also for the sphere-to-plate gap in figure 13 in which case the positive and negative curves actually cross at $^3/_4$ diameter spacing where the dissymmetry becomes sufficiently pronounced.

4. For the electrode shapes and arrangements having substantial dissymmetry, as stated in conclusion 1, the 60 cycle flashover voltage is less by a relatively small amount than the positive impulse minimum flashover voltage. This indicates, as confirmed also by other observations and tests, that 60 cycle flashover occurs on the positive polarity of the wave.

For the electrode arrangement where the electric field departs only slightly from uniform, as stated in conclusion 3, the 60 cycle and negative impulse flashover voltage are practically identical.

5. The presence of corona and streamer formation which precedes breakdown with the electrode shapes and arrangements having substantial dissymmetry also tends to modify and alter the effective physical electrode shape, particularly at 60 cycles, in which case corona persists diffusely for a considerable time before actual

sparkover occurs. The effects associated with corona and streamers are complex and introduce complicating factors in the phenomena of breakdown. An example of this corona effect is found in figures 9 and 10 where, at the wider spacings the flashover for the rod-to-plate gap is greater than that of the sphere-to-plate gap.

6. The 60 cycle flashover voltage of a sphere-to-plate gap bears a definite relationship to the rod-to-plate flashover voltage which for practical purposes may be expressed quantitatively. Thus from table III, the ratio of the flashover voltages for the 2 types of gaps at a given spacing expressed in sphere diameters is practically a constant for the various sizes of spheres and therefore may be plotted as a single characteristic curve.

Rod and Plate Electrodes

Description of Test, Technique of Measurement, Correction Factors

The electrode arrangement for the rod-to-plate gap is illustrated in figure 1. It consists of a 0.5-inch square cut, square rod suspended vertically above the center part of a horizontal 0.25 inch thick, 120 by 170 inch steel plate lying flat on the ground. A clearance from the gap to adjacent objects of not less than 4 times the largest gap opening was maintained. Observance of actual breakdown, both

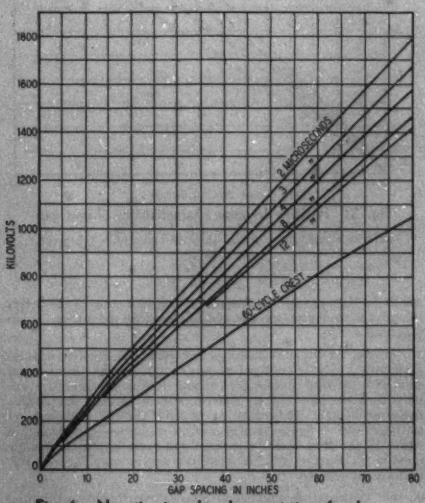


Fig. 4. Negative impulse characteristics of rod gap

Relative air density = 1.00; absolute humidity = 6.5 grains per cubic foot

with 60 cycle and impulse voltages, indicated consistent flashover from the rod to the center of the plate, thus confirming that a condition of a true rod-to-plate gap existed. This fact was strikingly shown as any material reduction in the plate dimensions for the wider gap openings would be evidenced by a flashover between the rod to a corner of the plate, particularly with negative impulses.

The rod-to-plate gap with rod extension above the plate was exactly the same as illustrated in figure 1 except that in addition a segment of the rod of the desired length was set at the center of the plate extending vertically toward the suspended rod. The

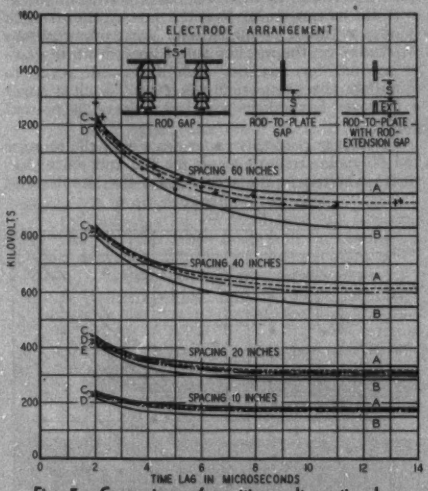


Fig. 5. Comparison of positive voltage time-lag curves for rod, rod-to-plate, and rod-to-plate-with-rod-extension gaps

Relative air density = 1.00; absolute humidity = 6.5 grains per cubic foot

A. Rod gap
B. Rod-to-plate gap
C. Rod-to-plate-with-rod-extension gap; ext. = 40% S
D. Rod-to-plate-with-rod-extension gap; ext. = 20% S
E. Rod-to-plate-with-rod-extension gap; ext. = 10% S

rod gap was mounted horizontally and conformed closely in its arrangement to the prescribed requirements for the coördination gap.[9,10] A clearance of more than 4 times the largest gap length was maintained from these gaps to surrounding objects. The 3 gap arrangements are shown in figure 5.

The impulse tests were made with a standard 1.5-40 microsecond wave. The data were analyzed according to the established methods, the voltage being measured at the crest and the time lag scaled on the oscillogram from the point on the front of the wave corresponding to the 60 cycle flashover voltage to the point of flashover on the tail. The test data were obtained under atmospheric conditions which departed usually less than 3 per cent from unity relative air density (25 degrees centigrade and 760 millimeters mercury) and varied from standard humidity (6.5 grains per cubic foot) on the average less than 3 grains. In order to compare all the data for one

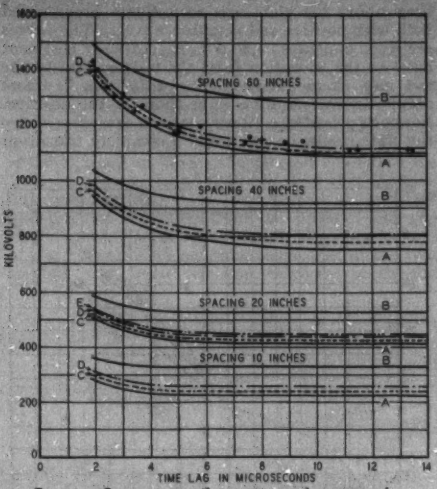


Fig. 6. Comparison of negative voltage time-lag curves for rod, rod-to-plate, and rod-to-plate-with-rod-extension gaps. (See figure 5 for gap arrangement)

Relative air density = 1.00; absolute humidity = 6.5 grains per cubic foot

A. Rod gap
B. Rod-to-plate gap
C. Rod-to-plate-with-rod-extension gap; ext. = 40% S
D. Rod-to-plate-with-rod-extension gap; ext. = 20% S
E. Rod-to-plate-with-rod-extension gap; ext. = 10% S

electrode arrangement on a common basis of unity air density and standard humidity, corrections were applied. For air density a correction inversely proportional to the relative air density was applied. The correction used for humidity for the various time lags was in accordance with the most recent data.[8–9]

The 60 cycle tests were made with a 1,000-kv 500-kva testing transformer having for engineering purposes a good sinusoidal wave form. The 60 cycle voltage was measured with the sphere spark gap as a reference standard using the most recent calibration.[5] The humidity correction factor applied for the 60 cycle voltage was 3 per cent per grain per cubic foot. This is the best correction factor now available based upon past tests, though observations of the experimental data obtained in the tests reported here indicate the possibility of further refinements in the correction factor applicable for the various electrode arrangements.

In general the air density and humidity correction factors applied to the experimental data counteract each other so that the effective correction is on the average 2 to 3 per cent and seldom more than 5 per cent. The interesting fact observed was that both the impulse and 60 cycle data, even when corrected by present methods to a common basis for comparison, could be reproduced on the average within 2 to 3 per cent and seldom would repeated check tests give curves departing as much as 5 per cent from previously established curves. Thus it is evident, though the corrections applied for atmospheric conditions may not be perfect, that the data presented here can be reproduced with sufficiently good engineering accuracy. As a matter of fact, however, more difficulty was experienced in checking 60 cycle data than for the case of impulse data, probably due to the correction factors.

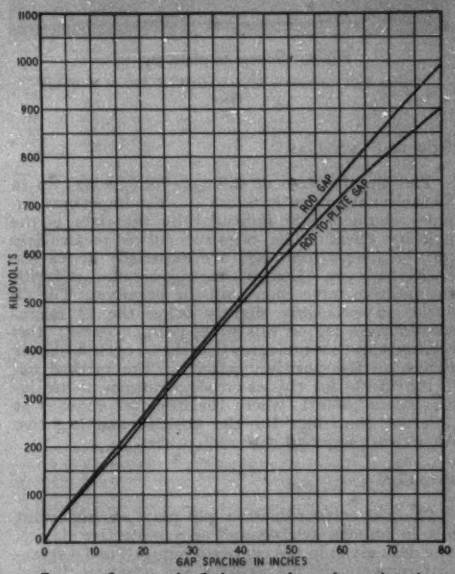


Fig. 7. Sixty cycle flashover voltage for rod and rod-to-plate gaps

Relative air density = 1.00; absolute humidity for rod gap curve = 3.0 to 3.7 grains per cubic foot and for rod-to-plate gap curve = 4.3 to 4.4 grains per cubic foot

Table I—Comparison of Positive and Negative Impulse Flashover Voltage for Rod-to-Plate Gaps

Gap Spacing Inches	Ratio of Negative to Positive Flashover Voltages for Various Time Lags				
	2 μsec	3 μsec	4 μsec	8 μsec	Full Wave*
10	1.67	1.79	1.90		2.18
20	1.42	1.52	1.59		1.86
40	1.29	1.37	1.44	1.58	1.68
60	1.25	1.33	1.38	1.40	1.54
80	1.25	1.32	1.35	1.44	1.48

* The voltage corresponding to full wave is only slightly less than that for the longest time lag as shown in the curves.

Fig. 8. Sphere-to-plate gap

Standard 25 centimeter sphere; 0.25 × 120 × 170 inch plate

Rod-to-Plate Gap

The impulse data of this gap for spacings up to 80 inches are given in figure 2. The important impulse characteristic indicated by the data is the polarity effect. The negative curves particularly for the longer time lags are materially above the positive curves. Longer time lags are observed with the positive wave than with the negative. The 60 cycle curve is only slightly below the 12 microsecond time lag or full wave positive curve; this relationship thus indicates that the 60 cycle flashover occurs on the positive polarity. The marked polarity effects for this electrode arrangement are indicated in table I, where the flashover voltages at different time lags for the positive and negative waves are compared with each other.

Rod Gap

The rod or coördination gap plays an important rôle in impulse testing and as a protective device. The data given in the curves of figures 3 and 4 represent respectively the positive and negative characteristics of the rod gap. Since the rod gap approaches a symmetrical arrangement it, therefore, is not affected by polarity effects as much as the rod-to-plate gap. It is enlightening to compare the relative flashover voltages for the rod-to-plate and the rod gaps. This comparison is made in table II.

Rod-to-Plate Gap With Rod Extension Above Plate

The data in table II thus infer that a transition region exists between the charactersitics of the rod-to-plate and of the rod electrode arrangements. A rod-to-plate gap with various degrees of rod extensions above the plate was accordingly investigated both with positive and negative waves. The curves are given in figures 5 and 6 and reveal very pertinent data on the transition from the rod-to-plate to the rod gap characteristics. The transition is more abrupt for the negative wave than for the positive. For both polarities a 20 per cent rod extension above the plate results in practically a complete transition

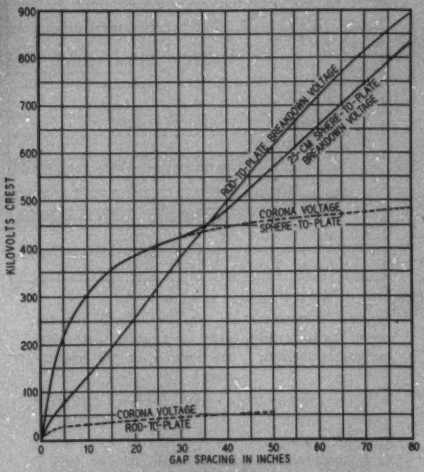


Fig. 9. Sixty cycle flashover and corona voltages for 25 centimeter sphere-to-plate and rod-to-plate gaps

Relative air density = 1.00; absolute humidity for sphere-to-plate gap data = 2.5 grains per cubic foot and for rod-to-plate gap data = 4.3 to 4.4 grains per cubic foot

from rod-to-plate to rod gap characteristics. The curves plotted in figures 5 and 6 for various amounts of extension are average data. The actual points, as illustrated for a few of the curves, are quite scattered and indicate a rather erratic performance in the transition from one gap to the other. For either the rod gap or the rod-to-plate gap the actual points (not shown) depart only a few per cent and seldom more than 5 per cent from the average curves indicated. The observations of flashover during the test are of practical interest as these have a bearing on the interpretation of the actual data. In the case of the positive wave a small rod extension above the plate resulted in a flashover from the suspended rod partly to the rod extension and partly to the plate, whereas for the negative wave, flashover occurred consistently between the suspended rod and the rod extension above the plate.

With 60 cycle voltage there is no great difference in flashover voltage between the rod and the rod-to-plate gaps; this can be seen from figure 7. In both cases breakdown is preceded by diffuse corona

discharge as is expected due to the low corona level of both gaps. The small departure of each curve from the corresponding positive impulse flashover for long time lag indicates 60 cycle flashover is associated with positive polarity. Due to the small difference between the 2 curves it was rather difficult to establish clearly the transition at 60 cycle voltage from the rod-to-plate to the rod gap. At 80 inch spacing, however, where the difference between the 2 curves is appreciable, the tests show that for various extensions above the plate there is a consistent and uniform transition from the curve of one gap to the other. At this spacing, the flashover voltage of the rod gap is 10 per cent above that of the rod-to-plate gap. A 10 per cent extension of the rod

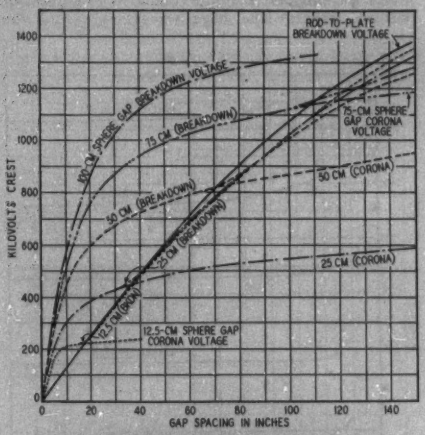


Fig. 10. Sixty cycle flashover and corona voltages for 12.5, 25, 50, 75, and 100 centimeter sphere-to-plate gaps and flashover voltage for rod-to-plate gap

For source of data see reference 17 at end of paper

above the plate increases the flashover, above that of the rod-to-plate gap, 3 per cent; a 20 per cent extension increases the flashover 5 per cent; and a 40 per cent extension, 7.5 per cent.

Sphere and Plate Electrodes

Description of Test, Technique of Measurement, Correction Factors

The electrode arrangement for the sphere-to-plate gap is illustrated in figure 8. The sphere electrode consists of a 25 centimeter standard sphere attached to a vertical, 2 inch rod, and the plate electrode is the same as described in connection with figure 1. The same measures were taken as in all previous tests to keep surrounding objects well removed from the gap. It was observed that even at the widest gap opening, flashover occurred consistently from the sphere to the center of the plate.

Data was obtained following exactly the same technique of testing and measurement as described previously for rod and plate electrodes.

For the sphere-to-plate electrodes the data are corrected to the common basis of unity relative air density; i. e., the correction factor applied is inversely proportional to the relative air density. It was deemed best not to apply any correction for humidity but rather to give the actual absolute humidity for

Table II—Comparison of Impulse Flashover Voltages for Rod-to-Plate and Rod Gaps

Gap Spacing Inches	Flashover Strength in Per Cent of Positive Rod-Gap Flashover							
	Positive Polarity				Negative Polarity			
	Rod Gap		Rod-to-Plate Gap		Rod Gap		Rod-to-Plate Gap	
	2 μSec	Full Wave*	2 μSec	Full Wave*	2 μSec	Full Wave*	2 μSec	Full Wave*
10	100	100	91	83	117	127	150	178
20	100	100	94	84	114	124	132	158
40	100	100	95	86	111	117	124	144
60	100	100	95	87	110	114	130	134
80	100	100	97	88	111	114	121	131
Average	100	100	94	86	113	119	129	149

*The voltage corresponding to full wave is only slightly less than that for the longest time lag as shown in curves.

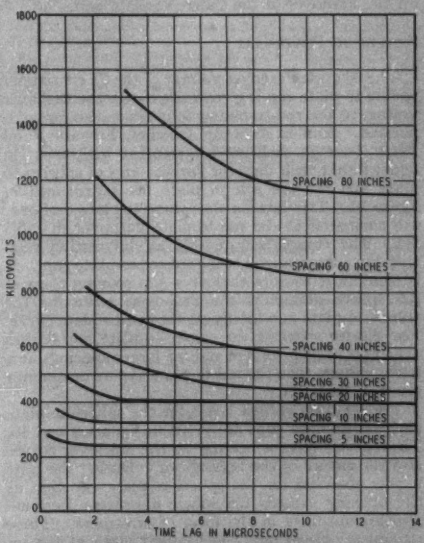


Fig. 11. Positive voltage time-lag curves for 25 centimeter sphere-to-plate gap

Relative air density = 1.00; absolute humidity in grains per cubic foot as follows: 80 inch spacing, 8.3; 60 inch, 8.1; 40 inch, 7.1; 30 inch, 7.1; 20 inch, 6.3; 10 inch, 4.2; 5 inch, 4.4

the data. The atmospheric conditions departed, however, only slightly from standard: the air density was not greater than 2 per cent and the humidity was seldom more than 2 grains per cubic foot from standard. Previous investigations on the sphere spark gap[1-7] have shown that for relatively short

Table III—Comparison of 60 Cycle Flashover Voltage of Sphere-to-Plate and Rod-to-Plate Gaps

Spacing in Sphere Diameters	Ratio of Sphere-to-Plate Flashover Voltage to Rod-to-Plate Flashover Voltage for Equal Spacings				
	12.5 cm Sphere	25 cm Sphere	50 cm Sphere	75 cm Sphere	100 cm Sphere
0.5		310	344	340	340
1	250	242	240	231	230
2	170	150	147	144	142
3	116	113	110	111	110
3.5	102	102	101	103	102
4	97	96	97	98	
5	97	94	94	98	
7.5	97	94	94		
10	97	95			
15	96	96			
20	95				
30	98				

gap spacings humidity has no effect on sparkover; it is only therefore for the wide spacings, where breakdown is preceded by streamer formation or corona, that humidity would be expected to have any effect on the flashover of the sphere-to-plate gap.

Sphere-to-Plate Gap

The 60 cycle flashover voltage of the 25 centimeter sphere-to-plate gap is given in figure 9; the flashover voltage of the rod-to-plate gap is given also for comparison. Similar data by Goodlet, Edwards, and Perry,[17] are in such good agreement with those in figure 9 that their data for various sizes of spheres to plate and for the rod to plate are reproduced in figure 10. The data for the sphere-to-plate flashover are compared to the rod-to-plate flashover in table III. The comparison reveals an interesting relationship characteristic of the sphere-to-plate gap. It is significant to note that at a gap spacing close to 3.6 sphere diameters the flashover curve for the sphere-to-plate gap intersects the rod-to-plate curve. For shorter spacings the sphere-to-plate gap flashes over at a higher voltage and for larger spacings at a lower voltage than the rod-to-plate gap by an amount given in table III.

The 60 cycle corona levels for the sphere-to-plate and rod-to-plate gaps are given in figures 9 and 10. These levels have a bearing on the flashover curves and the nature of the breakdown. During the tests it was observed for the sphere-to-plate gap that as the opening exceeds 3.6 sphere diameters "corona" appears abruptly in the form of streamers. These streamers extend out 2 inches and more at the instant they first appear and increase in length as the gap spacing is further increased above the critical value. This sudden streamer formation on the sphere-to-plate gap is rather contrasting when compared to the corona glow gradually increasing into diffuse corona and streamers which precede flashover of the rod-to-plate electrode.

The impulse characteristics of the sphere-to-plate gap are given in figures 11 and 12. Each curve is based upon 10 or more actual points which deviate individually less than 2 per cent in general from the average curve drawn; only a few points in all the experimental data depart as much as 5 per cent. It should be noted that for spacings up to one sphere diameter the voltage-time lag curves are flat down to 1 or 2 microseconds; thus, these curves are similar to corresponding curves for the sphere-to-sphere gap.[7] For the larger gap spacings the curves assume more and more the same form as for the rod-to-plate gap. Another pertinent characteristic is that the voltage-time lag curves for the negative waves are substantially flat compared to curves for positive waves. The negative values exceed the

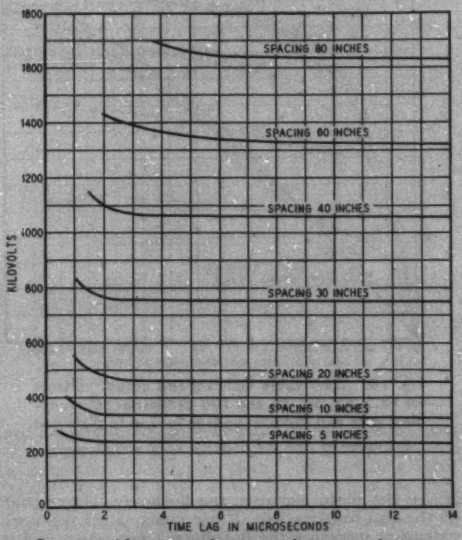


Fig. 12. Negative voltage time-lag curves for 25 centimeter sphere-to-plate gap

Relative air density = 1.00; absolute humidity in grains per cubic foot as follows: 80 inch spacing, 7.9; 60 inch, 7.4; 40 inch, 6.8; 30 inch, 6.6; 20 inch, 6.5; 10 inch, 3.1; 5 inch, 3.4

positive for spacings greater than one diameter over the range of time lags investigated.

A comparison of the 60 cycle and the full wave impulse flashover curves for the sphere-to-plate gap is shown in figure 13. For spacings $^3/_4$ diameter and less the positive impulse curves are above the negative, whereas the negative and 60 cycle are practically identical, thus indicating a similar character-

istic as for the sphere-to-sphere gap,[6-7] an example of which is shown in figure 14. The negative and positive curves cross each other at a spacing about $^3/_4$ sphere diameter and beyond this the negative curve exceeds the positive a greater and greater amount with wider gap spacings. The polarity effects become strikingly evident between 2 to 3 sphere diameter spacings, yet in this transition region the data could be reproduced and checked within an accuracy of 2 per cent from the average.

It was indicated in conjunction with figure 9 that above 3 diameter spacings the 60 cycle flashover curve for the sphere-to-plate gap is nearly the same as the rod-to-plate curve. This characteristic is again revealed in figure 13 where beyond the transition region near 3 diameters the positive and negative impulse curves are practically identical with the corresponding curves for the rod-to-plate gap in figure 2. Furthermore, the 60 cycle curve in figure 13 is relatively close to the positive impulse curve as compared to the negative. All these observations

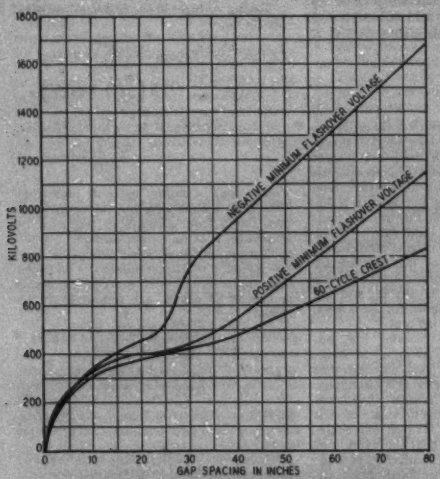


Fig. 13. Positive and negative impulse, and 60 cycle flashover voltage for 25 centimeter sphere-to-plate gap

Relative air density = 1.00; absolute humidity as per figures 9, 11, and 12

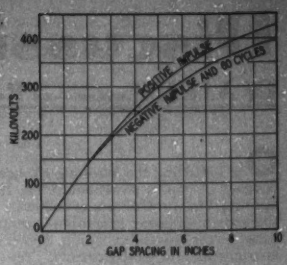
thus show in a simple and general way the similarity of the characteristics of the sphere-to-plate gap as compared to the rod-to-plate gap.

Sphere-to-Sphere Gap

This type of gap is particularly important as a reference standard for voltage measurement where its use is limited to spacings below one diameter.

Fig. 14. Positive and negative impulse, and 60 cycle flashover voltage for 25 centimeter sphere-to-sphere standard spark gap

Relative air density = 1.00



Comprehensive investigations of its 60 cycle and impulse characteristics have been published during the past year.[6-7] The impulse characteristics of the sphere spark gap to very short impulse waves are given in a recent publication.[7] Figure 14 gives the impulse and 60 cycle flashover voltage of the 25 centimeter sphere gap up to one diameter spacing; these curves are typical of the characteristics of sphere gaps of other sizes.

References

1. Characteristics of Surge Generators for Transformer Testing P. L. Bellaschi. A.I.E.E. Trans., v. 51, 1932, p. 938–45.

2. Calculating Surge-Generator Waves, F. H. McAuley and F. R. Benedict. *Elec. Jl.*, v. 30, Aug. 1933, p. 326–8.

3. Impulse Generator Circuit Formulas, J. L. Thomson. Elec. Engg., v. 53, Jan. 1934, p. 169–76.

4. The Measurement of High Surge Voltages, P. L. Bellaschi. A.I.E.E. Trans., v. 52, 1933, p. 544–52.

5. Impulse Calibration of Sphere Gaps, P. L. Bellaschi and P. H. McAuley. *Elec. Jl.*, v. 31, June 1934, p. 228–32.

6. Sphere Gap Calibrations, J. R. Meador. Elec. Engg., v. 53, June 1934, p. 942–8.

7. The Sphere Gap as a Voltage Standard—Its Usefulness and Limitations, P. L. Bellaschi. Scheduled for publication in *Elec. Wld*.

8. Influence of Humidity on Surge Flashover, F. D. Fielder. *Elec. Jl.*, v. 29, July 1932, p. 348–9.

9. High-Voltage Surge Tests on Standard Air Gaps, F. D. Fielder. *Elec. Jl.*, v. 29, Oct. 1932, p. 459–61.

10. Coördination of Insulation, V. M. Montsinger, W. L. Lloyd, and J. E. Clem. A.I.E.E. Trans., v. 52, June 1933, p. 417–27.

11. Influenza dell' Umidita dell'Aria sulla Tensione Critica degli Isolatori, E. Alessandri. *L'Elettrotecnica*, Aug. 5, 1934.

12. Humidity Data on 60-Cycles, Trafford and Sharon Laboratories. (Not Published.)

13. High-Voltage Insulation, J. L. R. Hayden and C. P. Steinmetz. A.I.E.E. Trans., v. 42, 1923, p. 1029–41.

14. Untersuchungen über den elektrischen Durchschlag und Überschlag in unhomogenen Felde, E. Marx. *Arch. für Elektrotechnik*, v. 19–20, 1928, p. 589–606.

15. The Influence of Polarity on High-Voltage Discharges, F. O. McMillan and E. C. Starr. A.I.E.E. Trans., v. 50, 1931, p. 23–32.

16. Surge Impulse Breakdown of Air, J. J. Torok. A.I.E.E. Trans., v. 47, 1928, p. 349–55.

17. Dielectric Phenomena at High Voltages, B. L. Goodlet, F. S. Edwards, F. R. Perry. Instn. of E.E. *Jl.*, v. 69, June 1931, p. 695–727.

18. Sphere-Gap and Point-Gap Arc-Over Voltage as Determined by Direct Measurement, J. S. Carroll and B. Cozzens. A.I.E.E. Trans., v. 48, 1929, p. 1–10.

19. Dielectric Phenomena in High Voltage Engineering, F. W. Peek, Jr. Chap. V. (A book.)

20. Progress Report on Impulse Testing of Commercial Transformers, F. J. Vogel and V. M. Montsinger. A.I.E.E. Trans., v. 52, 1933, p. 409–10.

21. Recommendations for Impulse Voltage Testing, Lightning and Insulator Subcommittee. A.I.E.E. Trans., v. 52, 1933, p. 466–71.

22. Flashover Voltages of Insulators and Gaps, Lightning and Insulator Subcommittee. Elec. Engg., v. 53, June 1934, p. 883–6.

Discussions

Of A.I.E.E. Papers—as Recommended for Publication by Technical Committees

ON THIS and the following 15 pages appear all remaining unpublished discussions of papers presented at the 1934 A.I.E.E. summer convention, Hot Springs, Va., June 25–29, as follows: (1) all papers except one presented at the session on power generation (complete discussion on one paper was published in the November issue); and (2) all papers presented at the session on instruments and measurements. All discussions of the foregoing papers received in complete and acceptable form at Institute headquarters, and subsequently reviewed and recommended for publication by A.I.E.E. technical committees, are included. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

Members anywhere are encouraged to submit written discussion of any paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions of papers scheduled for presentation at an A.I.E.E. meeting or convention will be closed 2 weeks after presentation. Discussions should be (1) concise; (2) restricted to the subject of the paper or papers under consideration; and (3) typewritten and submitted in triplicate to C. S. Rich, secretary, technical program committee, A.I.E.E. headquarters, 33 West 39th Street, New York, N. Y.

A 7,000-Ampere Station Bus

Discussion and authors' closure of a paper by H. L. Unland, W. B. Morton, and V. R. Bacon published in the June 1934 issue, and presented for oral discussion at the power generation session of the summer convention, Hot Springs, Va., June 29, 1934.

F. R. Dallye: The authors of the paper which has just been presented are to be commended for presenting data in practical form on a subject as timely as this one. Channel conductors for heavy currents were introduced by the Aluminum Company of America in 1929 after the erection of a complete blooming and structural mill for rolling strong alloy structural shapes. This permitted the fabrication of high purity aluminum channels in lengths up to 90 ft. The first large installation of these channel conductors was in the company's own plate mill at Alcoa, Tenn., where 2 parallel 3-phase circuits, 1,600 ft long, distribute 440-volt power to various mill motor, electric furnace, and lighting loads.

In the development of this new use for structural channels a variety of current rating tests were conducted on several sizes. These were carried out in a complete enclosure 35 ft long, having a cross section of about 6 by 7 ft, to accommodate the 30-ft length of conductors under test. This allowed circulation of air around the buses but prevented drafts.

One important finding is believed to be of general interest, namely, that the amount of space between the flanges of 2 channels forming a phase conductor materially affects the current rating. One experiment employed 8-in. channels having a web thickness of 0.395 in. and a total cross sectional area of 9.56 sq. in. for the 2 channels. It was found that with the flanges butted together, in effect forming a rectangular tube, 3,800 amp caused an average temperature rise of 30 deg C. With a $^1/_4$-in. space between flanges the current was increased 15 per cent, and with a $^3/_4$-in. space 30 per cent for the same temperature rise. When channels of this size are assembled in the usual square formation this space between flanges is $3^1/_4$ in. and the corresponding current for 30 deg rise is 5,800 or an increase of over 50 per cent.

A striking example showing the advantageous distribution of metal in structural channel sections was demonstrated when $3^1/_2$-in. extra heavy IPS (iron pipe standard) aluminum tubular bus was tested along with a conductor made up of 2 4-in. channels having 0.247 inch web thickness. It will be noted that the width and height of both of these conductors is 4 in. and that their cross sectional areas are exactly the same, 3.68 sq in. A current of 2,000 amp produced a temperature rise of 30 deg C in the tube, which was new and bright. The channels carried 2,960 amp with the same temperature rise. The finish of new rolled channels is not quite as bright as the new tubing, but even well weathered tubing of this size has a rating of only 2,300 amperes in comparison.

H. B. Dwight: The tests made on practical busbars at currents up to 7,000 amp will undoubtedly prove very useful in the design of this type of apparatus. The tests made with 3-phase current of this large amperage are noteworthy.

The shifting of the hottest spot by reversal of the phase rotation, shown in Fig. 3 of the paper, evidently corresponds to the similar behavior of the heating of the sheaths of single-conductor cables with flat spacing, for which a calculation was given by eq 22 in my paper, "Proximity Effect in Cable Sheaths," A.I.E.E. TRANS., September 1931, p. 997. The phenomenon can be illustrated by simple wire circuits shown in Fig. 1 of this discussion.

Let there be 9 long parallel wires as in the figure, the lower pairs forming short-circuited loops. Let R be the resistance per cm in absolute units, and r the radius of the wires in the loops, and let the power currents be

$$I_A = (-0.5 + j\,0.866)I$$
$$I_B = I$$
$$I_C = (-0.5 - j\,0.866)I$$

Taking voltages in the first loop and dividing by $j\,\omega$,

$$I_A \log_e \frac{b^2}{a^2} + I_B \log_e \frac{s^2 + b^2}{s^2 + a^2} + I_C \log_e \frac{4s^2 + b^2}{4s^2 + a^2} + 2I_1\left(\frac{R}{j\omega} + \log_e \frac{c^2}{r^2}\right) + 2I_2 \log_e \frac{s^2 + c^2}{s^2} + 2I_3 \log_e \frac{4s^2 + c^2}{4s^2} = 0 \quad (1)$$

where $\log_e$ denotes natural logarithm. This and 2 equations for the other loops give the 3 loop currents in terms of the amperage, I, of the power current.

Putting $a = 8$ in., $b = 12$ in., $c = 4$ in., $r = 0.5$ in., $s = 5$ in., frequency $= 60$ cycles, and conductivity $= 20$ per cent of that of copper at 20 deg C, the following are obtained:

$$(0.0372 + j\,0.358)I + (8.32 - j\,9.02)I_1 + 0.989\,I_2 + 0.297\,I_3 = 0 \quad (2)$$

$$0.1697\,I + 0.989\,I_1 + (8.32 - j\,9.02)I_2 + 0.989\,I_3 = 0 \quad (3)$$

$$(0.0372 - j\,0.358)I + 0.297\,I_1 + 0.989\,I_2 + (8.32 - j\,9.02)I_3 = 0 \quad (4)$$

Then $|I_1| = 0.0289\,I$, $|I_2| = 0.0141\,I$, and $|I_3| = 0.0306\,I$.

The right hand loop has 6 per cent more current, and 12 per cent more heating, than the left hand loop. If the phase rotation were reversed, the left hand loop would have the larger current.

If a round tube is bent into a square shape, the a-c resistance is increased because, in addition to the crowding of the current toward the outer surface, the current also crowds to some extent toward the corners.

In Fig. 5 of the paper it is shown that the heating of a steel member depends on its resistance and its heat dissipating surface, as well as on its size and its nearness to the current. The value of practical tests is obvious.

The indirect method of measuring the a-c resistance of the large conductors, as described in the paper, is interesting and accurate. The writer has used an alternative

method of obtaining this result. See the test curves of skin-effect resistance ratio in Figs. 4 and 5 in "A-C Conductivity of Iron Pipe," *Electric Journal*, June 1926, p. 297. A curve of watts loss against temperature rise was first determined by direct current, and then the watts loss with alternating current at a certain temperature rise was taken to be the same as the

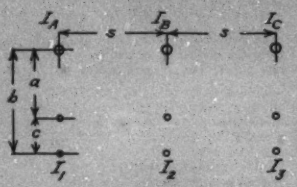


Fig. 1. Arrangement of wires

watts loss with direct current at the same temperature rise.

It may be of interest to state that the curve of temperature rise by free convection for a stationary body, plotted on watts loss as a base, is a curve which bends slightly to the right, as in Figs. 1 and 2 of the article on iron pipe previously mentioned, or as shown by tests on copper conductors. As the temperature increases, the flow of air becomes faster and the watts dissipated become greater in proportion.

H. C. Forbes: Regarding the determination of the a-c resistance of buses, the authors state that "to measure directly the a-c resistance of large conductors of irregular section considerable difficulty and expense would be encountered and even then the accuracy would be subject to question." I agree with that statement, and I would like to call attention to the fact that an indirect method of determining the a-c resistance of rectangular conductors which was described by L. J. Gorman and myself in a paper entitled "Skin Effect in Rectangular Conductors" (A.I.E.E. Trans., June 1933, p. 516) is well suited to the determination of the a-c resistance of conductors such as the authors describe. This method consists of making tests at high frequency on miniature conductors having dimensions proportional to those of the conductor for which the information is desired.

Details of this method are given in the paper to which I have referred. Its application requires some rather special equipment which it is hardly worth while to set up where an investigation of only one conductor is desired. In order to overcome this difficulty I am hopeful that some of our electrical manufacturers or perhaps our universities may see fit to install a permanent outfit in their laboratories so that they would be able to determine the skin effect of any conductor of irregular cross section by making a measurement on a miniature model. I believe that if such a service were available it would be patronized rather extensively by the electrical industry and I make the comment at this time with the thought that it may help to arouse an interest in the matter.

Discussions—
Publication and Correlation

Among the several important features of the unified publication plan put into operation by the Institute beginning with the January 1934 issue of Electrical Engineering were improvements in the method of handling discussions. Among the desired improvements were: (1) reduction in the time delay prevailing between presentation and publication; (2) making discussions accepted for publication available to the entire membership of the Institute; (3) convenient and thorough indexing, and effective correlation.

Prompt Publication. The bulk of the discussion presented at the 1934 winter convention was published in the March and April issues of Electrical Engineering and, under normal circumstances, would have been completed in the May and June issues. However, the development of the 50th anniversary issue in May, together with the necessity for advance publication of technical papers on the programs of the summer and Pacific Coast conventions, required that the publication of further discussion be suspended until September. Recovery from that situation has been steady, however, if slow. With this December issue, the publication of summer convention discussion including closures is completed; discussions and closures from the Pacific Coast convention are scheduled for the January and February 1935 issues. Thus the schedules will be cleared, so that the publication of discussion from the forthcoming winter convention can, with the coöperation of discussors and reviewers, be begun in the March issue and continued on a regular and further improved program.

Complete Circulation. Beginning with its publication in Electrical Engineering, under the unified publication plan, discussion was made available to the entire membership, thereby effectively rounding out the Institute's publication service, and making generally available a greatly increased quantity of important and timely information.

Annual Index. References to discussions will constitute an important part of the hundreds of entries that will appear in the 1934 Annual Reference Index. Particular care has been exercised to carry out a comprehensive system of multiple entries embracing all discussions published during the year. A reference to all discussion (if any) of a paper will be given in this index under *each* of the several (average 5) entries of the subject and title of *each* paper.

The 1934 Annual Reference Index will be issued in January 1935 and mailed without charge to all members or subscribers who request it.

W. M. Hanna: Although the authors made their study to obtain an answer to a specific problem, the test data which they have obtained forms a considerable addition of useful information on heating of magnetic members. The results of the experiments on short-circuiting strips and grids are especially interesting and are of probably the most direct and immediate value to the industry.

The heating of the bus itself has been only touched on, and properly so because it was soon found out that the one consideration of importance was forced convection. It would be interesting to know what air velocities are found necessary to keep the bus cool, and what effect this air has on the temperature of the nearby structural members.

In Figs. 5 and 10 is shown an apparent inconsistency in that the 10-in. beam ran hottest, the 24-in. beam next, and the 20-in. beam coolest. Heating should be directly proportional to some function of the beam dimension parallel to the conductor, and should be inversely proportional to functions of the cross section area and periphery. The principal flux concentration is in the surface next to the conductor. A large cross section provides better heat transfer away from the hot spot and a large periphery provides better heat dissipation. Examination shows that the 20-in. beam is larger in proportion to its depth than the 24-in. beam, and in consideration of the foregoing it is logical that it should be cooler.

Other factors affecting the heating besides dimensions are the permeability, resistivity and roughness of the magnetic material. The authors made comparative tests on silicon and carbon steel beams and found that the difference was negligible. It would be very interesting to see if the values of permeability and resistivity of the 2 beams were very nearly the same.

The variation of test points from the curves as plotted would indicate the effect of such variables as air movement, surface roughness, etc., and data concerning this variation would be very valuable to future investigators.

L. J. Gorman: This paper gives valuable information based on a comprehensive series of tests, particularly in reference to the induced current and consequent heating in metallic structures adjacent to buses carrying large currents. The data given in the paper are a valuable contribution to the knowledge on this subject. I have noted with particular interest the paragraph on skin effect and the test method of determining a-c resistance by means of heating and cooling curves.

In the calculation of a-c resistance, the authors assume that the ratio, thickness to diameter, for a cylindrical conductor could be replaced by the ratio of thickness to the side of the square in the case of the hollow square conductor. Based on the results of tests on solid conductors, published in a paper presented by H. C. Forbes and the writer at the January 1933 A.I.E.E. convention in New York City, it is believed that this assumption will give calculated values of a-c resistance that are from 5 to 10 per cent too low. The tests here referred to showed that the ratio of a-c to d-c

resistance in a solid square conductor is appreciably higher than in a solid round conductor having the same parameter. Although no experimental data were obtained on tubular or hollow square conductors, it is believed that the general relationship between solid, round, and square conductors would hold more or less in the case of tubular and hollow square conductors of the same parameter. In the square structure there seems to be a tendency for alternating current to crowd into the corners, thereby increasing the skin effect. It is believed, therefore, that the test values for a-c resistance given in the paper are more nearly in accordance with the facts than the calculated values would indicate.

Referring to items Nos. 3 and 4 in Table I giving the d-c resistance, and to the test a-c resistance values for the same test bars, it will be noted that the ratio of a-c to d-c resistance is 1.53 in the case of item No. 3 and 1.6 in the case of item No. 4. These ratios correspond very nearly to the a-c to d-c resistance ratios for solid strip conductor having a width and thickness ratio of 8 to 1 and corresponding parameters. This result seems to indicate good design in the hollow square conductors from the standpoint of skin effect and a-c resistance.

The tests reported by Mr. Forbes and the writer were made on miniature buses at high frequencies ranging from 22 to 287 kc. The test results agreed very closely with results obtained at lower frequencies and published by Messrs. Kennelly, Laws, and Pierce. It is believed that the high frequency method of test could be very readily applied to the type of bus discussed in the paper. The heating and cooling method mentioned by the authors is of particular interest in that it requires no special testing equipment.

L. A. Kilgore: The authors of this paper have made a very real contribution to the knowledge of losses and heating in structural steel and other metal parts near a high current bus. Their chief purpose was to solve a practical problem and they have done this very well by experimental set-ups in the laboratory and a check test on the actual structure.

It would seem at first glance that the problems presented here are too complicated for any quantitative theoretical analysis. However, by making use of certain principles which have been used with considerable success in the determination of losses due to stray fields in electrical machines, the writer was able to predict roughly the magnitude of loss and temperature and the behavior of copper bands and amortisseur grids.

Such a method of analysis if carried out very carefully and checked against the existing test data should be useful in extending the results to other special cases, and perhaps to develop some approximate formulas or curves to apply to general cases.

The principles referred to are the use of graphical flux mapping, as described by J. F. Calvert (*Electric Journal*, March to October 1928) and others, to determine the flux and current distribution; and the use of Rosenberg's formula or some of the other formulas for calculating the current and loss produced by the flux traveling in the surface of the adjacent iron parts.

The method of graphical flux mapping may also be used as shown in Fig. 2 of this discussion to determine the actual current distribution in a conductor of the type described. The effective depth of penetration of the flux for 60-cycle flux in copper at 60 deg C as calculated by Steinmetz's formula is 0.256 and for the current the effective depth of penetration is 0.361. In plotting the field the assumption is made that no flux goes deeper than the effective depth of flux penetration shown by the dotted line in Fig. 2.

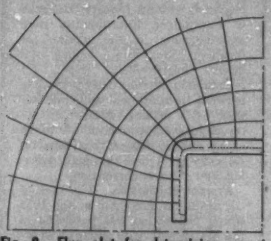


Fig. 2. Flux plot for determining current distribution in 6-in. channel conductors

The loss is calculated for each element of current from the width of the element in the copper and the effective depth of current penetration. This gives a net ratio of a-c to d-c resistance at 60 cycles and 60 deg C of 1.56. The authors' test results indicate a ratio of 1.6. This method may also be applied where the conductors are sufficiently close to affect the current distribution in each other; about the only limitation is that the actual copper be thicker than the effective depth of penetration.

For the case of a single steel beam parallel to current carrying conductors the flux field is 2 dimensional and can be readily plotted for 2 special cases. Figure 3 was plotted on the assumption that the iron has infinite permeability and no damping. Figure 4 was plotted on the assumption that the iron is a perfect damper. These 2 fields permit calculation of the actual flux and loss in the beam. In Fig. 3 the total flux entering the beam is assumed to divide on the 2 sides of the beam in a certain ratio, and the ampere turns for each side calculated. If the ampere turns on each side are not equal, a new division is tried. The distribution of the currents induced in the beam will be approximately the same as that shown in Fig. 4. The ampere turns per inch (H) are calculated as:

$$H = \frac{f}{\rho B_s}\left(\frac{\phi \text{ in.}}{5040}\right)^2$$

where f = frequency, ρ = resistivity (ohms per in. cube), and B_s = saturation density (use 120,000).

The current required to produce a certain flux as determined from Fig. 3 and the current required to balance the induced currents produced by the flux are determined from Fig. 4. These are added at 45 deg phase difference to give the total current in the conductor. This 45 deg phase displacement between flux and current was derived by Steinmetz and has been demonstrated by test.

The loss density W in watts per sq in. may be calculated from the flux per inch (ϕ in.) traveling in the iron surface by Rosenberg's formula:

$$W = \frac{2.4}{\rho B_s}\left(\frac{}{60}\right)^2\left(\frac{\phi \text{ in.}}{10^4}\right)^2$$

In the case of the 24-in. beam, 17 in. from the conductor as shown in Fig. 11 of the paper, the average watts per sq in.

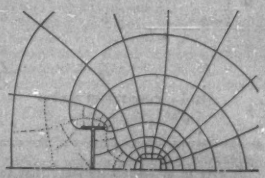


Fig. 3. Flux entering a steel beam parallel to a single conductor, assuming infinite permeability and neglecting damping

were calculated to be 0.27 and 0.15 at 7,000 and 5,000 amp, respectively. This loss density gives a calculated rise of 33 deg and 18.5 deg for the 2 cases, which checks the test value quite well.

The case of beams at right angles to the conductors is somewhat more difficult, since the field is not truly 2 dimensional

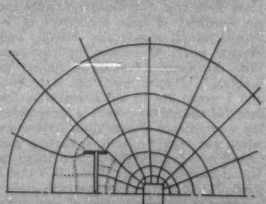


Fig. 4. Flux plot for determining current required to balance induced currents plotted, assuming the steel to be a perfect damper

and some approximate assumptions are necessary. For the case of the 3 phase conductors $5^1/_2$ in. from a 15-in. beam, as shown in Fig. 3 of the paper, the total flux entering the beam was determined by Fig. 5 of this discussion, using an average spacing equal to the distance to the center of the beam.

In order to simplify the flux plotting, the 3-phase current was resolved into 2 components: One flows in on phase A and out on C equal to 0.866 times the maximum phase current, and a second component (equal to the phase current) flowing in on phase B with half returning in phases A and C. These components are 90 deg in time phase. The flux fields assuming infinite permeability are shown for the 2 components on the left and right halves of Fig. 5.

Two flux plots assuming the iron to be a perfect damper were made and the current and loss calculated as before for each component separately. An accurate calculation of the exact loss distribution would require that the resultant current at each point be determined. The average power per unit cube for the 15-ft beam shown in Fig. 3 of the paper was calculated as 0.22 watts per sq in., which gives an average rise of 50 deg C for a beam covered with about 8 in. of concrete. The calculation of the maximum temperature involves the flow of heat along the beam as well as the actual distribution of loss; this is more difficult but not impossible.

The shift in the point of maximum temperature with the reversal of phase rotation as shown in Fig. 3 of the paper can be explained at least qualitatively as follows: If the 3-phase current is resolved into the 2 components of current mentioned above, these 2 components of current are 90 deg in time phase but the currents induced by them in the beam are not 90 deg apart. The first component flowing in the 2 outer conductors produces considerable demagnetizing ampere turns, so that the net current in the beam due to this component lags the total current by something less than 45 deg. The induced currents due to the second component are not very effective in limiting the flux entering the beam, hence the flux is nearly in phase and the induced current about 45 deg out of phase with the conductor current.

If the induced currents lagged the conductor currents by the same angle for each component, the loss distribution would be symmetrical about the center conductor. But with the difference in lag mentioned above, the induced currents due to the 2 components do not add at right angles, hence the resultant current on one side is higher. Since reversing the phase rotation is equivalent to reversing one component, it changes the side on which the resultant current is highest and so produces the observed shift in the maximum temperature.

The authors mention the possibility of currents induced in loops formed by conduit and show how it can be protected from a 3-phase bus by a copper grid. In stations

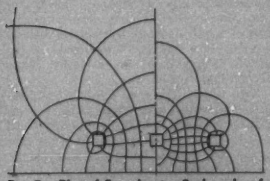


Fig. 5. Plot of flux about a 3-phase bus for 2 components of the current

where the phases are separated on different floors, the structural steel will form similar loops unless the joints are insulated. Calculations made using the principles outlined above show that in such a structure with a 5,000-amp bus about 900 amp flows in the adjacent beams with about 30 deg C rise. It is difficult to protect the beams against this circulating current unless they are insulated. An amortisseur grid to protect the beams would in this case have to carry nearly as much current as the main conductors.

H. W. Paget: The work of Messrs. Unland, Morton, and Bacon reveals the multitude of problems which are encountered in conductor design when the usual current capacities are exceeded. Either the problem of installing a 7,000-amp bus in the space allotted for one of 4,000-amp capacity or that of overcoming magnetic heating difficulties encountered when such highly inductive currents must pass near steel work represents one of large proportions. The fact that extensive investigations of this nature have been made before and yet very little of the information previously obtained was of assistance in solving the particular problems involved in this case, show the necessity that existed for more research work to establish quantitative relations between alternating currents, temperature rise of conductors, and induced heating in steel work.

It is of interest to note that the increase in capacity from an old 4,000-amp bus to a 7,000-amp bus was accomplished with an increase in copper from 27 lb, to only 51.2 lb per ft at the same time that external conditions became decidedly more unfavorable.

Ordinarily in new station design most of the magnetic problems encountered in this installation could be avoided. However, it is only through the experiences as described by the authors on such necessary modifications in existing plants that the necessary precautions can be foreseen and provided.

O. R. Schurig: The authors have presented data on a-c resistance and temperature rise of a compact form of double-channel copper bus carrying up to 7,000 amp, and have contributed new data pertaining to the heating due to currents induced by a-c buses in nearby structural steel members, both bare and embedded in concrete. Earlier researches established certain fundamentals and empirical rules based on tests at currents up to 5,800 amp. (Temperature Rise and Losses in Solid Structural Steel, O. R. Schurig and H. P. Kuehni. A.I.E.E. TRANS., v. 45, 1926, p. 184.) The present authors have not only extended the range of current, but have also presented comprehensive test data on iron heating due to 3-phase circuits, together with data pertaining to the design of copper short-circuit loops and grids for reducing the temperature rise in the steel members.

While the authors were primarily concerned with obtaining design information for a specific installation, their data on heating of steel and on means of preventing excessive temperatures in structural members covered a variety of conditions and will therefore be of value to others facing similar iron heating problems.

The skin effect resistance ratio of the special channel sections of approximately $^1/_2$-in. wall thickness in the double-channel hollow-square arrangement was 1.60 for the 6-in. channels, and 1.52 for the 8-in. channels at 60 cycles (based on data reported in Table I on p. 996 and on p. 998. Tubular conductors of corresponding dimensions would, as the authors point out, have somewhat lower skin effect, but would not necessarily run cooler than the channel structure unless effective internal ventilation were used.

The authors point out that the optimum wall thickness for a copper tubular conductor is approximately $^1/_2$ in., meaning that for a given outside diameter of tube, the one having a wall $^1/_2$-in. thick will have a lower 60-cycle resistance than other tubes of the same outside diameter but having thicker or thinner walls. In other words, the tube with a $^1/_2$-in. wall will carry more current for a given temperature rise than other tubes *of the same outside* diameter. It will be remembered, however, that the amount of copper used in the tube of $^1/_2$-in. wall will carry more current for the same temperature rise if built into a tube of larger diameter with a thinner wall.

If the same consideration is applied to the double-channel conductor it will be concluded that the channel of $^1/_2$-in. thickness does not use the copper as economically in respect to current carrying capacity as a larger channel with a thinner wall employing the same amount of metal. Unless, therefore, space is extremely limited and minimum over-all dimensions of channel structure are required, a channel of less than $^1/_2$-in. thickness will be the more economical in respect to the amount of metal needed to carry a given current at a given temperature rise. The actual thickness of channel to be selected will then be governed by such factors as mechanical strength and stiffness of channel beam structure, rolling limitations, and size and cost of clamps and fittings for supporting the structure.

It would be of interest to know how much the temperature rise of the channel bar structures would be increased due to proximity effect if the phases were in horizontal spacing, say 30 in. apart.

In Fig. 1 the clearance between the 2 channels forming the hollow square is shown as $^3/_8$ in. Did the authors determine how the current carrying capacity is affected by varying the clearance?

The interpretation and analysis of the data on inductive heating presented by the authors would be materially aided if a magnetization curve and resistivity data for the various steel members tested were available.

The temperature distribution curves shown in Figs. 3, 4, and 6 of the paper for various iron members crossing at right angles to a 3-phase circuit show clearly that the steel member has its highest temperature peak opposite one of the outside phases while the temperature opposite the other 2 phases is lower, the difference being as much as 25 per cent. Moreover the maximum temperature in the beam is shifted to the other outside phase when the phase rotation of the current is reversed. Since the explanation of the unsymmetrical heating is not an obvious one, the problem will be briefly discussed.

As a first approximation one might consider the beam replaced by 3 closed secondary loops, one under each of the phases, as in Fig. 6a. The voltages induced by the primary currents in the outside loops will then be found to be equal in magnitude but somewhat larger than that induced in the loop under the middle phase. These voltages would then induce circulating currents of equal magnitude in the 2 outside loops,

though the center loop would carry a smaller current since the average distance between this loop and the return conductors A and C is smaller than that for the outside loops.

It is seen that this analysis is far too rough to give even approximate results since it does not take into account the voltages induced in each of the secondary loops by the circulating currents flowing in the other secondary loops. If, then, calculations of circulating currents are made taking into consideration the voltages induced in the secondary loops by all secondary currents as well as by the currents in the 3 buses, unequal currents will be obtained in the secondary loops under the outside phases.

A complete analysis of eddy current heating in the beam would of course involve considering induced currents in the iron due to both axial and transverse fluxes. Such a study will not be made at this time.

However, attention will be called to a related problem on which test data are available, namely, that of unsymmetrical heating and current flow in balanced 3-phase buses having 2 or more parallel conductors per phase. The multiple bar conductor like the iron beam has secondary short circuit loops linked by fluxes due to the currents in the 3 phases. In the multiple bar conductor the secondary loops are formed by the parallel members of each conductor, as indicated in Fig. 6b.

In the case of 2 members per phase as shown in Fig. 6b, there is a closed secondary loop in each phase, and, unless the plane of the loop is perpendicular to the plane of the conductors, induced circulating currents will flow around the loops. In the figure, for instance, the current induced in any one of the loops such as phase A will be determined by the voltages induced by the phase currents I_B and I_C as well as by the circulating currents in the loops of phases B and C.

The unsymmetrical current division is shown clearly in Fig. 6c based on measurements. It may be seen, for example, that the maximum current in the phase A group is 932 amp or about 13 per cent higher than the largest current in the phase C group, which is 822 amp, although on the basis of symmetry alone equal current components would be expected.

In Fig. 9 of the paper the authors have shown that the maximum temperature rise of a beam crossing a 3-phase circuit is less than that crossing a single conductor with return conductors remote, other things being equal. Likewise, the percentage differences between 3-phase heating and single-phase heating are shown to diminish with reduced spacing between conductors and iron members. The differences in question can be readily accounted for on the basis of the demagnetizing effect of the return conductors, which effect is present in the 3-phase arrangements shown but essentially absent in the single-conductor test with return conductor remote. Moreover, the percentage differences can be numerically estimated by calculating the resultant air field intensities at the center of the iron members and applying the empirical rules given in the 1926 A.I.E.E. paper already referred to.

The data presented by the authors in Figs. 16, 17, and 18 on reduction of inductive heating in various structural members by copper bands and grids indicate the effectiveness of the copper members, if properly applied, for lowering the temperature rise in the iron. The copper bands and grids have to be of sufficiently large section to prevent overheating of the copper bands themselves. The authors' data cover a sufficient range so as to permit selection of the proper members and their proper location in a variety of practical cases.

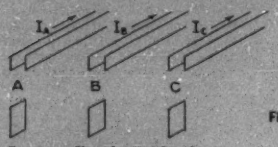


Fig. 6a. Closed secondary loops under each phase

Fig. 6b. Secondary loops formed by parallel members of each conductor

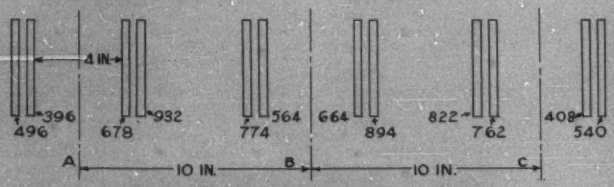


Fig. 6c. Illustration of unsymmetrical current division

V. R. Bacon: Before commenting on the discussion, I wish to call attention to 2 omissions in the paper which should be corrected for the sake of completeness. The tests covered by Figs. 13 and 17 were made with 5,000 amp flowing in the conductors. This information was inadvertently omitted from the figures.

O. R. Schurig amplifies and clarifies the authors' reference to the $^1/_2$-in. optimum wall thickness for copper tubes and states that the interpretation of the test results would be simplified by a knowledge of the magnetic and resistance characteristics of the various steel members tested. The authors are in agreement with Mr. Schurig's treatment of the reference to optimum wall thickness. No information was obtained on the magnetic and resistance characteristics of the steel, since such data were not pertinent to the purpose of the tests.

Mr. Schurig also inquires concerning the variation of temperature rise with the spacing between buses and separation between channels. No tests were made to determine the effects of bus spacing or channel separation, since space limitations were the predominating influence in the bus design. However, some light on the effect of bus separation was contributed by F. R. Dallye in his discussion. His data are not strictly applicable to the sections tested by us, since the greatest increase of capacity found by Mr. Dallye corresponded to a separation providing a square formation. Separation of the copper channels beyond $^5/_8$ in. would have produced an oblong-shaped bus, which would have destroyed the symmetry with probably undesirable current distribution and consequent heating.

W. H. Hanna is interested in knowing the air velocities necessary to keep the bus cool and the effect of such cooling on the temperatures of nearby structural steel. He also inquires concerning the relative permeabilities and resistivities of the carbon and silicon steels tested.

No information on air velocities is now available since no tests were made and the design of the ventilating system has not yet been started. Data on the magnetic and electrical properties of the 2 steels were not obtained since the tests showed them to be unimportant as affecting the immediate problem.

The mathematical discussion contributed by H. B. Dwight probably accounts for a part of the temperature difference observed where a steel member crosses a 3-phase bus but his calculations would indicate lower temperatures in the middle phase than in either of the 2 outside buses, with expected lower temperature of the steel member at this point. This was not confirmed by tests. The effect of an interposed copper plate in reversing all relative temperatures of the outside points does not obviously follow Mr. Dwight's explanation.

The explanation of the shift of temperatures with phase reversal as given by L. A. Kilgore is logical, but we are not convinced that it contains the explanation in the case of the copper plate interposed between the bus and steel member.

Mr. Kilgore asks if the amortisseur bars were installed parallel to the isolated phase buses. No amortisseurs were installed along the main isolated phase buses during the tests described. The amortisseurs were in place only along the generator lead runs from the generator terminals to the isolated phase buses. These runs constitute a flat 3-phase system from the generator to the first or lower bus. Above the lower bus the amortisseur, with its end short circuited, forms 2 large open loops. Amortisseurs parallel to the main buses were not considered necessary because of the large

clearance between the buses and nearest conduits. Where structural members cross the main buses at right angles with close clearances, the steel is protected by short-circuited bands.

Mr. Kilgore brings out the fact that an amortisseur grid must carry material values of current in order to provide protection. This was confirmed in the field tests, where the cross section of the amortisseur grid was increased in order to avoid excessive losses in the amortisseur conductors.

The method of testing for resistance, as outlined by Messrs. Gorman and Forbes, is entirely logical but it would have involved a greater expense for testing equipment than was warranted. The limited background of this method of testing would render it open to the same objection as miniature tests; at least superficial confirmation would be required on full-sized sections.

A Survey of Hydroelectric Developments

Discussion and closure of a paper by the A.I.E.E. subcommittee on hydroelectric survey published in the June and July 1934 issues, p. 988–93 and 1086–94, and presented for oral discussion at the power generation session of the summer convention, Hot Springs, Va., June 29, 1934.

A. F. Bang: Mr. Karpov and his committee are to be congratulated on the vast amount of statistical information presented on hydroelectric developments the world over. Much of the information is entirely new and the whole, it is believed, forms a more complete survey than any similar compilation yet published. Note in particular the interesting maps, Figs. 1 and 2, and accompanying tabulation of all major North American hydroelectric developments.

In our day with the continuous agitation for the development of our water power resources as a general panacea, and for doing this with public money almost regardless of whether the development is economical or not, it is highly instructive by means of such a survey to see water power—important as it is—being put in its proper place in relation to other sources of power and fuel. Take, for instance, Tabulation 2, which shows that in 1929 (the last year recorded) there was more animal power available in the United States of America than water power and over 110 times as much automobile horsepower. And if you consider this statement misleading due to the fact that water power largely is operating day and night and therefore produces relatively more energy than the other sources of power, take Tabulation 1, which shows that of the amount of energy produced in the world in 1927 from all sources, only 5.1 per cent was by water power. Such information is, indeed, surprising to many and would seem to warrant the continuation of such studies as presented here.

In his remarks introducing the statistical material, Mr. Karpov gives a somewhat sketchy outline of the main features that influence the economical development of water power. In one of his first paragraphs he points out that in several industries, notably electrochemical industries, the cost of power is such a large item that it may be economical to regulate the demand of power in accordance with the available supply of hydroelectric energy and gives several interesting examples of this. These cases, I believe, are rather exceptional. Usually, of course, industry demands continuous service in the quantity required whenever there is a demand for their own product. Mr. Karpov also stresses the influence of interconnections of utility systems on the economic development of water power. This is, undoubtedly, correct. The higher load factor obtainable in periods of high flow and the higher peak and stand-by service obtainable in periods of low flow of an unregulated river makes it economical to develop a greater part of the river flow when connected to a large system. An example of this can be had in the various developments on the Susquehanna River. Here 4 major plants were built from 1904 to 1931, as shown in Table I of this discussion.

Table I—Susquehanna River Developments

Name	Start of Operation	River Flow Corresponding to Ultimate Plant Capacity
York Haven	1904	12,000*
Holtwood	1910	30,000
Conowingo	1928	70,000
Safe Harbor	1931	96,000

*Later by replacement of turbines increased to about 20,000 cfs.

All these plants have installed capacity several or many times the minimum river flow, but the interesting fact is that, although on the same river with the same available river flow, each successive plant was built for a larger ultimate utilization of the river flow, as illustrated in the tabulation. The cause is, no doubt, the changes in load available and visualized by the designers as time progressed.

One feature brought out by Table XI is interesting; namely, that so many hydroelectric plants in the United States are now from 20 to 30 years old, and apparently still going strong; this brings out the well-known sturdiness of the hydraulic turbines and the relatively slow obsolescence of the plants, which is one of the great economical advantages of such developments compared with other sources of energy.

J. B. Crane: In these days, when the theorists and economists are trying to run the country, it is quite essential that they have some basic facts to work on and our engineering societies can supply them without fear of being accused of spreading propaganda. Mr. Karpov and the subcommittee are to be congratulated on the preparation of this report and it will prove of importance to a great many interests.

The paper not only gives a condensed and very clear outline of the present status of hydroelectric developments, but also shows the part such developments take in our present economical system. From the data included in the survey it is clear that at present in the world as a whole and particularly in the United States the energy requirements are very manifold and extensive. These energy requirements are supplied by a number of sources. The combined energy drawn from all these sources is the base on which our present civilization is built. No one of the single sources of energy in itself can be considered of major importance. The diagram, Fig. 1, shows the relative importance of some of the energy sources. The prime mover capacity per capita of the different prime movers in the United States is shown from the years 1869 to 1929. So far as water power is concerned, not only the relatively small prime mover capacity per capita is to be noticed, but also the very slow increase of the per capita capacity as compared with the increase in the per capita capacity of prime movers in automobiles. The part of the total available prime mover capacity covered by water power is decreasing with surprising rapidity.

In Fig. 1 of the survey is shown how localized the developed water powers are, so that probably considerably less than one quarter of the area of the United States can be considered within the area influenced by the present developments and any possible in the future.

The tendency to consider water power as one of the major energy sources is based on a misinterpretation of the actual conditions. Water power, although localized, is important, but to a much smaller extent than many

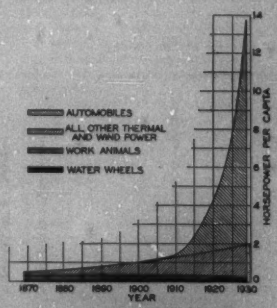


Fig. 1. Horsepower per capita of prime movers installed in the United States

other energy sources. It should be realized that no matter what efforts will be made the water power in the United States never can be expected to cover more than 5 per cent of the total energy requirements.

Figure 2 of the survey is of considerable interest, making clear the relative importance of the different drainage basins in North America and indicating the future power possibilities of the northern part of Canada. The fact that the St. Lawrence River drainage basin shows a larger aggregate development than the whole Pacific Coast, and the large total horsepower developed on the Atlantic Coast, are rather surprising.

The high state of present development of the south eastern part of the United States

in which the Tennessee Valley Authority is starting its operation indicates that this section of the country has done pretty well for water power supply even without government financed developments.

The method used in the survey to collect information on the aggregate horsepower capacity of all hydraulic turbines manufactured in the world should be commended. In no other way would it be possible to give such a complete picture of the relative importance of the different developments. That during the 5-year period 1928 to 1932 the medium head developments are still responsible for over 80 per cent of the developments in the United States and Canada and over 66 per cent in the whole world indicates that the Francis turbine, in one form or other, probably for many years yet to come will be the leading turbine of the world.

I hope the work of the committee can be extended to cover India and South America, where we have members of the Institute who have lived in those countries for many years and have there been identified with the hydroelectric developments, and I know will be glad to coöperate in every way possible.

A. V. Karpov: In connection with the diagram given in J. B. Crane's discussion, it is of interest to form a general picture of the importance of power in our present civilization.

Diagram, Fig. 2, shows the prime mover horsepower capacity per capita in United States, Europe, and mainland of Asia since the year 1000 A.D., and gives an engineering representation of the cultural development of mankind during that time period. The data pertaining to the United States are fairly accurate. The data pertaining to Europe and Asia are less reliable and must be considered as reasonable estimates.

At the dawn of mankind, the amount of power represented by the human body was so nicely balanced that all the energy available had to be spent for the bare necessities of life. The first traces of advancement from the animal state are to be found when, due to tribe organization, the head of the tribe managed to put at his disposal the prime mover capacity of other members of the tribe. This gave him the opportunity to devote part of his time and energy to creative work, and laid the foundations of human civilization. For many thousands of years afterward the progress made by humanity was due to one kind or another of feudal system or slavery by means of which large prime mover capacities were put at the disposal of a few. Such organization did not increase the total amount of power at the disposal of mankind. The utilization of wind power and the introduction of work animals were the first and very timid efforts to increase the per capita prime mover capacity at the disposal of mankind. The Mongol rule of nearly 400 years' duration was based on an increase of prime mover capacity per capita due to very extensive use of horses.

From a modern point of view this increase of prime mover capacity per capita was very insignificant but at that time it was sufficient to create a domination by the Mongol races, which so far as the areas and the percentage of the total population of the world were concerned never was repeated.

About the beginning of the nineteenth century, after the human race had existed for a period of about 30,000 years, the conditions began to change radically in some parts of the world. Until that time there was no noticeable difference in prime mover capacity per capita in any part of the world. The work animals were the main source, the water and wind power next. The prime mover capacity of thermal movers started to enter into the picture with such rapidity that it is necessary to draw the diagram on a logarithmic scale to visualize the picture.

The curves of prime mover capacity per capita between the year 1800 and the present time represent the differences in the average state of civilization in the different parts of the world. At present the United States is in a stage of development that could not be predicted even 50 years ago. The prime mover capacity per capita is increasing with an amazing rapidity, indicating clearly the changes taking part. Europe follows at a much reduced rate. The mainland of Asia is stationary or even may be going backward.

The aggregate horsepower capacity of hydraulic turbines manufactured in the world mentioned in Mr. Crane's discussion is illustrated on the diagram, Fig. 3, which makes clear the tendencies during the past five years in Europe, United States and Canada, and Japan.

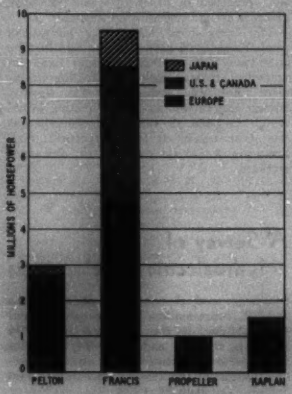


Fig. 3. World production of hydraulic turbines, 1928–32 inclusive

The conclusions drawn by Mr. Bang are of very considerable interest and importance. His table of the Susquehanna River developments gives the best illustration of the present tendency to improve the utilization of the available water flow.

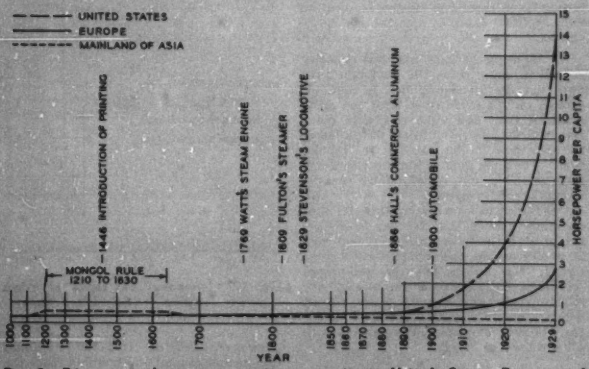


Fig. 2. Prime mover horsepower capacity per capita in United States, Europe, and mainland of Asia since the year 1000 A.D.

Calibration of the Sphere Gap

Discussion and author's closure of a paper by J. R. Meador published in the June 1934 issue, p. 942–8, and presented for oral discussion at the Instruments and measurements session of the summer convention, Hot Springs, Va., June 29, 1934.

P. L. Bellaschi (Westinghouse Elec. and Mfg. Co., Sharon, Pa.): The recent contributions and discussions on the calibration of sphere gaps reveal the many aspects of this important subject. The writer wishes to discuss in particular certain interesting empirical relationships on the sparkover voltage of sphere gaps.

The following empirical expression can readily be derived from experimental data presented in a published article. ("Impulse Calibration of Sphere Gaps," P. L. Bellaschi and P. H. McAuley. *The Elec-*

tric Journal, June 1934. Mr. Vogel had previously established a similar graphical relationship from 60-cycle data. See his discussion, p. 1658, for the 60-cycle calibration of sphere gaps.) For a given ratio of sphere gap spacing S to sphere diameter D, the ratio of sparkover voltage E to sphere gap spacing S can be expressed mathematically as:

$$\frac{V}{S} = A - B \log D \qquad (1)$$

where A and B are coefficients that are evaluated in the following from the experimental data. This linear relationship between $\frac{V}{S}$ and $\log D$ holds in particular for sphere gaps of sphere diameters, ranging from 12.5 to 200 cm. Inasmuch as the negative impulse and the 60-cycle flashover voltages of sphere gaps are substantially alike, the following analysis is for the present confined to the negative impulse and 60-cycle flashover voltages.

The coefficients A and B for various values of S/D can readily be evaluated from the experimental data referred to. We have with a good degree of approximation:

S/D	A	B
0.1	34.9	4.4
0.2	33.5	4.4
0.3	32.0	4.4
0.4	30.2	4.4
0.6	26.8	4.4
0.8	24.2	4.4
1.0	22.2	4.4

Substituting in eq 1 the term A as a function of S/D the equation becomes

$$\frac{V}{S} = f\,(S/D) - 4.4 \log_{10} D \qquad (2)$$

From a practical standpoint, the next step would be to establish $f\,S/D$ as a simple mathematical function. Plotting A against $\log_{10} S/D$ we thus obtain Fig. 1 of this discussion. We note the linear relationship from $S/D = 0.4$ to 1.0 inclusive and accordingly between these limits A can be expressed as:

$$A = 22.2 - 20.3 \log_{10} S/D$$

Equation 2 then becomes

$$V = (22.2 - 20.3 \log_{10} S/D - 4.4 \log_{10} D) \qquad (3)$$

Table I of this discussion compares the sparkover voltages as given by eq 3 with the actual experimental values given in "Table II—Recommended Sphere Gap Calibration . . ." of the paper previously referred to.

Table I—Comparison of Sphere Gap Negative and 60-Cycle Sparkover Voltages From Eq 3 With Experimental Values

S/D	Sphere diameter, cm									
	12.5		25		50		100		200	
	Eq	Exp	Eq	Exp	Eq	Exp	Eq	Exp	Eq	Exp
0.4	127	126	242	239	456	454	830	863	1,630	1,630
0.6	164	165	308	308	577	579	1,074	1,080	2,000	2,004
0.8	195		361	360	668	667	1,230	1,232	2,350	2,356
1.0	217		402	395	736	728	1,340	1,340	2,430	2,430

Eq = Equation 3. Exp = Experimental values.

The agreement between the simple relationship given by eq 3 for the sphere gap sparkover voltage and the experimental data is good. The general relationship for sphere gap sparkover which is valid for all spacings is given by eq 2, where S/D is evaluated from Fig. 1. The above relationships, which are derived from the experimental data, suggest the possibility of deducing the sparkover voltage of the sphere gap directly from fundamental considerations. At any rate, the sparkover data now made available should encourage studies of the kind.

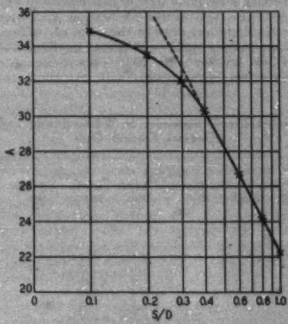


Fig. 1. Curve of coefficient A as function of S/D

P. L. Bellaschi and **Wm. L. Teague** (both of Westinghouse Elec. and Mfg. Co., Sharon, Pa.): Since the adoption of the sphere gap as a voltage measuring device 2 decades ago, the calibration of sphere gaps has been questioned frequently. With the advent of impulse testing the inadequacy of the sphere gap became manifest and subsequently it was possible to measure the inaccuracies involved in the present calibrations. An inherently fundamental method of impulse voltage measurement was developed at the Trafford laboratory in 1928 and in 1931 it was adopted at the new Sharon laboratory. Since the develop-

ent of this fundamental method has con-
ibuted preponderantly to the correct
easurement of impulse voltages, we wish
point out its essential features and also
compare the results obtained by this
ethod of measurement for the calibration
f sphere gaps on surge voltages to the data
btained by the method as outlined by
Mr. Meador. ("Impulse Calibration of
phere Gaps," P. L. Bellaschi and P. H.
McAuley. *The Electric Journal*, June 1934.
ee also "Better Standards Needed for
urge Testing," F. D. Fielder. *Electrical
Vorld*, Sept. 30, 1933.)

This fundamental method of voltage
neasurement makes use of a resistance
ivider and a cathode ray oscillograph
vith accurately calibrated voltage plates.

The resistance divider consists of a
oninductively wound low stray capacity
il-immersed resistor connected to a low-loss
ead-covered cable which is terminated by a
esistance equal to the cable surge im-
edance. The terminal resistance is lo-
ated at the oscillograph and the deflecting
plates are connected across the resistance.

Extensive laboratory studies ("The Meas-
rement of High-Surge Voltages," P. L.
Bellaschi. A.I.E.E. Trans., v. 52, June
933, p. 544) and experience have es-
ablished the full reliability of the resist-
nce divider. Direct comparison with the
apacity divider has furnished convincing
xperimental evidence of its performance.
The division of voltage is accomplished
vith strict proportionality and inappreciable
listortion of wave form.

The oscillograph deflecting plates are
alibrated on continuous voltages measured
vith either a conventional voltmeter or a
D'Arsonval type milliammeter in series
vith a standard resistance. The continuous
voltage supply must be smooth and free
from ripples.

The sensitivity of the oscillograph de-
flecting plates remains essentially constant
but frequent calibration and careful con-
trol of the cathode voltage minimize natural
oscillograph errors. Table II gives the
positive and negative voltage sensitivity of
one of the cathode ray oscillographs. The
sensitivity calibrations were made under
identical conditions and over practically
equal intervals of time during the period of
one year. These calibrations indicate the
full reliability of the cathode ray oscillo-
graph when proper care is taken in its use.

For the calibration, the sphere gaps were
set up to conform as nearly as possible
with the A.I.E.E. requirements of Standards
No. 4. The surge generator was carefully
adjusted to give a smooth wave form, free
from superimposed oscillations. The gen-
erator voltage was increased in small in-
crements until sparkover of the sphere gap
would occur approximately 50 per cent of
the time, then several oscillograms for this
voltage setting were taken. The average
value of the voltage as scaled from these
oscillograms gave the calibration for the
particular gap and spacing used. This
measured voltage was corrected propor-
tionately to the relative air density to
obtain the equivalent sparkover voltage
at the standard condition of 25 deg C and
760 mm pressure. No measurable varia-
tions in the sparkover of sphere gaps with
change in humidity were detected.

For a given gap setting, successive meas-
urements of the voltage seldom deviate

from each other more than 1 to 2 per cent as indicated in published data. Repeated calibrations at different times with all conditions reproduced as closely as possible may deviate on the average 2 to 3 per cent. Since the accuracy obtained from the resistance divider and cathode ray oscillograph method is within 2 per cent, this indicates a possible variation in sphere gap performance greater than that in measurement.

Sphere gap calibrations for the 6.25, 12.5, 25, 50, 75, 100, 150, and 200-cm sphere gaps, based on the resistance-divider method of

Table II—Calibration of Cathode Ray Oscillograph Voltage Plates

Calibration No.	Positive Voltage Sensitivity, Volts per Inch Deflection	Negative Voltage Sensitivity, Volts per Inch Deflection
1	845	790
2	840	790
3	840	790

voltage measurement, are given in detail in the first reference given. A comparison between the Westinghouse and the General Electric companies' recommendations is given in Table III of Mr. Fielder's discussion. This comparison indicates a sufficiently close agreement for practical purposes between the 2 sets of data to enable an early revision of the present A.I.E.E. Standards No. 4.

The method of impulse voltage calibration of sphere gaps adopted by Mr. Meador is based, first, on a correct calibration of the 200-cm sphere gap to 60-cycle voltages up to 30-cm gap spacing; second, on the extrapolation of the 60-cycle calibration of the 200-cm sphere gap up to 50-cm gap spacing; and third, on the assumption, based on 60-cycle voltage polarity characteristics, that the 200-cm sphere gap calibration to impulse voltages is independent of polarity and identical for both impulse and 60-cycle voltages up to the 50-cm gap spacing. In this way Mr. Meador has calibrated the smaller sphere gaps by comparing them directly to the 200-cm sphere gap for both positive and negative impulse voltages. This method of impulse voltage calibration of sphere gaps is indirect when compared to the straightforward method using the resistance divider and calibrated cathode ray oscillograph. However, when carefully carried out, this indirect method is capable of good results as is indicated from the generally good agreement between the recommendations of the 2 companies for sphere gap calibrations.

J. E. Clem (General Electric Co., Schenectady, N. Y.): This paper by Mr. Meador should be of great value to the instruments and measurements committee in their study of impulse flashover and sphere gap calibrations. It also has what might be termed a by-product which should be of considerable interest to the operators. Mr. Meador has shown that the calibration curves previously in use have indicated too high a voltage. When the new calibration curves are used for insulation testing, a greater spacing will be used for the same indicated voltage, thus imposing a test on the equipment higher than that previously given. This will mean that the operators will be getting better equipment when the new calibration curves come into general use.

F. D. Fielder (Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.): The calibration of sphere gaps is important because some laboratories have continued to base impulse data on sphere gap measurements. In addition, 60-cycle flashover values have been based on sphere gap calibration data. Apparently some of the A.I.E.E. sphere gap standards have been in error, as well as many of the calculated sphere gap calibration curves above the range covered by the A.I.E.E. standards. It is important to revise the present standards, and to extend their range as soon as satisfactory agreement can be reached.

The Westinghouse Company has been studying the characteristics of sphere gap calibrations for the past 2 years. Early results were presented in discussions at the A.I.E.E. 1933 winter convention, and later more complete data in the form of calibration curves were published in *Electrical World* for Sept. 30, 1933. Since then the data has been checked and extended, resulting in a complete presentation in *The Electric Journal*, June 1934. Briefly, the methods used involved an individual calibration of each size of gap by means of the cathode ray oscillograph and resistance divider, a cross check of results among 3 different laboratories, a further cross check by a direct comparison between gaps of different sizes, and finally an analytical development of the data. Reducing all results to a common basis with gradient curves decreased probable errors of measurement of individual points. As a result a complete table of recommended calibration curves of sphere gaps from 6.25 to 200 cm in diameter has been presented.

Table III—Comparison of Westinghouse and General Electric Data

Gap Size, Cm	Positive Max. Diff., %	Positive Avg. Diff., %	Negative Max. Diff., %	Negative Avg. Diff., %
200	2.5	1.4	2.5	1.6
*200	6.1	2.6	3.6	2.3
100	1.8	0.8	1.5	0.6
75	1.9	1.0	2.8	1.8
50	4.8	2.2	6.2	3.3
25	2.5	1.4	2.6	0.9
†12.5	2.7	1.3	2.7	2.1
†6.25	5.3	3.3	5.3	3.1

* Based on extrapolated values.
† Spacing up to 1/3 diameter.

Since this paper also presents recommended calibration points for nearly all the standard sizes of sphere gaps, it is now possible to make a direct comparison between the Westinghouse and General Electric companies' recommendations. Comparison was made by noting the difference between each value as shown in Tables III to IX and the corresponding Westinghouse value as shown in *The Electric Journal*, June 1934, p. 231. The maximum differences and the average differences are shown in Table III of this discussion.

In general the agreement is good. The large percentage errors for the 6.25-cm sphere are caused by differences of only 2 kilovolts at low spacings. The large error in the 200-cm data is undoubtedly due to the methods of extrapolation, and would probably be reduced by actual tests. Westinghouse data are higher than General Electric data for about half of the points, with the variation the other way for the other half. Specifically, however, the Westinghouse data for the 50-cm gap are in all cases higher, and generally higher for the 75-cm gap. Westinghouse data are generally lower for the 200-cm gap and for the 25-cm gap. Particularly good agreement is found in the data for the 100-cm gap.

It is evident that the data are sufficiently close for practical purposes. An average of the 2 sets of data will yield curves which are accurate within the range of the accuracy of individual measurements. For purposes of standardization, however, it may be desirable to further study the data which are different by more than 2 per cent on the average. With the progress shown by the 2 groups of results, it appears likely that A.I.E.E. Standards No. 4 can be revised at an early date.

R. E. Hellmund (Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.): The data presented in Mr. Meador's paper, together with those given by Messrs. McAuley and Bellaschi in the June 1934 issue of *The Electric Journal* and referred to in Mr. Fielder's discussion, represent a marked advance in high voltage testing technique. The material given is the result of extensive investigations in a number of the best equipped high voltage industrial laboratories in the country. Different methods of attack were used in the different laboratories, and in none of the cases can it be claimed that the methods employed were of sufficient accuracy for establishing an absolute primary standard. However, they are practical methods carried through with sufficient refinement to yield data accurate enough for most practical purposes. It must further be considered that aside from the testing methods, certain inaccuracies always enter into this work because of the fact that the relation of the spheres to surrounding and grounded objects cannot, in practice, be uniformly controlled. In view of all this, it is surprising that the results obtained are in such close agreement, and even better agreement undoubtedly can be obtained in the near future after some of the tests have been checked.

In view of the close agreement then expected, it would seem highly desirable to establish a new A.I.E.E. standard and to use as this standard the average of the results obtained in the various laboratories. Even with the average value of the present data, the following results will be accomplished:

1. Standard calibration curves for sphere gaps above 75 cm in diameter will be made available, filling a long felt need. Such curves will differ from the various data given here less than 1 per cent for spacings of less than 50 per cent of the sphere

diameter, and less than 2 per cent for spacings up to the sphere diameter.

2. The new curves will be available for the smaller sphere gaps and will correct errors in the present A.I.E.E. curves which are in the order of 4 per cent for spacings up to 50 per cent of the sphere diameter, and as high as 9 per cent for larger spacings. These corrections are large enough to be of practical importance and therefore are highly desirable. Again, it is found that for spheres of 25, 50, and 75-cm diameters the new curves would differ from the results of the different laboratories only about 1 per cent for spacings up to 50 per cent of the sphere diameter, and only in one case slightly over 2 per cent for the larger spacings.

3. The test results have established definite relations for surge testing with both polarities and indicate the desirability of carrying out most of the surge testing with spacings which are below 40 or 50 per cent of the sphere diameters. Such practice will naturally reduce the influence of surrounding and grounded objects, which are bound to be somewhat different in different laboratories.

It is believed that with the data now available and the plan as suggested, sphere gap calibrations sufficiently accurate for all practical engineering work will be made available. Insulation testing with 60 cycles and surge tests can hereafter be carried on with considerable confidence in the accuracy obtained, which is a marked step forward over the condition prevailing only a year or 2 ago. Any calibration of greater accuracy can be considered only of scientific value and importance, and work along this line should be left to laboratories of scientific institutions.

C. M. Foust (General Electric Co., Schenectady, N. Y.): Since its introduction some 20 years ago the sphere spark gap has been a most important part of the equipment of every high voltage laboratory. As a method of measuring high voltages the sphere gap has advantages which are not present in other measuring methods. Some of these advantages are as follows:

1. The simplicity of its construction permits the quick detection of defective arrangements.

2. Because the sphere gap depends for voltage indication upon the breakdown of an insulating medium, usually air, its use provides an immediate comparison of the dielectric strength of any insulation being tested with the strength of air. This air breakdown between symmetrical electrodes and within a field of uniformly distributed potential gradients has been found to vary but slightly. The conditions of voltage application, such as polarity, frequency, and wave shape, should be known if the sphere gap is used for measurement purposes.

3. The sphere spark gap measures directly all voltages at full amplitude. All the numerous problems involved in the design of an accurate and reliable voltage divider are eliminated by the use of the sphere gap.

4. The sparkover of the sphere gap is visible and audible. For demonstrating relative insulation strength the sphere gap has advantages over other methods which require supplementary measurements of circuit constants or development of films before values are available. An immediate indication of voltage level is obtained.

The disadvantages of the sphere spark gap are quite as definite and important as the advantages. Among these disadvantages are the following:

1. The unknown voltage must be repeated several times in making sphere spark gap measurements.

2. The sphere gap indicates only crest voltage and gives no indication of time elements involved or wave shape.

3. The sphere gap occupies considerable space, especially for high voltages.

4. Temperature, pressure, humidity, and ionization conditions affect the flashover of the gap slightly.

Other laboratory workers can undoubtedly describe additional advantages and disadvantages. As suggested in advantage 2, the sphere spark gap is in reality a calibrated insulation-breakdown device. Most measuring devices are based upon electromagnetic laws common to other types of electrical equipment, but the sphere spark gap sparkover as an insulation-breakdown has an electrical mechanism which is not well understood. No fundamental electrical laws which have been tested and demonstrated are available upon which to base calculated sparkover voltages.

The sparkover of the gap must be calibrated directly and for such a calibration some reference or basic method of voltage measurement must be available. At power frequencies the transformer ratio method has been used and it appears that the early sparkover values actually obtained by test were not in great error. Where extrapolations were resorted to at higher voltage levels and for larger sized spheres, however, errors were introduced. Also, the assumption that surge voltage sparkover for either polarity took place at the 60-cycle crest value over the range of spheres and spacings calibrated has been shown to be in error. But such errors had to do with lack of suitable calibrating facilities, not to anything erratic in the behavior of the sphere spark gap. This point should be carefully considered in estimating the future value of the sphere gap.

At present no absolute basis for sphere gap calibration on surges is available. It is quite possible to compare values obtained by sphere spark with those obtained by resistance divider and cathode ray oscillograph. Agreement between the 2 methods serves to establish confidence in results obtained. A great disagreement usually requires attention to and readjustment of the resistance divider and cathode ray oscillograph. The last named are complicated arrangements subject to a variety of difficulties and therefore must be given attention when they do not check the sphere gap. The method of calibrating the sphere gap wherein one sphere size is utilized as a reference basis has great value. However, much would be gained if a direct reference standard for surge calibration of sphere gaps were available. Lacking such a reference it is quite possible that good calibrations can be obtained through low frequency flashover data, intercomparison of flashover on various sized spheres, and comparison of results with those obtained by resistance or capacitance dividers and cathode ray oscillograph.

The practical laboratory man who must include a wide variety of kinds of surge testing in his daily work has no doubts concerning the value of the sphere spark gap. He cannot do without it. But he needs better calibrations and Mr. Meador has accomplished a worthwhile effort in assisting him to obtain them.

G. D. Floyd (Hydro Electric Power Commission of Ontario, Toronto, Can.): I would ask the author if he considered any alternative method for measuring the voltage to that using the rectifier and d-c milliammeter? It is very desirable when any calibration is made that the standard instrument have an accuracy better than the one being calibrated, and, if possible, both should be connected directly in the same circuit.

An instrument such as above described is available in Dr. Whitehead's corona voltmeter. It reads the crest value of voltage, as does the sphere gap, it is connected directly in the same circuit as the sphere gap, and it has an accuracy, when properly and carefully used, several times that claimed for the sphere gap. The 6.25-cm and 12.5-cm gaps could have been checked against an inexpensive type of corona voltmeter, and a calibration obtained against a standard dependent only on physical dimensions and air density.

I hope that if such a check test has not already been made, it will shortly be undertaken. The use of the sphere gap as a simple and, within limits, reliable instrument for measurement of crest values of high voltage has been extended greatly within recent years, and it is very necessary that its accuracy of calibration be established definitely against a standard of proved and unvarying constancy.

W. A. Hillebrand (University of California, Berkeley): Because of the urgent need for authoritative sphere gap sparkover voltages, the work of Mr. Meador and that of Mr. Bellaschi, as published in *The Electric Journal* for June 1934, is most welcome. The substantial agreement in results obtained by quite different methods is convincing proof of their accuracy. However, the differences, although relatively small, are important and it is to be hoped that they will be reconciled in the near future.

The sample data sheet recorded in Table I of the paper shows a spread of 4.5 per cent in the observations recorded. Differences of this order are due, at least in part, to residual charges on the spheres, as pointed out by Mr. Meador, and also, possibly, to error in the assumption that the electric breakdown strength of air in bulk is sufficiently constant to constitute what amounts to a primary standard. However, as again indicated by Mr. Meador, the data were obtained under the conditions of practical use in order that they might be directly applicable to the average laboratory.

In practice, the sphere gap is used to calibrate the testing transformer against the primary voltmeter. This means that, in making this calibration, there may be an uncertainty in any one reading of at least 2.25 per cent. I would like to ask Mr. Meador how many observations he considers it necessary to take in order to establish a reasonable average for the primary voltmeter reading that should correspond to the flashover of a given sphere gap setting. In obtaining this average, is it not reasonable to disregard "strays" that depart widely from the mean?

W. L. Lloyd, Jr. (General Electric Co., Pittsfield, Mass.): In Mr. Meador's paper reference is made to the calculated sphere gap curves upon which the A.I.E.E. calibration curves of 1914 and 1928 were based. I would like to point out an interesting fact in connection with such calculations. The formula for the sparkover voltage of the nongrounded sphere gap is ("Dielectric Phenomena in High Voltage

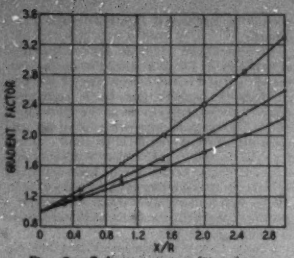


Fig. 2. Sphere gap gradient factors

□ = Calculated points
+ = Calculated points
× = Measured points
⊙ = Measured and calculated points

Engineering," F. W. Peek, Jr. Third ed., p. 27, McGraw-Hill Company, 1929),

$$e_s = \frac{g_s X}{f}$$

where g_s is the apparent strength of air, X is the length of the air gap, and f is a factor which is found from theoretical considerations to vary with the spacing X and the sphere radius R in the following manner (Dean, *Physical Review*, December 1912 and April 1913, and *G. E. Review*, v. 16, 1913, p. 148. Peek, A.I.E.E. Trans., v. 33, part 1, 1914, p. 923. See especially, Table VI on p. 930):

$$f = \frac{1}{4}\left(\frac{X}{R} + 1 + \sqrt{\left(\frac{X}{R} + 1\right)^2 + 8}\right)$$

Values of f for different values of X and R are given in the lower curve of Fig. 2 of this discussion. Within the limits given in Mr. Meador's paper these values of f are checked by measurements in the laboratory. That is, the measured and calculated values for the sparkover voltage of a given size and setting of sphere gap within the specified limits agree when the value of f as indicated by the theoretical formula is used.

For the one side grounded sphere gap, however, the formula is:

$$e_s = \frac{g_s X}{f_1}$$

in which the present theoretical formula for the factor f_1 does not apply. The theoretical formula given by Dean and Peek is

$$f_0 = \frac{1}{2}\left(\frac{X}{R} + \sqrt{\left(\frac{X}{R}\right)^2 + 4}\right)$$

Values of f_1 for different values of X and R as indicated by this formula are given in the upper curve of Fig. 2, but these values are not checked by laboratory measurements. The values of f_1 required to be used to make measured and calculated values agree within the limits given in Mr. Meador's paper are given by the middle curve of Fig. 2. No theoretical formula has been derived to fit this middle curve but Royal Meeker and the writer have written an empirical equation which gives the required values of f_1 in terms of X and R for any size of grounded sphere gap. This formula is as follows:

$$f_0 = \frac{1}{3}\left(\frac{X}{R} + \frac{1}{2} + \sqrt{\left(\frac{X}{R} + \frac{1}{2}\right)^2 + 6}\right)$$

The close resemblance of this empirical equation with the 2 theoretical formulas is striking. The theoretical reason for this would be interesting as the resemblance seems more than a mere coincidence.

J. T. Lusignan, Jr. (Ohio Brass Co., Barberton): There are a few factors relating to sphere gap sparkovers which I should like to bring up in connection with Mr. Meador's work.

I would like to ask Mr. Meador if, in his work with sphere gaps, he has found a condition wherein the breakdown values for the first few sparkovers on a given sphere gap are appreciably lower than those obtained later during the same test. I believe that several previous investigators (Carroll and Cozzens, A.I.E.E. Trans., January 1929, p. 1) have found this sphere gap behavior. It has generally been attributed to a surface condition of the spheres rather than to anything in the intersphere space. I believe that in some cases this has occurred even though some care had been taken to clean the spheres beforehand. My reason for bringing this up here is that I feel some mention should be made in any revised sphere gap testing standards in regard to the care necessary in preparing sphere surfaces for sparkover measurements. Undoubtedly, more or less of an attempt is made in all laboratories to clean sphere electrodes before their use, but some sort of an authoritative statement in a sphere gap testing standards, giving the necessary surface preparation, would be of value. This would tend to eliminate erroneously low sparkover values when tests are being made to meet customers' specifications. Often the customers' inspectors take cognizance of such low values, particularly when only a few measurements are made, so that there should be some standardized procedure which will prevent such low values, or else allow them to be corrected for if they are inevitable.

As Mr. Meador states, the existence of a polarity effect in sphere gaps has been known for some time. Dr. Reukema gave an interesting theoretical analysis suggesting the reason for this polarity effect in sphere gaps in a discussion published in the A.I.E.E. Trans., January 1929, p. 257.

In calibrating the high voltage transformer sets at our Barberton laboratory we have found appreciable inconsistencies when plotting the voltage values obtained with different diameters of the spheres, using the recognized sphere gap calibration curves. As a rule, the larger the spheres the lower would be the measured values on the high voltage side for a given voltmeter coil reading. It seems that this might be caused by 2 factors: first, curves from theoretical calculations do not take into account the probability of more impurities being present on the surfaces of and in the space between large spheres than would be the case with smaller spheres; second, the stored condenser energy for energizing approaching streamers would be greater in the case of the larger spheres due to their greater electrode areas and shorter spacings for the same voltage settings.

The polarity effect present in sphere gaps is inherently due to the asymmetrical electrostatic field introduced as soon as one sphere is grounded. Obviously, the greater the clearance of the spheres from the ground the less the field dissymmetry. For this reason any new standards for sphere gap testing should specify ample clearances, particularly for the larger sphere gaps. It is possible that some of the differences now found among 60-cycle insulator flashover measurements of various laboratories may be due to the fact that voltage calibrations are taken with sphere gaps mounted in different manners. For example, the polarity effects of the same size of spheres mounted in a frame, hung from a roof, and supported out from a wall may all be sufficiently different to cause appreciable variations in flashover measurements on the same type of insulators having consistent polarity characteristics.

K. B. McEachron (General Electric Co., Pittsfield, Mass.): To measure high voltages accurately requires some form of measuring device which can be calibrated with reasonable accuracy. As the paper indicates, the calibration of a sphere gap cannot be accomplished by direct means in the present state of the art, and must necessarily be accomplished through the use of some method of triangulation.

The sphere gap is convenient to use, and for many laboratories which are not equipped with cathode ray oscillographs it represents the only method available for checking high potentials, either transient or periodic. Therefore the calibration of the sphere gap is important, and the changes which Mr. Meador has indicated represent a sufficient deviation from the A.I.E.E. standard curves that a revision of the A.I.E.E. standard values should be undertaken.

Laboratories, particularly those in colleges, make use of small sphere gaps at small settings for the measurement of both transient and low frequency potentials, and it is very desirable, therefore, that further study be made of the smaller sphere gaps so that data, corresponding to that given by Mr. Meador, will be available for the smallest sphere gaps in use. In this connection, it should be remembered that the use of ultra-violet light with small sphere gaps is very useful in reducing the time lag and making sparkover values more consistent. The use of ultra-violet light was found useful by the writer in connection with "The Measurement of Transients by the Lichtenburg Figures," presented to the Institute in 1926, where light from an arc lamp was used. More recently the mercury vapor lamp has been used successfully.

The good check obtained between the results given by Mr. Meador and those reached by Mr. Bellaschi, as appearing in the June 1934 issue of *The Electric Journal*, serves to inspire confidence in the results obtained by both of the investigating laboratory groups. This is particularly true since quite different methods were used in arriving at the results.

Since the use of the resistance divider has been a matter of some discussion, it seems desirable to introduce here a brief

discussion of the history of the dividers and their use.

In the first published use of the cathode ray oscillograph in the United States, for the purpose of measuring single transients, a capacitance divider was described. ("Study of Time Lag of the Needle Gap," K. B. McEachron and E. J. Wade. A.I.E.E. Trans., 1925, p. 832.)

The capacitance divider in this form is not suitable for high voltages, because of the necessity of locating the divider at some distance from the cathode ray oscillograph.

In 1925, Mr. Wade developed a so-called compensated resistance divider for use up to 100,000 volts, which really consisted of a bridge circuit with resistance in 2 arms and capacity in the other 2 arms. This resistance divider was first described in *Electric Light and Power*, May 1929.

In 1927, Gabor described a cable divider and gave the theory of its operation. ("Forschungshaft der Studiengesellschaft für Hochstspannung - spanlagen"—1. Heft. Sept. 1927, p. 42). By the proper circuit arrangements, the cable may be used with a resistance divider, and reproduces, with reasonable accuracy at the receiving end, the transient applied at the entering end. The cables used are not absolutely distortionless, but are sufficiently good for the work to be done, providing the proper precautions are taken.

Since Gabor introduced the resistance-cable divider, its use has spread until most laboratories today are familiar with its use and have found it a very helpful circuit arrangement for the measurement of extremely high voltages.

F. O. McMillan (Oregon State College, Corvallis): It is indeed, gratifying that progress is being made in the general recognition of the 60-cycle polarity characteristics and the difference in the positive and negative calibration of the sphere gap.

In October 1929, J. T. Lusignan, Jr., presented his paper "A Study of High Voltage Flashovers" (A.I.E.E. Trans., v. 48, 1929, p. 246–54) in which he described some 60-cycle research work done in the Harris J. Ryan high voltage laboratory. In his paper he called attention to the observation that a 50-cm grounded sphere gap at diameter separation always flashed over when the upper ungrounded sphere was negative, and at 69 cm separation flashovers occurred at both polarities. At the larger sphere spacing he observed about twice as many positive as negative flashovers.

In September 1930, we reported the results of research work at Oregon State College in a paper "The Influence of Polarity on High Voltage Discharges" (A.I.E.E. Trans., v. 50, 1931, p. 23–33). In this paper complete characteristics were shown graphically using the percentage of the 60-cycle sparkovers that were positive as ordinates, and the sphere gap spacing in centimeters as abscissas. These curves were called "Polarity Distribution of 60-Cycle Sparkovers," and they are identical with those Mr. Meador has called "60-Cycle Polarity Characteristics." Complete curves were shown for a 6.25-cm sphere to plane gap and for 2.54-cm and 6.25-cm sphere gaps. The 25-cm sphere gap characteristic was shown up to 10-cm spacing which was the limit of the 60-cycle voltage available. The sphere gap curves all show the same general characteristics. See Figs. 9, 10, and 12 of the paper referred to. At close spacings sparkover was found to occur on both polarities, at intermediate spacings sparkover occurred only when the ungrounded electrode was negative, and at somewhat more than diameter spacing a rapid transition from 100 per cent negative sparkover to 100 per cent positive was found.

Mr. Meador shows in Fig. 3 a 60-cycle polarity characteristic for a 6.25-cm sphere gap that has a rather high percentage of positive sparkovers occurring over the entire range of spacings up to 8 cm. This is not in agreement with our findings. For the past 4 years the determination of the 60-cycle polarity characteristic for either a 6.25- or 12.5-cm grounded sphere gap has been one of our regular high voltage laboratory experiments. This laboratory work has given an opportunity to obtain the data for and examine a number of characteristics for the 6.25-cm sphere gap. During the past year E. D. Harrington and K. M. Klein, seniors in electrical engineering, made an extended investigation of the influence of the ground plane position on the 60-cycle polarity characteristic of the 6.25-cm sphere gap. The gap was placed at various distances above the ground plane ranging from 1 to 20 sphere diameters. Over this large variation in ground-plane relationships, a definite range of gap spacings in which no positive sparkovers were obtained was always observed. The extent of the range of sparking distances over which no positive sparkovers occurred was changed by the position of the gap with respect to the ground plane, but a definite range always remained in which all of the sparkovers were negative. It is, therefore, our belief that the 60-cycle polarity characteristic shown in Fig. 3 was obtained as a result of some extraneous cause not directly related with the polarity characteristic of the 6.25-cm sphere gap.

We have observed that it is absolutely necessary to have the circuit free from corona discharges of any magnitude when these characteristics are taken on gaps with small diameter spheres, because the transient disturbances in the circuit voltage caused by corona will completely upset the polarity distribution of the sparkover on such gaps. The reason corona discharges cause more trouble on small gaps than on large ones is obvious when consideration is given to the fact that the voltage disturbances caused by corona constitute a much greater percentage of the total voltage when the relatively low sparkover voltages for small sphere gaps are involved. Because of this, and further, because over a period of 4 years under widely different conditions it has been possible to consistently obtain typical 60-cycle polarity characteristics for both a 6.25-cm sphere gap and also for a smaller 2.54-cm gap, we are convinced that the 60-cycle polarity characteristic shown in Fig. 3 is not the true characteristic for a grounded 6.25-cm sphere gap. It is believed that the data in Table V and Fig. 10 of our 1930 paper are more nearly representative of the 60-cycle polarity characteristic of the 6.25-cm sphere gap. The corona disturbance may also account for the fact that the 60-cycle test curve in Fig. 3 is lower than the calculated curve and not in as good agreement with it as the experimental curves obtained for the 12.5- and 25-cm sphere gaps which gave normal 60-cycle polarity characteristics and were in quite good agreement with the calculated curves.

In the 1930 paper it was pointed out that the phenomenon of sparking over on 60-cycle symmetrical voltage only when the spheres have a definite polarity relationship with respect to ground showed conclusively that the positive and negative sparkover voltages must be quite different for the sphere separations that select one sparkover polarity continuously, otherwise grounded sphere gaps would spark over on either polarity indiscriminately for all sparking distances. Tabulated data and curves were presented which showed that the unidirectional impulse sparkover characteristics of the sphere gap gave excellent correlation with the 60-cycle data. See Tables VI and VIII and Figs. 11, 13, and 14. These data were obtained by taking advantage of the fact that, at close spacings, the sphere gap has no appreciable polarity effect, and, therefore, a large sphere gap may be used for the impulse voltage calibration of a smaller gap.

At relatively short sphere gap sparking distances no appreciable difference was found in the positive and negative impulse sparkover, at intermediate spacings the sparkover voltage was lower when the ungrounded sphere was negative than when it was positive, and at long sparking distances (more than one sphere diameter for the spheres investigated), the negative sparkover rapidly approached the positive value, became equal to it, and finally increased to a considerably larger value. The complete impulse characteristic for the 6.25-cm sphere gap is shown in Fig. 11 of the 1930 paper. These data showed clearly that for the smaller sizes of spheres, for which accurate experimental 60-cycle calibration data were available in the A.I.E.E. Standards, the crest a-c calibration curves were quite accurate for impulse voltage measurements when the ungrounded sphere was negative, but the positive values of voltage obtained by the use of the 60-cycle curves were much too low. The latter was especially true when voltages were measured near the maximum recommended sparking distance for a particular size of spheres. The maximum differences observed between the positive and negative sparkover voltages were very much larger than the permissible errors of measurement in high-voltage testing.

The impulse characteristics obtained had the same general characteristics as those found by Mr. Meador. The principal variation is in the magnitude of the difference in the positive and negative sparkover voltages and the point at which the positive and negative curves cross. The only impulse characteristic Mr. Meador has carried up to the cross-over point is shown in Fig. 15, which is for the 12.5-cm sphere gap. These curves cross over at 10 cm gap spacing or only 80 per cent of sphere diameter. It is rather surprising that the cross-over occurs at such a small sphere separation. This is particularly true in view of the fact that the 60-cycle polarity characteristic

in Fig. 4 does not show any appreciable percentage of positive sparkovers at 15 cm spacing or 120 per cent of sphere diameter separation. We have found better correlation between the 60-cycle polarity characteristic and the impulse characteristics for the 6.25-cm sphere gap. See Figs. 10 and 11 of the 1930 paper. For this sphere gap the transition from negative to positive sparkovers on the 60-cycle polarity characteristic starts at 144 per cent of sphere diameter separation, and the impulse characteristics cross over at a separation of approximately 134 per cent of sphere diameter. Mr. Meador is not recommending the use of the sphere gaps in this range of sizes beyond a spacing of 50 per cent of the sphere diameter; nevertheless, it is believed the complete characteristics are a good index of the extraneous influence present at the time the characteristics were taken and, therefore, constitute a measure of the reliability of the calibration data.

There is considerable evidence that the sphere gap is influenced by extraneous fields and grounded objects to a much greater extent than has heretofore been recognized. It would, therefore, appear that these influences should be studied and the conditions under which the sphere gap is to be used specified in a great deal more detail in any future standards than are adopted.

L. N. Robinson (consulting engineer, Corning, N. Y.): A sphere gap is essentially a center-zero voltmeter which is used in an electrostatic field whose intensity depends on the voltage being measured. Each body of insulating material and each body of conducting material which is in the vicinity of the sphere gap distorts the electrostatic field and produces more or less "proximity effect" on the sphere gap. If the combined proximity effects of neighboring bodies are the same on both spheres, the scales on both sides of the zero are affected alike or, we may say, the calibration curve is shifted as a whole. If the combined proximity effects of neighboring bodies are greater on one sphere than on the other, there will be an "apparent" polarity effect because the scale on one side of the zero will be affected more than that on the other side.

Therefore, it is necessary to define the spheres, their supports and especially their surroundings in specific detail for a primary standard sphere gap before it can be assumed that a standard calibration curve will apply. Sphere gaps which are not primary standards should be provided with individual calibration curves.

Mr. Meador and others have observed apparent polarity effects in vertical sphere gaps, but we find no evidence that polarity effects are inherent in sphere gaps in general.

Vertical and asymmetrical sphere gaps may manifest polarity effects which are actually proximity effects or due to vertical drafts of air which would act equally on both electrodes of a horizontal, symmetrical sphere gap. The heating of the dielectric prior to sparkover causes some upward draft, and there will be vertical drafts in the room if there is much temperature difference between the floor and the ceiling.

There is no reason to imagine that a horizontal sphere gap, in which identical spheres are symmetrically supported by identical insulators and equidistant from each extraneous body, will manifest any polarity effect.

Mr. Meador states that, during his tests, "the height of the grounded sphere above the floor was maintained at from 3 to 5 diameters." With reference to polarity effect, he says: "The large ground surface near the grounded sphere is the upsetting factor." Evidently, the clearance of 3 to 5 diameters did not eliminate the proximity effect of the floor. However, the effects of vertical drafts of air and the proximity effect of the floor could have been equalized with respect to both spheres so as not to have produced any polarity effect if the centers of both spheres had been on a line parallel with the floor and the spheres supported by identical insulators.

There does not appear to have been any inherent electrical characteristic which brought vertical sphere gaps into use. The preference seemed to be due to the apparent cheapness of wooden frames for supporting medium-sized spheres before the possible polarity effects of the asymmetrical frames were recognized.

The needle gap was, and is, practically always of the horizontal type. In fact, early sphere gaps consisted of spheres with thin shanks which were mounted in place of needles in horizontal needle gap stands.

Since impulse tests of high voltage insulations are very essential and polarity effects in sphere gaps can hardly be tolerated, the polarity effects, which appear to be unique in vertical sphere gaps, may be a very good reason why horizontal sphere gaps should be adopted as standard or, at least, for primary standards.

F. J. Vogel (Westinghouse Elec. and Mfg. Co., Sharon, Pa.): The inaccuracy of present sphere gap calibrations in 60-cycle measurements and the relationship between the 60-cycle and negative surge calibrations are the high spots of this investigation.

In past years the writer has had occasion to design numerous testing transformers. There was a demand for accurate indicating voltmeters, and the production of pure sine waves for testing. Several equipments were sold with guarantees as to the accuracy of voltage measurement. At that time, the process was reversed; that is to say the fact that the meter checked the sphere gap readings was taken as proof that the meter was satisfactory and the guarantees met. It should be noted that the tests were made on commercial designs, with no thought of finding sphere gap inaccuracies, and my object in reporting them is to confirm Mr. Meador's data, in general, and point out slight conflicts in some cases.

In 1925, the Westinghouse company furnished 2 testing equipments, one for 500 and one for 750 kv. These were made using 2 and 3 units in cascade, respectively. The transformers were of comparatively large capacity, and accordingly the regulation should be negligible. Further, since the magnetizing current was relatively small, no reason can be seen, nor was in fact found, for error due to cascade connection. The performance of the voltmeter coil and several sphere gaps was quite carefully checked.

Table IV—Calibration of 25-Cm Sphere Gap

Sphere Gap Setting, Mm	Voltage From Voltmeter Coil, Kv rms	Voltage, Present A.I.E.E. Std., rms
1 Unit		
38.2	74.6	75
53.3	99.5	100
69.9	124.0	125
88.0	150.0	150
139.9	192.0	200
2 Units in Cascade		
53.3	97.0	100
88.0	147.5	150
139.9	195.0	200
191.0	237.0	250

Instead of using a crest voltmeter to obtain the voltmeter coil voltage, a sine wave was maintained at the transformer terminals, the ratio between the crest and the root mean square values being $\sqrt{2}$ within 2.2 per cent.

A tabulation of the results obtained with the 25-cm gap is given in Table IV of this discussion.

At that time, an effort was also made to obtain data with a 50-cm gap at higher voltages, but the gap was not strictly in accordance with A.I.E.E. standards, and a comparison with the 25-cm gap (Fig. 3) made us fearful of its accuracy or the possibility of a check. It also made the accuracy of the 25-cm gap doubtful above 200 kv.

Later the 3 units were set up in the customer's plant, and a check with a 100-cm gap was possible. Unfortunately, this gap, being horizontal, is not quite in accordance with A.I.E.E. rules, but since the openings used were comparatively small, it is believed that it is accurate.

A tabulation of the data taken on the meter sphere with 1, 2, and 3 units is given in Table V.

From this data it may be seen that the present 25-cm gap calibration has been found reasonably accurate, but that variations might be expected above half opening. Likewise, it seems that voltmeter coils in

Table V

Sphere Gap Setting, Cm	Voltage From Westinghouse Curves, Kv rms	Voltage by Voltmeter, Rms	Coil, Kv Crest	Interpolated Values From Meader's Recommended Calibration Table IV, Kv Crest
1 Unit				
10.7	200	202	286	288
13.6	250	250	354	352
2 Units				
10.7	200	196	277	288
13.6	250	250	354	352
23.1	400	380	550	566
3 Units				
13.6	250	242	342	352
23.1	400	384	542	566
53.0	750	*810	*995	1,018

* For previous data the wave shape was closely a sine wave. Distortion in generator voltage wave present in this reading was checked by oscillograph and wave analysis. The crest factor was found to be 1.43 instead of 1.41.

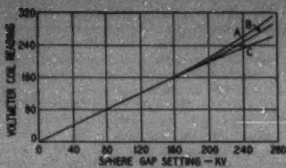


Fig. 3. Comparison of sphere gap readings

A. 25-cm gap in parallel with 50-cm gap
B. 50-cm gap
C. 25-cm gap taken alone

cascade units, with proper characteristics, unless the wave shape is poor, can also be used to measure voltage to a fair degree of accuracy. It may also be seen that the meter sphere gap calibration curves as used by the Westinghouse company are substantially correct.

Later, 2 units for 350 kv in cascade were calibrated. These units furnished data for the 50-cm sphere as well as the 25-cm sphere. For purposes of simplicity comparison is made by tabulating the sphere gap voltage, corrected in line with the present A.I.E.E. standards, and the voltmeter coil voltages.

Data With 25-Cm Gap		Data With 50-Cm Gap			
Sphere Gap Voltage, Kv rms	Voltmeter Coil Voltage, Kv rms	Sphere Gap Voltage, Kv rms	Voltmeter Coil Voltage, Unit No. 1	Kv rms, Unit No. 2	
50	49.2	58.8	60.8	59.5	
75	75.0	98.0	100.6	99.5	
100	100.7	122.5	124.8	122.8	
125	126.0	147.0	147.5	144.5	
150	150.3	171.5	169.0	164.0	
175	174.7				
		Units 1 and 2 in Cascade			
		173.5	173		
		197.0	198		
		247.0	249		
		296.0	294		
		345.0	342		

To sum up, data taken both the single units and with units in cascade confirm the present A.I.E.E. standards for the 25- and 50-cm gaps. The calibration curve as used by the Westinghouse company for the 100-cm gap is also checked. Further, due to the effect of surroundings it is seen that variations in spark gap readings occur at openings over $^1/_3$ the sphere diameter and it is recommended that for precise work gap openings over $^1/_3$ the sphere diameter should not be used.

Acknowledgment is hereby made of the work of J. K. Hodnette and W. L. Teague in obtaining some of the data here presented.

J. R. Meador (General Electric Co., Pittsfield, Mass.): Referring to Messrs. Bellaschi's and Teague's discussion of their method of measuring impulse voltages, 3 methods of voltage measurement were considered for the impulse tests reported in this paper. These alternatives were: 1, the capacitance divider with cathode ray oscillograph; 2, the resistance divider with cathode ray oscillograph; and 3, a sphere gap calibrated by voltmeter coil measurement on 60 cycles and used, in the range where its polarity effect was negligible, as a standard for the impulse distribution of the other sizes of spheres.

The third method of voltage measurement was used because: 1, a testing transformer with a voltmeter coil of high accuracy was available; 2, it was believed that the 60-cycle polarity characteristic gave a sufficient indication of the impulse polarity effect; 3, by using one sphere gap as a reference, all of the sizes of spheres should agree on voltage indications; and 4, it was felt that there was not sufficient proof of the accuracy of the capacitance and resistance dividers to permit their use in the determination of sphere gap calibrations.

With regard to the comparison between the General Electric and the Westinghouse data given by Mr. Fielder, I believe that in general the agreement is very good. The maximum differences in the 200-cm sphere gap curves are at spacings in which both sets of data are obtained by extrapolation. The differences in the 50-cm sphere gap curves are hard to explain, however. When taking the General Electric data, the 50-cm spheres were compared with the 100-cm spheres. Then, the 50-cm spheres were used for a comparison with the 25-cm spheres. The agreement between the General Electric and the Westinghouse calibrations of the 100- and 25-cm sphere gaps is excellent, whereas the agreement on the 50-cm spheres is only approximate. I would suggest that Mr. Fielder compare his 25-, 50-, and 100-cm sphere gaps in the manner described above in a search for possible errors. A further check may be obtained by taking a 60-cycle calibration of the 50-cm sphere gap up to a spacing of one diameter. I feel confident that these discrepancies can be reduced by coördinated efforts between the 2 groups of investigators.

I hesitate to draw any definite conclusions from the 60-cycle data presented by Mr. Vogel. The sparkover data on the 50-cm sphere gap show an average difference of 2 per cent between 2 different testing transformers. Furthermore, there is the possible error of 2.2 per cent due to variation in wave form. I do not agree that there are appreciable variations in sphere gap readings on 60-cycles above 50 per cent of diameter spacing. When properly calibrated, the sphere gap may be used with confidence up to a spacing of one diameter if a reasonable clearance is maintained. The only data points above 50 per cent of diameter spacing shown by Mr. Vogel are taken with 2 or more testing units in cascade. Under this condition the error in each unit is cumulative and a high degree of accuracy is not to be expected.

Mr. Bellaschi's empirical equation for sphere gap sparkover voltages is very interesting and may lead to more study of the fundamental mechanism of sparkover. However, for the present, it is very doubtful that calculated sphere gap sparkover curves will be well received by laboratory men in view of their past experience with them.

Mr. Bellaschi uses the gradient curves from the paper that he mentions ("Impulse Calibration of Sphere Gaps," by P. L. Bellaschi and P. H. McAuley, *The Electric Journal*, June 1934) in deriving his empirical equation. Referring to this paper, I erroneously assumed at first reading that the points on the gradient curves of Fig. 14 were actual test points or, at least, points taken from the curves drawn through an average of the test points. On closer inspection of the sparkover curves given on Figs. 4 to 11 inclusive, however, it is obvious that there are discrepancies. On Fig. 7 the negative polarity curve for the 75-cm sphere gap is drawn through 10 test points. At diameter spacing the average gradient is 13.2 kv per cm, whereas this point on Fig. 14a is plotted as 13.85 kv per cm—a discrepancy of 5 per cent. Similarly, at 80 per cent of diameter spacing, a discrepancy of 3 per cent exists. The 100-cm spheres at diameter spacing, both polarities, show changes of 2 per cent. I would expect some isolated test points to vary this much from an average sparkover curve but once the curve is drawn, it does not seem advisable to change it to agree with a gradient curve having no fundamental basis.

The corona voltmeter mentioned by Mr. Floyd was not used in this investigation. It should prove very useful in obtaining accurate calibration curves for small sphere gaps.

Mr. McMillan emphasizes the effect of ground and extraneous fields on the 60-cycle polarity characteristics of sphere gaps. The lack of agreement on the 6.25-cm sphere gap between his previously published data and that reported in this paper may be due to such causes. As stated in the paper, the 6.25-cm sphere gap was tested entirely in accordance with present A.I.E.E. recommendations as to distance above ground, size of frame, and distance from nearby line and ground potential surfaces. A series resistance was used in the line lead. The tests were made under the same conditions that would occur for normal use of the sphere. It is encouraging to learn that the important work reported by Mr. McMillan in 1930 is being continued.

Mr. Robinson is undoubtedly correct in assuming that the polarity effect of vertical sphere gaps mounted near the floor is really a proximity effect that produces an asymmetrical field. The use of horizontally mounted spheres would be very cumbersome under average laboratory conditions where floor space is at a premium. A complicated supporting structure would be necessary for spheres of the order of 100 and 200 cm in diameter. The objection to the polarity effect of vertical sphere gaps should be eliminated if calibration curves are taken on both polarities.

Professor Hillebrand's question as to the number of readings necessary for 60-cycle calibration by the sphere gap is a very pertinent one. For the data in this paper from 10 to 20 readings were taken for each sphere gap spacing. Ten readings should be sufficient if the voltage is brought up slowly just previous to arcover. "Strays" that depart widely from the mean should be disregarded since it is felt that they are not a measure of the average sparkover voltage. Some strays can be traced to too rapid an application of voltage; others, to sudden air currents. If as many as 20 or 25 per cent of the total readings are strays, usually some condition exists that should be corrected.

I have never encountered the condition

where the first few sparkovers were low, as brought up by Dr. Lusignan, except when the spheres were dirty or wet. Often, when the laboratory has been operating at high humidities, condensation forms drops of water on the sphere arcing surface. At times a few sparkovers will remove these beads of moisture that cause local concentration of voltage. A similar effect is sometimes produced by dust particles. Usually if the spheres are actually dirty, however, successive sparkovers will not clean them. Another cause of low initial sparkovers is the residue of the metal polish used to clean the spheres.

I agree with Dr. Lusignan that it would be of great advantage to have some method for determining when the sphere surfaces are adequately cleaned.

The lack of agreement on voltage measurement between the various sizes of spheres found by Dr. Lusignan has undoubtedly been the cause of a certain amount of dissatisfaction in the use of sphere gaps. The method used in my paper for making impulse calibrations should eliminate the possibility of disagreement among different sizes of sphere gaps, since each size is calibrated by comparison with another size.

Cross Current of a 5-Arm Network

Discussion and author's closure of a paper by A. C. Seletzky and J. R. Anderson published in the June 1934 issue, p. 1004–9, and presented for oral discussion at the instruments and measurements session of the summer convention, Hot Springs, Va., June 29, 1934.

I. M. Stein (Leeds and Northrup Co., Philadelphia, Pa.): Both this paper and the companion paper, dealing with cross potential of a 4-arm network, are very commendable contributions to the art of electrical measurement, but I am somewhat disappointed that the authors did not see fit to include a specific practical example of the actual application of the method. While it is true that the introduction to the earlier article refers to practical applications in very general terms, the practical example discussed in detail in the present paper is not really a practical example of the application of the method, but is merely a sample calculation in accordance with the method. It seems to me that the most important practical application of the method would occur in connection with that type of impedance bridge measurement in which the reading is obtained not by balancing the bridge, but by reading the deflection of an instrument connected so as to carry the cross current. It is not clear that the method would have practical application in connection with impedance bridges in which the reading is obtained by balancing the bridge either manually or automatically, particularly as the method is not applicable to many of the problems encountered in practice. The limitations are clearly stated in the paper. Of course, it is well known that even when operating a bridge in the balanced condition, the simple equations representing such balanced conditions are not sufficient because these give no idea of the magnitude and phase of the cross current resulting from an unbalance, and it is necessary to know both the magnitude and phase of the cross current in order to properly select and adjust the detecting circuit. However, there are several fairly simple methods for calculating the magnitude and phase of the cross current for a particular unbalance, and these are perfectly general in their application, being applicable to cases where more than one arm is varied to effect a balance and also to those cases in which the arms are varied in a manner outside of the limitations as stated in the paper. In general, these methods consist in first determining from the simple equation for the balanced condition the value of a particular variable to give this condition, and then determining from the general equation for the cross current the magnitude and phase of the cross current for a specific value of the particular variable, which differs from the value of that variable for the balanced condition by the minimum deviation that it is desired to detect in the measurement. If the complex notation is used, the 2 components of the cross current are easily determined.

At the present time I can see the opportunity for the immediate application of the method in connection with the one practical application which I have mentioned and, of course, the future may disclose some important practical applications in connection with calculations pertaining to bridges operated in the balanced condition.

The only other comment is one which I believe may be helpful to others who may wish to study the papers carefully. In the present paper, the statement is made "the locus of the cross current is a circle" and a similar statement appears in the earlier paper with regard to potential. Also the diagrams in both papers show complete circles. This statement is somewhat misleading. I think it would be better to say "the locus of the cross current lies on a circle" because, in most cases, the locus is really only a small part of a circle.

A. C. Seletzky (Case School of Applied Science, Cleveland, Ohio): In the preceding paper (ELECTRICAL ENGINEERING, v. 52, no. 12, December 1933, p. 861–7) which treated the variation of cross potential, the network employed for the numerical example was chosen, not as an illustration of any particular type of bridge, but as a simple network which would serve to illustrate the use of circular loci for both fixed and variable frequency of applied voltage. Fortunately, from the standpoint of computation, the loci for a goodly number of bridge circuits follow circles at variable frequency with fixed arms. However, it was desired to use a network in which the cross potential at variable frequency would follow the sum of 2 circles; and it was for this reason that the circuit in question was employed. When it came to the question of selecting a network to illustrate the application to cross currents, the authors considered it advisable, for the sake of continuity, to use the same circuit. Whether or not the network employed is a "practical example" or a "sample calculation" is secondary to the consideration of the employment of a simple circuit to demonstrate the numerical work entailed in the determination of the loci. If the reader comprehends the application of circular loci after studying the network used in the present paper, the authors consider that the "practical example" or "sample calculation" has served its purpose.

In regard to the question of what is the most important practical application of circular loci, the authors prefer to rest with the statement that the method presented is one which gives the locus of cross current when the variable, be it frequency or impedance element, ranges from zero to infinity. Whether or not the method is the simplest available for particular conditions of unbalance depends upon how much information is desired. Doctor Kouwenhoven, in his discussion of the preceding paper (ELECTRICAL ENGINEERING, v. 53, no. 3, March 1934, p. 478) considered the advantages of circular loci to determine the orthogonality of variation in cross potential caused by changes of resistance and reactance elements in a bridge arm when close to balance.

Selsyn Instruments for Position Systems

Discussion of a paper by T. M. Linville and J. S. Woodward published in the June 1934 issue, p. 953–60, and presented for oral discussion at the instruments and measurements session of the summer convention, Hot Springs, Va., June 29, 1934.

Paul MacGahan: See discussion below.

A Telemeter With Pilot Coil Transmitter

Discussion and author's closure of a paper by L. J. Lunas and H. L. Bernarde published in the June 1934 issue, p. 974–6, and presented for oral discussion at the instruments and measurements session of the summer convention, Hot Springs, Va., June 29, 1934.

Paul MacGahan (Westinghouse Elec. and Mfg. Co., Newark, N. J.): The complete data on the characteristics of the telemeter described in the paper by Lunas and Bernarde will be found in one of the current-type telemeter columns listed in the report of the joint committee on telemeters, a revised edition of which report is practically finished at this time. This telemeter replaces the vacuum tube telemeter which was listed in the original report of this committee and gives quicker response. A speed of response equal to that of ordinary indicating instruments is being demanded by many operating engineers for indications in telemeter systems. The speed obtainable is shown well in the oscillograph slide shown by Mr. Lunas, made since the original paper was published.

In addition, the report containing the column for the high rate impulse-type telemeter includes the data on an entirely new form of such telemeter, a paper on which was planned but not completed in

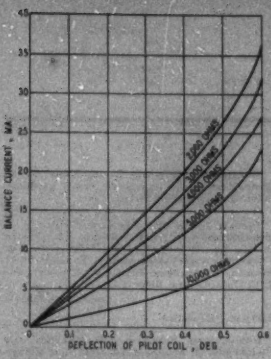


Fig. 1. Current-deflection characteristics of pilotel telemeter for various line resistances

time for presentation at this session. This impulse telemeter, however, is quite fully described in the June 1934 issue of the *Electric Journal*. The novel feature is a condenser reservoir device at the receiving end to store energy of the impulses and deliver them at a constant voltage as a steady current to the receiving instruments.

The study of the report may possibly bring up the thought that there is a needless number of different principles of operation used for telemeters and too many varieties in use. This, however, is due to the very great differences in requirements of local conditions, distance and character of available transmission channels, and quantity measured, and is, to a large extent, inevitable. The 4 principal types used are the impulse, voltage, current, and position.

The Westinghouse low rate impulse types operate at not over 15 impulses per minute at full load, and are used for integrating work on account of the requirements at the receiving end where ratchet mechanisms are used to drive integrating or demand registers.

The low rate impulse type is not suitable for indicating or graphic receivers because it is difficult to avoid fluctuation of the receiving instruments caused by the slow period impulses, while at the same time making their response to changes in load quick enough.

The high rate impulse system operating at approximately 250 impulses full load per minute is used for indicating or recording receivers. Generally speaking, this system is used where communication channel conditions or extremely long distances prevent the use of the current systems, such as exemplified by the pilot coil transmitter of the paper by Lunas and Bernarde.

The voltage type telemeter is seen at its best in the paper by Mr. Zogbaum which describes an installation in the New York district. It is peculiarly applicable to the local conditions in New York where the problem is largely one of voltage regulation, or of totalization of generator loads which do not vary too fast to allow the thermal converter transmitters and potentiometer receivers to follow correctly. For other system conditions where short-circuit currents are high, or where loads change rapidly, a telemeter having quick response may be preferable, even if less accurate.

The voltages measured are of the order of magnitude of millivolts, and in view of the prevalence of stray potentials, such as trolley return paths in a large city, presumably special care must be taken to use only high grade communication channels such as leased telephone lines.

The position telemeter class is exemplified in the paper by Linville and Woodward.

The authors have covered the theory of the position type instruments in a very valuable manner. The information in the paper is, however, more generally applicable to devices of this general character than indicated in the title and text, which refers to the trade name of "selsyn."

Numerous other trade names for similar apparatus are in effect, such as "autosyn," "synchrotie," etc., and the broad theory so well presented by the authors would seem to apply to all of these.

It should be clear that the salient pole member may be either the rotor or the stator. In some makes preference is indicated for placing the salient poles on the rotor. In the "Synchrotie" make, the designers have preferred to make the rotor smooth and the stator salient, on account of heat radiation condition being more favorable from the stator than from the rotor.

Concerning further the question of nomenclature, it is confusing to have to contend with so many trade names on such devices. The only A.I.E.E. standardization seems to be that adopted in connection with instrument standards, in which telemeters operating on the principle in question are termed "position" types. A similar basis for a standard name for such a system, when not used for telemeters, would seem to be in order.

M. E. Reagan (Westinghouse Elec. and Mfg. Co., East Pittsburgh, Pa.): From the point of view of the application engineer, the development of the new current balance telemetering equipment by Messrs. Lunas and Bernarde is of more than usual interest.

The current balance type of telemetering, in the past, has been the most used, the most satisfactory, and the simplest. Two major improvements in performance, high speed of response and small line current, make this new development stand out as a major improvement.

The error produced by leakage on the line is usually very small. Open lines are more subject to leakage than the usual telephone cable circuit because of fog, damp weather, and other by-passes on the receiving element such as limbs lying across the lines.

Since this type transmits much less line current than the older types, the transmitting voltage is proportionately less and, therefore, the chances of leakage or error of transmission is reduced. This reduction of transmission losses combined with indicating meter accuracy will make an ideal system.

The equipment also lends itself to mounting attractively on switchboards with switching and protective equipment since its dimensions follow the standardized trend of mounting on 6-in. centers. The appearance is pleasing and harmonizes fully with other established designs.

L. J. Lunas (Westinghouse Elec. and Mfg. Co., Newark, N. J.): The discussion by Mr. MacGahan covers all of the telemeter papers read at this convention, and the questions he touches upon in relation to the other papers will doubtless be covered by the closure statements of their authors. The forthcoming report of the telemeter subcommittee will be a very useful document, judging by the extended use made of this committee's previous report.

While it is true that at the present time there seems to be an unnecessary number of varieties under each general type, it is quite likely that with further experience the best methods will become more clearly apparent and the number of varieties will tend to diminish. Thus, for example, instead of 8 Westinghouse current types these may be reduced to one.

The system described by Mr. Zogbaum emphasizes high accuracy where quick response is not essential. The system I have described is intended to give the same speed of response and the same accuracy as obtained in the usual indicating switchboard instruments.

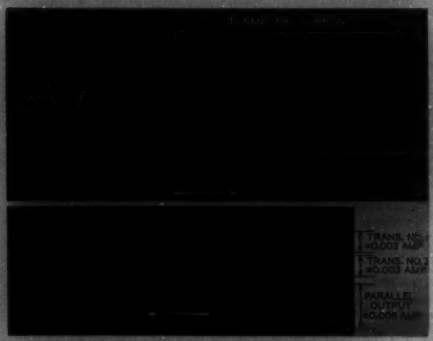


Fig. 2. Oscillograms of current in pilotel telemeter

Top trace. Rate of current rise when power is applied

Lower trace. Performance of 2 transmitters in parallel with a sudden rise in the load of one at the same instant that the load suddenly decreases in the other

News

Of Institute and Related Activities

Winter Convention Technical Program Announced

THE technical program for the winter convention of the A.I.E.E. to be held in the Engineering Societies Building, 33 West 39th Street, New York, N. Y., January 22–25, 1935, will include a wealth of engineering information for the profession. New developments, the latest practice, and recent trends toward standardization in various fields of the industry will be presented and discussed. The convention will convene on a Tuesday and technical sessions will be held both mornings and afternoons for the first 3 days. The evenings will be taken up by social events and arrangements are being made for a smoker Tuesday night, the Edison Medal presentation Wednesday night, and the dinner-dance Thursday night. Friday will be devoted exclusively to inspection trips to various places of interest in and about New York. Further details of these features now being arranged will be announced in the January 1935 issue of ELECTRICAL ENGINEERING.

TECHNICAL SESSIONS

Twelve technical sessions have been planned to present some of the latest developments in the electrical industry to the membership. Five of these sessions are symposiums which treat the subjects of transformer loading, noise, electronics, and induction motors. The transformer and noise symposiums will give the trends toward standardization in these fields and tell what is being done to bring about the more quiet operation of electrical equipment. Two symposiums on electronics will described the developments and various uses of electronic tubes in the fields of power, measurement, and industrial control. The induction motor symposium will deal with the locked saturation curves, losses, and performance of these machines.

In addition to the foregoing symposiums several other sessions are sure to be of outstanding interest. At the session on education the importance of the social sciences will be stressed by several well-known engineers and executives, and realization by the young engineer of the importance of personality characteristics should be valuable. At the session on general overhead line problems an analysis of lightning phenomena and protective measures against it will be discussed as well as system grounding and the timely subject of d-c power transmission. Another session will treat the subject of illumination. Still others will deal with the subjects of communication, electric welding, electrical machinery, and cables. Thus the program is of broad scope and timely interest which should leave but little to be desired by the average engineer or the specialist.

Technical Program

The schedule for the 12 sessions and the papers to be presented at each session are given in the following columns. All papers to be presented at the convention are scheduled for publication in ELECTRICAL ENGINEERING prior to the convention. The majority of these papers have already been published in this and preceding issues, beginning with the papers for the illumination session which appeared in the August 1934 issue. All remaining papers which are received in time will be in the January 1935 issue. For the papers which already have been published, reference to the issue and page is given after each title in the list which follows. Members who wish to follow the presentation in detail and discuss the papers are urged to take the necessary issues, or clippings therefrom, to the convention. Excellent discussion should result from the ample opportunity afforded for careful advance study of the papers.

Tuesday, January 22

9:00 a.m.—Registration

10:00 a.m.—Opening of Convention

10:30 a.m.—Electrical Machinery

HEAT FLOW IN TURBINE GENERATOR ROTORS, C. E. Peck, Westinghouse Electric & Mfg. Co. Oct. issue, p. 1359–65

OUTPUT WAVE SHAPE OF CONTROLLED RECTIFIERS, F. O. Stebbins and C. W. Frick, General Electric Co. Sept. issue, p. 1259–65

TRANSIENTS IN MAGNETIC SYSTEMS, C. P. Wagner, Westinghouse Electric & Mfg. Co. March issue, p. 418–25

10:30 a.m.—Communication

WIDE BAND TRANSMISSION OVER COAXIAL LINES, Lloyd Espenschied and M. S. Strieby, Bell Telephone Laboratories, Inc. Oct. issue, p. 1371–80

COAXIAL COMMUNICATION TRANSMISSION LINES, S. A. Schelkunoff, Bell Telephone Laboratories, Inc. Dec. issue, p. 1592–3

BROAD BAND TRANSMISSION OVER BALANCED LINES, A. B. Clark, American Telephone & Telegraph Co. Scheduled for Jan. 1935 issue

2:00 p.m.—Transformer Symposium

EFFECT OF OVERLOADS ON TRANSFORMER LIFE, L. C. Nichols, Allis-Chalmers Mfg. Co. Dec. issue, p. 1616–21

OVERLOADING OF POWER TRANSFORMERS, V. M. Montsinger, General Electric Co., and W. M. Dann, Westinghouse Electric & Mfg. Co. Oct. issue, p. 1353–8

IMPULSE AND 60 CYCLE STRENGTH OF AIR, P. L. Bellaschi and W. L. Teague, Westinghouse Electric & Mfg. Co. Dec. issue, p. 1638–45

RECOMMENDED TRANSFORMER STANDARDS, H. V. Putman, Westinghouse Electric & Mfg. Co., and J. E. Clem, General Electric Co. Dec. issue, p. 1594–7

2:00 p.m.—Education

ENGINEERING EDUCATION IS MEETING THE CHALLENGE, H. W. Bibber, The Ohio State University. Oct. issue, p. 1357–9

ON THE SCHOOLING OF ENGINEERS, Alex Dow, Detroit Edison Co. Dec. issue, p. 1589–91

ENGINEERING IN THE SOCIAL SCIENCES, J. C. Lincoln, The Lincoln Electric Co. Scheduled for Jan. 1935 issue

CHARACTERISTICS OF A GROUP OF ENGINEERS, Thomas Spooner, Westinghouse Electric & Mfg. Co. Dec. issue, p. 1571–6

Wednesday, January 23

10:00 a.m.—General Overhead Line Problems

LIGHTNING PERFORMANCE OF 220 KV LINES, Lightning and Insulator Subcommittee. Nov. issue, p. 1443–7

OVERVOLTAGES ON TRANSMISSION LINES, C. L. Gilkeson, Edison Electric Institute, and P. A. Jeanne, American Telephone & Telegraph Co. Sept. issue, p. 1301–9

EXPULSION PROTECTIVE GAPS ON 132 KV LINES, Philip Sporn and I. W. Gross, American Gas & Electric Co. Scheduled for Jan. 1935 issue

MULTIPLE LIGHTNING STROKES, K. B. McEachron, General Electric Co. Dec. issue, p. 1633–7

VIBRATION ANALYSIS—TRANSMISSION LINE CONDUCTORS, W. B. Buchanan, Hydro-Electric Power Commission of Ontario. Nov. issue, p. 1478–85

CARRIER CURRENT RELAYS, O. A. Browne, Turners Falls Power & Electric Co., and W. L. Vest, Jr., Western Massachusetts Cos. Scheduled for Jan. 1935 issue

CONSTANT CURRENT D-C POWER TRANSMISSION, B. D. Bedford and F. R. Elder, General Electric Co., and C. H. Willis, Princeton University. Scheduled for Jan. 1935 issue

10:00 a.m.—Noise Symposium

MEASUREMENT OF NOISE FROM POWER TRANSFORMERS, A. P. Fugill, The Detroit Edison Co. Dec. issue, p. 1603–8

MEASUREMENT OF NOISE FROM SMALL MOTORS, C. G. Veinott, Westinghouse Electric & Mfg. Co. Dec. issue, p. 1624–8

STANDARDIZATION OF NOISE METERS, R. G. McCurdy, American Telephone & Telegraph Co. Scheduled for Jan. 1935 issue

QUIETING A SUBSTATION, E. J. Abbott, University of Michigan. Scheduled for Jan. 1935 issue

THE MEASUREMENT OF NOISE FOR ENGINEERING PURPOSES, B. A. G. Churcher, Metropolitan-Vickers Electrical Co., Ltd. Scheduled for Jan. 1935 issue

2:00 p.m.—Illumination

CHARACTERISTICS AND USES OF THE CARBON ARC, W. C. Kalb, National Carbon Co., Inc. Aug. issue, p. 1173–9

LOW PRESSURE GASEOUS DISCHARGE LAMPS, Saul Dushman, General Electric Co. Aug. issue, p. 1204–12; Sept. issue, p. 1283–96

INCANDESCENCE—SOME THEORETICAL ASPECTS, S. G. Hibben, Westinghouse Lamp Co. Aug. issue, p. 1201–4

2:00 p.m.—Electric Welding

Transient Voltages in Welding Generators, A. R. Miller, Lehigh University.
Sept. issue, p. 1296–1301

A New Timer for Resistance Welding, R. N. Stoddard, Westinghouse Electric & Mfg. Co.
Oct. issue, p. 1356–70

A High Power Welding Rectifier, Daniel Silverman, Atma Engineering Co., and J. H. Cox, Westinghouse Electric & Mfg. Co.
Oct. issue, p. 1380–3

High Velocity Streams in the Vacuum Arc, R. C. Easton, Harvard University, F. B. Lucas, formerly Lehigh University, and F. Creedy, University of British Columbia. Nov. issue, p. 1454–60

Control of Transients in Welding Generators, F. B. Hornby, General Electric Co.
Dec. issue, p. 1598–1602

Thursday, January 24

10:00 a.m.—Electronics Symposium—I

Theory of Multielectrode Tubes, H. A. Pidgeon, Bell Telephone Laboratories, Inc.
Nov. issue, p. 1485–98

Cathode Ray Tubes and Their Application, J. M. Stinchfield, R.C.A. Radiotron Co., Inc.
Dec. issue, p. 1608–15

Limits to Amplification, J. B. Johnson and F. B. Llewellyn, Bell Telephone Laboratories, Inc.
Nov. issue, p. 1449–54

Electronic Devices in the Field of Measurements, J. W. Horton, Massachusetts Institute of Technology. Scheduled for Jan. 1935 issue

Vacuum Tubes as High Frequency Oscillators, M. J. Kelly and A. L. Samuel, Bell Telephone Laboratories, Inc. Nov. issue, p. 1504–17

10:00 a.m.—Cables

Dielectric Properties of Cellulose Paper—Parts I and II, J. B. Whitehead, and E. W. Greenfield, The Johns Hopkins University.
Oct. issue, p. 1389–96; Nov. issue, p. 1498–1503

Resistance and Reactance of 3-Conductor Cables, E. H. Salter, Electrical Testing Laboratories, G. B. Shanklin, General Electric Co., and R. G. Wiseman, Okonite Co. Dec. issue, p. 1581–9

Permissible Neutral Resistance or Reactance for Grounding of Cable Systems, J. E. Clem, General Electric Co.
Scheduled for Jan. 1935 issue

Transient Sheath Voltages on Single-Conductor Cables With Sheath Insulators, Herman Halperin, Commonwealth Edison Co., J. E. Clem, General Electric Co., and K. W. Miller, Utilities Research Commission, Inc.
Scheduled for Jan. 1935 issue

Dielectric Strength of Mineral Oils, F. M. Clark, General Electric Co.
Scheduled for Jan. 1935 issue

2:00 p.m.—Electronics Symposium—II

Ratings of Industrial Electronic Tubes, O. W. Pike, General Electric Co., and Dayton Ulrey, Westinghouse Electric & Mfg. Co.
Dec. issue, p. 1577–80

Industrial Electronic Control Applications, F. H. Gulliksen and R. N. Stoddard, Westinghouse Electric & Mfg. Co. Scheduled for Jan. 1935 issue

Industrial Applications of Electron Tubes, D. E. Chambers, General Electric Co.
Scheduled for Jan. 1935 issue

The "Thyratron" Motor, E. F. W. Alexanderson and A. H. Mittag, General Electric Co.
Nov. issue, p. 1517–23

The "Ignitron" Type of Inverter, C. F. Wagner and L. R. Ludwig, Westinghouse Electric & Mfg. Co. Oct. issue, p. 1384–8

2:00 p.m.—Induction Motor Symposium

Efficiency Tests of Induction Machines, C. C. Leader and F. D. Phillips, General Electric Co.
Dec. issue, p. 1628–32

Power Losses in Induction Machines, P. M. Narbutovskih, Stanford University.
Nov. issue, p. 1466–71

Induction Motor Locked Saturation Curves, H. M. Norman, Fairbanks, Morse & Co.
Apr. issue, p. 536–41

Rules on Presenting and Discussing Papers

At some of the technical sessions, a few papers may be presented only by title. This will permit the devotion of more time to discussion. At other sessions, papers will be presented in abstract, 10 minutes being allowed for each paper unless otherwise arranged, or the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion. Authors will be notified officially in each case about one month in advance.

Any member is free to discuss any paper when the meeting is thrown open for general discussion. Usually 5 minutes are allowed to each discusser for the discussion of a single paper or of several papers on the same general subject. When a member signifies his desire to discuss several papers not dealing with the same general subject, he may be permitted to have a somewhat longer time.

It is preferable that a member who wishes to discuss a paper give his name in advance to the presiding officer of the session at which the paper is to be presented. Each discusser is to step to the front of the room and announce, so that all may hear, his name and professional affiliations. Three typewritten copies of discussion prepared in advance should be left with the presiding officer.

Other discussion to be considered for publication must be submitted, typed double spaced, in triplicate to C. S. Rich, secretary of the technical program committee, A.I.E.E. headquarters, 33 West 39th St., New York, N. Y., on or before Feb. 8, 1935. Discussion received after this date will not be accepted.

International Music Hall, Radio City, in New York, N. Y., is one of the many points of interest which may be visited by those attending the Institute's winter convention, January 22–25, 1935, in New York. The Music Hall seats 6,200 persons, and the proscenium arch of the stage is 60 feet high. In this view the spectacular flooded ceiling bands with concealed 4 color lighting system are shown. In front of the stage is shown the $166,000 console or control board, by means of which the elaborate stage and auditorium lights are operated

A Special Hotel Bargain

This year an enterprising hotel within a 15 minute walk from convention headquarters is offering to A.I.E.E. members attending the convention a special "all-expense" rate of $11.20 covering all essential services as follows:

Room with bath, Jan. 21–24 inclusive
Meals, including dinners Jan. 21 and 23 and breakfasts Jan. 22–25 inclusive; choice of menus
Tips for all dining room service, and to bellmen for room service upon arrival

For those wishing to arrive after breakfast Jan. 22, a special rate will be made upon application. Reservations are being held for only 100, and these will be assigned in the order requested.

Those interested should write at once to National Secretary Henline for descriptive booklet and full information. In all other cases, hotel reservations should be made directly with the hotels.

Applied Mechanics Journal to Be Published. The American Society of Mechanical Engineers has decided to publish in 4 quarterly issues beginning 1935, a *Journal of Applied Mechanics*. The Journal will contain papers on applied mechanics which have been presented before the applied mechanics division of the Society, besides other papers not so presented, reviews of pertinent literature, and notes on important developments.

An editorial board will be appointed consisting of specialists covering the different branches of the field of applied mechanics, i. e., elasticity, plasticity, strength of materials, vibration, aerodynamics, thermodynamics, film lubrication, and electromechanics. The Journal will be sold to nonmembers at $5 per annum.

John Fritz Medal for 1935 Awarded Late F. J. Sprague

The John Fritz Gold Medal for 1935 was awarded to Dr. Frank Julian Sprague (A'87, M'97, F'12, HM'32, member for life, and past-president) for "distinguished service as inventor and engineer through the application and control of electric power in transportation systems." This medal, the highest distinction bestowed jointly by the 4 national societies of civil, mining and metallurgical, mechanical, and electrical engineers of the United States for "notable scientific or industrial achievement," was awarded Doctor Sprague unanimously by the John Fritz Medal board of award at its annual meeting October 19, 1934.

The presentation was to have been made with suitable ceremonies at one of the sessions of the A.I.E.E. winter convention to be held January 22–25, 1935. Unfortunately, Doctor Sprague's death occurred early in the morning of October 25, only a few days after the notification was sent to him that the medal had been awarded him.

Doctor Sprague was a pioneer in the application of electricity to street railways, steam railways, and elevators; among his numerous inventions are many relating to electric motors, multiple unit systems of train control and operation, electric street railways and high speed elevators. He had long been active in the Institute, having served as president 1892–93. A brief biographical sketch of Doctor Sprague's career appeared in ELECTRICAL ENGINEERING for May 1934, p. 791; an obituary item appears on p. 1685 of this issue.

The John Fritz Gold Medal is awarded not oftener than once a year for notable scientific or industrial achievement without restriction on account of nationality or sex. It is a memorial to the late John Fritz, a leader in the American iron and steel industry, the first medal having been awarded to Mr. Fritz in 1902. Members of the Institute who have received this medal include: Lord Kelvin (William Thomson) (HM'92); Elihu Thomson (A'84, F'13, HM'28, member for life, and past-president); Guglielmo Marconi (HM'17); Ambrose Swasey (HM'28); Herbert Hoover (HM'29); and M. I. Pupin (A'90, F'15, HM'28), member for life, and past-president). Other John Fritz medalists, no longer living, include: George Westinghouse (A'02); Alexander Graham Bell (A'84, M'84), and past-president); Thomas A. Edison (A'84, M'84, HM'28); Edward D. Adams (A'10); Elmer A. Sperry (A'84, M'93, and member for life); and John J. Carty (A'90, F'13, HM'28, member for life, and past-president).

Middle Eastern District Executive Committee Meets

A meeting of the executive committee of the A.I.E.E. Middle Eastern District (number 2) was held in Pittsburgh, Pa., October 20, 1934.

Those in attendance were:

Delegates

R. A. Hudson, chairman, Akron Section
J. H. Lampe, secretary, Baltimore Section
R. J. Jonas, chairman, Cincinnati Section
W. H. LaMond, chairman, Cleveland Section
A. S. Goodrich, chairman, Erie Section
Edgar Bell, secretary, Lehigh Valley Section
C. D. Fawcett, delegate, Philadelphia Section
H. A. P. Langstaff, chairman, Pittsburgh Section
F. J. Vogel, chairman, Sharon Section
G. W. Emery, delegate, Toledo Section
H. G. Dorsey, chairman, Washington Section
A. M. Wilson, vice president, District number 2
G. McC. Porter, counselor, District number 2
L. L. Bosch, secretary, District number 2

Non-Delegates

H. H. Henline, national secretary, New York, N. Y.
H. H. Schroeder, secretary, Akron Section
H. T. Killingsworth, secretary, Cleveland Section
C. A. Powel, secretary, Pittsburgh Section
W. I. Albert, member, Pittsburgh Section
W. A. Summer, secretary, Sharon Section
Columbus Section was not represented.

At this meeting, Prof. A. M. Wilson was elected representative from District number 2 on the national nominating committee. W. H. Harrison of Philadelphia, Pa., was unanimously nominated a candidate for the Institute's vice president from District number 2.

The following were elected as members of the District's coördinating committee: H. A. P. Langstaff, W. A. LaMond, H. G. Dorsey, and Edgar Bell. These elected members, together with the vice president, District counselor, and District secretary constitute the District's coördinating committee.

The following were nominated as members of the prize paper committee: Prof. T. B. Owens, Cleveland, Ohio; Prof. H. E. Dyche, Pittsburgh, Pa.; and F. C. Hanker, Pittsburgh, Pa. The election of the committee was, however, deferred until after all papers are submitted for consideration, so that a committee could be selected of which no member would be called upon to review a paper one of his students or co-workers had presented. The date of presenting papers was changed to September 1, so as to put responsibility for presenting papers upon only one group of officers. Vice President Wilson urged each Section to stimulate interest in the presentation of papers for prize consideration.

A motion was passed that a meeting of the Middle Eastern District be held in Akron, Ohio, during 1936.

North Central District Executive Committee Meets

The annual meeting of the executive committee of the Institute's North Central District number 6, was held at Denver, Colorado, on October 26, 1934.

Those in attendance were:

R. B. Bonney, vice president
T. H. Granfield, chairman, Nebraska Section
R. H. Owen, secretary, Denver Section
N. R. Love, representing G. S. Dring, chairman, Denver Section
W. G. Rubel, District secretary
Prof. H. S. Rush, Chairman of the District committee on Student activities, was unable to be present.

Mr. Bonney called for nominations for the office of vice president of District number 6, the candidate for this office to be voted for in the election of national officers in 1935. R. H. Fair, of Omaha, a charter member of the Nebraska Section, was unanimously nominated for the office of vice president of District number 6.

Prof. G. H. Sechrist of the University of Wyoming was appointed to be the member of the national nominating committee from this District.

The selection of a District committee on prize awards to act as judges in awarding prizes to the authors of meritorious papers presented at Section or Branch meetings during 1934 was next considered. It was decided that the executive committee would elect one member to serve as chairman of the committee, and request the 2 Sections in the District to each select one member to complete a committee of 3. W. D. Hardaway of Denver was chosen to act as chairman of the committee.

The District conference on student activities was next discussed. At a previous

Membership—

Mr. Institute Member:

You frequently ask "What do I get for my dues?" We take it that you mean "What am I doing with my dues through my Institute?"

You will find the answer in Electrical Engineering for:

March 1934, page 375–81, by E. B. Meyer
July 1934, page 1039–46, by J. Allen Johnson
November 1934, page 1542–3, by R. H. Tapscott

Your Section membership committee has reprints in convenient booklet form of Mr. Johnson's article. We suggest you use them in a Section meeting. You will be pleased to hear all of the good things you are doing through your Institute.

Chairman National Membership Committee

Branch conference, the Branch counsellors voted to meet in Fargo, North Dakota, at the North Dakota Agricultural College for the 1935 conference. The executive committee heartily approved the holding of the District Branch conference and the secretary was instructed to notify Prof. H. S. Rush, chairman of the committee on Student activities, of the action of the executive committee and request him to proceed with plans for a District conference in 1935.

After considerable discussion of Institute matters, particularly the activities of the section membership committees and program committees, the meeting was adjourned.

Announcement of A.I.E.E. Prizes for Technical Papers

AUTHORS who plan to present papers before the Institute during the calendar year 1935, those who have presented papers during 1934, and others who may wish to submit papers for prizes, would do well to bear in mind that such papers are eligible for consideration for Institute prizes. These awards are made each spring for the preceding calendar year, and fall into 2 main classes, national and District prizes.

In accordance with the practice followed during the past 2 years, the board of directors decided to omit the cash awards for papers presented during the calendar year 1934, except that a payment of $25 in cash will accompany each District prize for Branch paper. All certificates will be issued as usual, those for national prizes signed by Institute officers, and those for District prizes signed by the officers of the Districts concerned. In cases of joint authorship, a certificate will be issued to each author.

National Prizes

The national prizes which may be awarded at the discretion of the committee on award of Institute prizes are as follows:

1. Prizes for best papers in (1) *engineering practice*, (2) *theory and research*, and (3) *public relations and education*.
2. Prize for initial paper.
3. Prize for Branch paper.

The national prize for best paper in each of the 3 classes indicated may be awarded to the author or authors of the best original paper presented at any national, District, or Section meeting of the Institute, provided the author, or at least one of co-workers, is a member of the Institute.

The national prize for initial paper may be awarded to the author or authors of the most worthy paper presented at any national, District, Section, or Branch meeting of the Institute, provided the author or authors have never previously presented a paper which has been accepted by the technical program committee, and the author, or at least one of co-authors, is a member of the Institute or is a graduate student enrolled as a Student of the Institute.

The national prize for Branch paper may be awarded to the author or authors of the best paper based upon undergraduate work presented at a Branch or other Student meeting of the Institute, provided the author or authors are Student Branch members.

All papers approved by the technical program committee which are presented at any meeting will be considered by the committee on award for the prizes for best paper and initial paper without being formally offered for competition. All papers other than those presented to the technical program committee must, in order to receive consideration, be submitted in triplicate with a written communication to the national secretary on or before February 15 of the year following the calendar year in which they were presented. This may be done by the author or authors, by an officer of the Institute, or by the executive committees of Sections, or Geographical Districts.

District Prizes

The following District prizes may be awarded each year in each Geographical District of the Institute:

1. Prize for best paper.
2. Prize for initial paper.
3. Prize for Branch paper.

A District prize may be awarded only to an author who, or to co-authors of whom at least one, is located within the District, and for a paper presented at a meeting held within, or under the auspices of, the District.

The District prize for best paper may be awarded for the best paper presented at a national, District, or Section meeting, provided the author, or at least one of co-authors, is a member of the Institute.

The District prize for initial paper may be awarded for the best paper presented at a national, District, Section, or Branch meeting, provided the author or authors have never before presented a paper before a national, District, or Section meeting of the Institute, and the author, or at least one of co-authors, is a member of the Institute, or a Graduate student enrolled as a Student of the Institute.

The District prize for Branch paper may be awarded for the best paper based upon undergraduate work presented at a Branch or other Student meeting of the Institute, the author or authors of which are Student Branch members.

All papers to be considered in competition for District prizes must be submitted in duplicate by the authors or by the officers of the Branch, Section, or District concerned to the District committee on awards on or before January 10 of the year following the calendar year in which the papers have been presented.

Copies of a pamphlet entitled "National and District Prizes" may be secured, without charge, upon application to Institute headquarters.

Future AIEE Meetings

Winter Convention
New York, N. Y., Jan. 22–25, 1935

South West District Meeting,
Oklahoma City, Okla., Apr. 24–26, 1935

Summer Convention,
Ithaca, N. Y., June 24–28, 1935

Pacific Coast Convention,
Los Angeles vicinity, Fall 1935

Great Lakes District Meeting,
Indianapolis—Lafayette Section territory (Date to be determined)

A.S.T.M. Elects New Officers. Hermann Von Schrenk, consulting timber engineer, St. Louis, Mo., and senior vice president of the American Society for Testing Materials, was elected by its executive committee to the office of president on October 9, 1934, to fill the vacancy caused by the death of W. H. Bassett who died July 21, 1934 (see ELECTRICAL ENGINEERING for Sept. 1934, page 1326). The vacancy created by Doctor Von Schrenk's election was filled by the appointment of H. S. VASSAR (A'06, M'18) as senior vice president, Mr. Vassar having been elected a vice president last June; he is laboratory engineer for the Public Service Electric and Gas Company, Newark, N. J. A. C. Fielder, chief engineer, Experiment Stations Division, U.S. Bureau of Mines, Washington, D. C., has been elected junior vice president.

"Science Series" Will Be Reprinted

In response to the widespread demand that resulted from the preliminary announcement made in the preceding issue of ELECTRICAL ENGINEERING, the special "Science Series for Engineers" that has been appearing in the pages of ELECTRICAL ENGINEERING during the past year will be reprinted and made available for distribution approximately February 1, 1935. By the time of its conclusion in the January 1935 issue of ELECTRICAL ENGINEERING, this series will have consisted of 13 articles, each on one of the more important fields of present day science, and each prepared by an authority in the field discussed, and each fully up to date as of the month of publication.

The booklet will comprise between 80 and 90 pages ($8^1/_2 \times 11$ inches) substantially bound and covered. Such a booklet should be of particular value to the practicing engineer, the recent graduate, the engineering student, and the future study of engineering subjects, as it will afford an authoritative digest of important current developments in several fields of science closely related to electrical engineering. Although most of the advance requests recorded to date have come as individual orders, several inquiries for quantity lots

have been received from colleges and universities where it is contemplated that the reprint will be required reading for technical students.

Although the issuance of the reprint is assured, the number printed will be determined upon the basis of the total number of orders that have been filed with the A.I.E.E. editorial department by Monday, January 7, 1935. For convenience, an order blank appears in the advertising section of this issue.

American Engineering Council— And Its Relation to the Institute

SUPPLEMENTING other articles recently appearing in ELECTRICAL ENGINEERING which serve to acquaint the membership of the Institute with its activities, interests, and inner workings (such as the 3 articles referred to in the "membership" item on page 1664 of this issue) the following comments on American Engineering Council and the interrelation between Council and the A.I.E.E. are offered. This article was prepared by Dr. J. B. Whitehead (A'00, M'08, F'12, and Life Member) junior past-president of the Institute:

AMERICAN ENGINEERING COUNCIL

American Engineering Council was founded in 1920 with the object "to further the public welfare wherever technical and engineering knowledge and experience are involved, and to consider and act upon matters of common concern to the engineering and allied technical professions." It includes in its membership about 20 national, state, and local engineering societies. Its headquarters are in Washington, D. C., principally because one of its recognized duties is the offering of advice and assistance in the formulation of legislation involving engineering enterprise, and further because of the opportunities thereby offered for contact with various departments of the National Government which are commonly engaged in undertakings involving engineering advice and services. Two distinctly definite purposes are in view in these relationships. The first is that the engineering profession may be advised promptly of all legislation which may possibly affect the profession as a whole as well as its individual members, and second that the profession may make readily available to the Government, not only professional advice when such is desired, but also may have a rapid medium of exchange of information as to where engineers are needed and where suitable competent engineers may be obtained.

DESIRABILITY OF A CENTRAL ORGANIZATION

There are approximately 150,000 engineers of recognized professional standing in the United States; if those in subordinate technical positions be included, the number is more nearly 225,000. It is a remarkable and very unfortunate fact that this great body of professional men, having many interests and ideals in common, have not yet set up a central organization representative of the engineering profession as a whole, which is qualified and authorized to speak for it on matters of public interest.

The reason for this condition is that the 4 great national societies of civil, mechanical, mining and metallurgical, and electrical engineers were founded in an earlier period, in which the relationship of engineering undertakings to civic and national affairs was less important. Each of them has grown independently and in its own field, because the special aims of each are the advancement of the respective technical arts, and the elevation within those arts of professional standards. Nowhere apparently within the vision of the founders of the national societies, nor in their constitutions, is there evidence of a belief that questions arising in a future complexity of the relations of industrial enterprise to civic and national economy and government, should be directly attacked independently by the respective engineering societies.

The question is no new one. Throughout the years, these 4 founder societies have frequently coöperated with each other in matters of common concern, particularly in those involving material interests, through joint committees or other bodies with greater authority, such as United Engineering Trustees, American Standards Association, and others. These bodies however, exist for the specific purposes, such as the operation of the Engineering Societies Building, the Engineering Societies Library, and other matters of similar nature. They are not empowered to speak for the profession as a whole on matters of either professional or public interest or import. However, the founder societies, together with others throughout the country, have set up one joint agency which, through its original charter and subsequent development, in some measure meets the need of a single agency which concerns itself with the interests of the profession as a whole, and provides at least a forum and a medium for the discussion of the manifold inter-relationships in modern life among the engineering profession, the individual engineer, and the public welfare. The name of this body is American Engineering Council.

OTHER OPPORTUNITIES FOR COUNCIL

Thus American Engineering Council has many other opportunities and duties

A "Million Dollar Car"

ABOUT 5 years ago a fund was made available through the efforts of the Electric Railway Presidents' Conference Committee for the development of an improved type of street car. The result of the research work, carried on under the direction of Dr. C. F. Hirshfeld (A'05) of Detroit, Mich., is the car pictured here, which cost upward of $1,000,000 to build. This car, one of 4 designed as the outgrowth of the research work of the committee, incorporates many innovations in design. The car is practically noiseless, due partly to the resilient type of wheel obtained by the use of steel parts interlocked with rubber. Trucks are specially designed, rubber springs being used. In the construction of the body, a newly developed alloy corrosion-resisting steel known as "cor-ten" has been used, and welding is used extensively. The weight of the complete car is approximately 31,000 pounds, and it seats 50 passengers. Forced ventilation and indirect illumination are used. Among the unusual features of the car are its extremely rapid but smooth starting and stopping, it being claimed that the car can get under way 10 to 15 per cent faster than the most modern type of automobile. This is particularly important in maintaining high schedule speeds with frequent stops in congested traffic. The committee under which it was developed is composed of the leading executives of some 25 of the larger street railways in the United States. A number of the larger manufacturers of cars and equipment coöperated with the committee.

beyond those outlined in the opening paragraph above. It is within its proper province to develop discussion of any matter of public interest involving engineering services. Its annual reports, abstracts from which are published from time to time in ELECTRICAL ENGINEERING enumerate many instances of this type of activity. The wide range taken by these discussions is indicated by the list of special committees of of the Assembly, of which there are 12 or more active at present. Among these may be mentioned, as illustrating the scope of the Council's interests, the committees on administration of public works, communications, engineers water power policy, flood control, patents, relation of consumption, production and distribution, and the like. During the past year a number of questions were referred to the Institute, the proper study of which would involve far more time than could be given to them under the Institute's voluntary committee system, and which in general did not fall within the scope of the Institute's normal types of activity. Three such instances were: the effect of the N.R.A. codes on the profession, employment conditions for engineers imposed by the federal government, federal public works policies involving governmental competition. Such questions, always important not only to the electrical engineer, but to the profession as a whole, are frequently arising from both within and without the Institute. They are commonly referred to American Engineering Council. Council has always attacked such questions effectively. In many cases satisfactory action or answer have resulted. In others of more permanent nature, the interests of engineers are being constantly protected through the furnishing of information, or the dignified advocacy of the rights of engineers as based on the high principles of the profession.

COUNCIL COULD BE MADE MORE VALUABLE TO THE INSTITUTE

From the foregoing it will be seen that in 2 of its functions American Engineering Council should appeal especially to members of the Institute. First it is the only existing agency properly authorized for joint discussion and utterance on matters of interest to the engineering profession as a whole. With comparatively slight modification in organization, Council could probably be converted into the ideal body for this purpose. The second effective service being rendered by Council to members of the Institute is in its concern for the material and economic welfare of the individual engineer. This is one of its normal functions. Instances of activities of this type have been indicated above. Questions involving the welfare of the individual electrical engineer also frequently arise both within and without the Institute. They are referred to American Engineering Council as one of its prime concerns. For these and other reasons the board of directors of the Institute has indicated by repeated action that it believes that American Engineering Council should be supported and developed. The method for this development is through the joint and proportionate coöperation of the various engineering societies of the country, with the enthusiastic support of their respective memberships. At present, the annual appropriations of the supporting founder societies to American Engineering Council are only about $^1/_4$ their average value over a number of years up to 1931. Desirable activities for American Engineering Council are correspondingly limited. The present appropriations should be increased if the full value of the Council is to be realized.

A Reading List for Junior Engineers

A LIST of books recommended for reading by junior engineers has been prepared by a number of eminent men, many of them distinguished in the engineering profession. Systematic reading of worth while books adds breadth and vision to the background of an engineer and should be considered a part of the intellectual development designed to fit the young engineer for full professional recognition.

Instead of offering the entire list to the readers of ELECTRICAL ENGINEERING at one time, it is felt that its purpose will be served better if only a few books are mentioned each month. Accordingly, the suggested books which fall under the classification of "Natural Science" are presented herewith; books on other subjects, such as philosophy, economics, sociology, psychology, business and industrial management, literature, history, biography, travel, fine arts, and a general list are scheduled for publication in subsequent issues.

The list has been prepared on the basis of a generally accepted classification. It includes more than 100 titles, and it is suggested that over a period of about 4 years a minimum of 25 of these books might be selected and read, with the limiting recommendation that the selection made will include at least one book in each classification, preferably in accord with the individual engineer's most vital interests.

Natural Science

Concerning the Nature of Things, William Bragg. Harper, 1925. A simple account, with many photographs, of the properties of atoms, and of the nature of gases, liquids, and crystals. Author is a pioneer in X ray work.

History of Science and Its Relation to Philosophy and Religion, W. C. Dampier-Wetham. Macmillan, 1929. Evolution of scientific thought and research from dawn of history in Babylonia and Egypt, through the speculations of Greece, and past the blind alleys of the Middle Ages to the present.

Origin of Species, Charles Darwin. Appleton, 1900. The preservation of favored races in the struggle for life. Contains additions and corrections from the sixth and last English edition. Is not speculation, but evidence of what actually is.

New Conceptions of Matter, C. G. Darwin. Macmillan, 1931. Originally a series of lectures at Lowell Institute, Boston. Author is Tait Professor at University of Edinburgh. Book presents the broad features of the new theoretical physics in nontechnical terms.

The Nature of the Physical World, A. S. Eddington. Macmillan, 1928. Takes up both relativity and the quantum theory and traces the effect of modern concepts on free will and determinism.

Philosophical Basis of Biology, J. S. Haldane. Doubleday, Doran, 1931. Object of this volume is to present the theoretical basis of the nature of life which "biological observation seems to force upon us." Lectures were given under Donellan Foundation at Trinity College, Dublin.

Mysterious Universe, Sir James Jeans. Macmillan, 1933. A discussion for the layman of our relation to the universe. Man's increased knowledge has resulted in a new formulation of this problem which has interested philosophers for thousands of years. Presentation is simple and lucid and, of course, authoritative.

Human Life as the Biologist Sees It, Vernon Kellogg. Henry Holt, 1922. For the layman. Interprets in simple language what science teaches about mankind in its relationship to origins, heredity, everyday life, death, the soul, and the future.

The Living Past, J. C. Merriam. Scribner, 1930. A study of evolution from plant and animal life as indicated in footprints, bones, leaf imprints, skeletons, and other remains found in various parts of the country.

Grammar of Science, Karl Pearson. (London) A. & C. Black, second edition, 1900. Exposition of the meaning of scientific law. Interesting questions and analogies. Much destructive criticism of earlier scientists. This latest edition contains 2 new chapters: one on contingencies and correlations, and another on modern physical ideas.

What Industry Owes to Chemical Science, R. B. Pilcher and Frank Butler-Jones. Van Nostrand, 1931. A fine résumé of advances made in metallurgy and manufacture and various commodities and the application of scientific research. Very readable and most compact and a convenient history of industrial chemistry.

Man and Metals, T. A. Rickard. McGraw-Hill, Whittlesey House, 1932. A history of mining in relation to the development of civilization from prehistoric times. The author is an authority and the book full of information.

Flights From Chaos, Harlow Shapley. McGraw-Hill, 1930. The reader will find it valuable whether he knows little or much about astronomy. A good stretching exercise for the imagination.

Modern Science, Sir. J. A. Thomson. Putnam, 1930. The author discusses this question: Will the teachings of astronomy and science change our outlook on the universe as a whole, and the meaning of human life? Book is valuable as a means of provoking thought.

Geography, H. W. Van Loon. Simon and Schuster, 1932. Popular geography, emphasizing the human interest side of the world we live in. Discusses why we live where we do, where we came from, and what we are doing.

T.V.A. Orders Gas-Electric Locomotives. On what is reported to be their most important engineering project to date, the Tennessee Valley Authority is using 4 10-ton Plymouth-Westinghouse gas-electric locomotives to haul the nearly 1,000,000 cubic yards of concrete which will be required for the Norris Dam. The locomotives haul Insley concrete cars from the concrete mixing plant and operate the

motors to tilt the 4 cubic yard skips into the hand dump concrete buckets on the cableways spanning the valley and covering the entire dam, spillway, and power house area. The gas-electric generators on the locomotives supply the power for all of these operations to the buckets at the dam site. These 12 foot long locomotives are powerful and fast. The starting tractive effort with 25 per cent adhesion is 5,000 pounds; continuous tractive effort is 1,650 pounds. With a maximum safe speed of 23 miles per hour, the locomotive has a free running speed of 15 miles per hour and a 10 mile per hour speed when operating at the continuous tractive effort rating.

Services of Engineering Societies Library Available

THERE is a large group of engineers who cannot visit the Engineering Societies library because of distance or lack of time. Therefore the library maintains a "service bureau" to make available to each engineer the information he needs. This bureau searches for information on all phases of engineering, suggests books or magazine articles, prepares bibliographies tells what is in the bibliographies by means of abstracts, supplies photoprints of material in the library, and makes foreign language publications usable by providing accurate translations.

The services of the bureau range from suggesting a book or 1 or 2 articles on a given subject to the preparation of exhaustive bibliographies for use in engineering projects or in patent litigation. A loan collection of modern American engineering books is also maintained from the convenience of members of the 4 national societies of civil, mechanical, mining and metallurgical, and electrical engineers, and contributing societies. The investigations of the bureau are not limited to the extensive resources of the Engineering Societies Library. Engineering Societies Library searchers have access to all libraries in New York City and use them to answer questions in fields more or less related to engineering.

More than $^1/_6$ of the total number of people using the library each year cannot visit it in person, and as a part of the Engineering Societies Library, the service bureau has served engineers in every state of the United States as well as in more than 50 foreign countries.

Bibliographies

When bibliographies are furnished by the service bureau the mere possession of a list of books and articles may not solve the engineer's problem. He will probably need the information to be found in literature, rather than a mere list. Thus it has been necessary to extend the work of the service bureau so as to offer approximately the equivalent of a visit to the library. When bibliographies are compiled a note is appended to each article explaining what it is about, so that the recipient of the bibliography can tell whether he needs to read a given article as a whole, in part, or not at all. When he has determined what articles he should read, if he cannot obtain them at a local library, he may send a list of them to the Engineering Societies Library to have photostatic copies made. The library is equipped to supply photoprints of all material on file. But even the possession of an exact copy of an article may be insufficient if the article is in a foreign language. In such cases the service bureau supplies exact, technically accurate translations.

It is to be noted that the service bureau has on file more than 4,000 bibliographies already made up on special engineering subjects. Any of these may be procured by paying a moderate copying charge. As an example of the type of material contained in these lists, some of the bibliographies on various aspects of electrical engineering are listed in table I.

Some of the other electrical engineering subjects covered or partially covered by bibliographies already compiled and in the files are: Accelerator tubes, arc furnaces, arc rectifiers, arc welding, arcing rings, artificial electric lines, batteries, copper wire, dielectric constants, electric arcs, electric automobiles, electric boilers, electric cables, electric cells, electric condensers, electric conductivity, electric conductors, electric conduits, electric cooking, electric distribution, electric drives, electric elevators, electric furnaces, electric galvanizing, electric generators, electric heating, electric lamps, electric lines, electric locomotives, electric machinery, electric meters, electric

Table I—Examples of Type of Subjects on Which Bibliographies Are Already on File

Search Number	Number of References	Cost of Copy	Subject or title of list	Dates Covered
3874	23	$1.50	Power factor	1913–1923
4032	133	5.00	Muscle Shoals	1916–1925
4566	522	15.00	Interconnected networks (not annotated)	1918–1930
4380	15	1.25	Automatically controlled hydroelectric power stations	1923–1927
4556	40	1.75	Electric power plants	1927–1930
3921	78	5.00	Ventilation and temperature rise in electric machinery	1901–1924
3707	452	19.50	Power losses in electric machinery	1885–1922
4527	13	1.00	Prevention of frosting in relays, motors, etc.	1904–1927
4019	26	2.00	Third brush generator	1913–1920
3295	16	1.50	Designing and testing fractional horsepower motors	1901–1919
4525	18	1.25	Single-phase synchronous motors	1918–1926
4071	32	2.25	Magnetic leakage in induction motors	1903–1923
4038	7	0.50	Shaded pole a-c induction motors	1898–1931
4323	133	9.50	Electrolytic rectifiers	1866–1926
4263	8	0.75	Wind pressure on transmission lines	1920–1925
4261	11	0.75	Ice on transmission lines	1917–1926
3650	56	5.00	Rubber insulated wire	1895–1922
4391	13	1.25	Corrosion of underground lead cable	1907–1928
4358	100	7.00	Underground transmission and distribution	1929–1927
3941	36	2.25	Heating of buried electric cables	1900–1922
3559	21	1.50	Copper conductors	1911–1921
3772	358	11.00	Iron and steel electric wire and cables	1838–1924
4444	21	1.25	Impulse breakdown tests on dielectrics	1900–1928
3259	9	0.75	Sludging test for transformer oil	1911–1920
4453	7	0.50	Oxygen in insulating oils	1913–1928
2755	43	3.50	Materials for molded insulators, excluding porcelain	1910–1919
3054	7	0.75	Suspension insulators	1912–1930
4588	28	1.25	Transmission line masts (not annotated)	1925–1930
3538	10	0.75	Stresses in steel towers for transmission lines	1910–1921
3867	61	4.00	Steel towers for transmission lines	1891–1913
2126	26	1.75	D-c vs. a-c for urban distribution	1896–1918
4548	49	2.50	High voltage substations	1927–1931
4477	6	0.50	Storage batteries in substations	1926–1928
2321	18	1.50	Rheostats	1912–1918
4504	76	5.50	Lightning arresters	1924–1929
4344	13	1.00	Arcing rings	1921–1927
4180	12	1.00	Ground wires for overhead transmission lines	1913–1926
3537	14	1.00	Braun tube oscillograph	1897–1923
4015	15	1.00	Design and construction of solenoid type magnets	1911–1924
4637	54	3.50	Lifting magnets (American literature only)	1832–1929
4947	31	2.00	Electrolytic condensers	1908–1931
4395	25	1.50	Neon tubes	1927–1931
3539	158	5.00	Electrification of railroads (not annotated)	1913–1931
4326	43	3.00	Diesel-electric locomotives	1927
3324	69	6.00	Advantages of electric drive in industry	1916–1930
3155	31	2.50	Gas batteries	1839–1913
2844	10	1.00	Manufacture of storage batteries	1902–1917
3418	98	3.00	Design and manufacture of lead storage batteries	1911–1921
3865	13	0.75	Electrochemical and electrothermal processes	1910–1923
3710	5	0.50	A-c electrolysis	1907–1931
1343	15	1.00	Electricity direct from heat	1894–1904
4400	6	0.75	Thermocouple electric generators	1910–1925
2907	64	4.00	Electric heating and cooking	1918–1920
2957	33	2.00	Electric resistance furnaces	1914–1920
4037	49	2.50	Selenium cells	1903–1918
4651	8	0.75	X ray transmission and reception	1923–1930
2116	53	2.50	Poulsen's telegraphone	1899–1908
2758	91	3.50	Inductive interference between power and telephone circuits	1887–1919

motors, electric plowing, electric power plants, electric prospecting, electric railways, electric rates, electric shock, electric trucks, electric welding, electric wires and wiring, electricity, electricity from heat, electrification of railways, electrodeposition, electrodes, electrolysis, electrolytic condensers, electromagnets, electron tubes, foundations for electric machinery, frequency changing, frosting of electric machinery, glow lamps, grounds, high frequency circuits, high voltage transmission, hydroelectric plants, hydroelectric power, incandescent lamps, induction motors, inductive interference, insulating materials, insulating materials, insulators, interconnection, interference, lamp sockets, lamps, magnetic clutches, magnetic permeability, magnetic separation, magnetic testing, magnetism, magnets, mica insulation, motors, neon tubes, radio, railroad signals, rectifiers, relays, remote control, resistance, resistivity, resistors, rheostats, rotary converters, selenium cells, substations, telegraphy, telephony, Thury electric transmission, transformers, transmission lines, ventilation of electric machinery, watt-hour meters, wave filters, welding, wire, wired wireless, X ray testing, X rays.

Any of these bibliographies may be brought up to date or extended as far back as may be required. Estimates for such work will be furnished by the library on request. If a problem is not covered by one of the bibliographies on file, the service bureau will gladly try to find the information needed, and if that cannot be done within the time available for free work it will advise the member of the need for a search and its probable cost.

The resources of the Engineering Societies Library are thus made available to engineers everywhere. All services are rendered at cost. For information communicate with the Engineering Societies Library, 29 West 39 Street, New York, N. Y.

A.S.T.M. Reports on Electrical Research Activities

IN A supplement to the A.S.T.M. *Bulletin* for October 1934, there were reviewed in brief 51 A.S.T.M. committee projects "initiated primarily to extend and amplify the knowledge of the properties of materials," and 63 committee projects "devoted to methods of testing in connection with which there are conducted investigations . . . . . that may lead to the preparation of standard test methods. . . . . ." Among the latter 63 items were the following 10 under the jurisdiction of A.S.T.M. committee *D*-9 which are reflected here because of their probable interest value to electrical engineers in particular: (these summaries include "information not otherwise generally available except after laborious reference to reports of 60 research, joint, and standing committees.")

Tests of Insulating Varnishes. Investigation and development of the following methods for varnish films: hardness and oil resistance; acid and alkali resistance; and insulation resistance. See preprint, 1934 report of committee *D*-9.

Tests of Saturant Varnishes. Studies of such properties of saturant varnishes as impregnation, internal drying, bonding strength, and dielectric strength when the varnish is used as an impregnating medium in cotton fabrics. Work recently undertaken; not yet reported upon.

Tests of Molded Insulating Materials. Investigation of methods of measuring impact fatigue of molded phenol plastics, and studies of dimensional tolerances suitable for phenol plastic impact test specimens and of the effect of moisture content on impact and transverse strength of phenol plastic test specimens. Investigation of the effect of the type of mold used on the physical strengths of plastic molded test specimens. Also tests for density and particle size of molding powders and plasticity and cure tests. Improvements in impact specimens prepared; also methods of testing molding powders used in manufacturing molded electrical insulators developed, see preprint, 1934 report of committee *D*-9.

Tests of Insulating Papers and Fabrics. Investigation and development of methods and apparatus for testing insulating papers, as follows: Procedure for measuring thickness; instruments for determining tearing strength and folding endurance; tests for moisture in impregnated cable paper; acidity tests; air resistance of insulating paper and effect of humidity on dielectric strength of varnished cambric. Methods for thickness and folding endurance developed also specifications and tests for varnished cloth tape and flexible tubing, see preprint, 1934 report of committee *D*-9.

Tests of Insulating Sheets, Tubes and Rods. The following studies of laminated sheet insulating materials are being conducted: Method for determining compressibility as a function of time; methods of measuring the modulus of elasticity in compression; the effect of temperature variations on water absorption; effect of humidity on dielectric strength and on flexural strength; impact fatigue tests, arc resistance, hardness tests, punching quality, and insulation resistance tests; also methods of test for flammability and heat resistance. Indentation hardness test using Rockwell tester developed. For current progress, see preprint, 1934 report of committee *D*-9.

Tests of Liquid Insulation. Development of tests primarily applicable to circuit breaker oils, such as the determination of gas formed during arcover, measurement of carbon formed and precipitated during arcover, and a test for amount of water precipitated or emulsified during arcover; also low-temperature viscosities. Studies of the following tests of insulating oils: Neutralization value of both new and used oils; resistance of insulating oils to oxidation (sludge tests), tests for moisture content and for saponification value. Consideration being given to tests for cable oils. Methods for sampling both used and unused insulating oils adopted. Progress reported of work on neutralization number and sludge tests, see A.S.T.M. *Proceedings*, Vol. 33, Part I, p. 400 (1933); also preprint, 1934 report of committee *D*-9.

Tests of Insulating Compounds. Investigation of methods of test for solid filling and treating compounds used for electrical insulation, including: Coefficient of expansion; determination of insulation-resistance temperature characteristics; specimens and tests for dielectric strength; also viscosity tests of high melting asphaltic compounds. Procedures developed for measuring coefficient of expansion and for power factor and dielectric strength, see preprint, 1934 report of committee *D*-9.

Power Factor and Resistivity of Insulating Materials. Development and preparation of test methods for measuring dielectric constant and

Control Board of Radio City Music Hall Stage

MANY of those who will attend the Institute's 1935 winter convention to be held in New York, N. Y., January 22–25, will visit the International Music Hall at Radio City. The control board for the stage of this theater is shown here; from this point on the stage, the mechanism of what is reported to be the world's largest stage is operated. Three giant hydraulic plunger elevators that can be lowered 30 feet below stage leve and alsed 15 feet above stage level make up the huge stage. Built into all 3 elevators is a sectional revolving stage. Thus, when the 3 stage elevators are locked together electrically, they travel as one elevator with revolving stage working while the elevators are going up or down as a unit. The control board of the huge contour curtain that masks the proscenium is also shown, illustrating the method of gaining any contour desired by presetting the 13 push buttons controlling the 13 motors that raise and lower the curtain.

power factor of liquid insulation and of solid insulating materials. Resistivity methods for liquid and solid insulation adopted, also procedures developed for power factor and dielectric strength of solid insulation at 100 to 1,500 kilocycles, 1,000 cycles, and 25 to 60 cycles. See preprint, 1934 report of committee *D-9*. In connection with this work see papers by W. B. Kouwenhoven and L. W. Marks on "A Comparison of the Methods for Testing Insulating Materials for Power Factor and Dielectric Constant at 1,000 Cycles" and by P. H. Dike, W. B. Kouwenhoven, and J. B. McCurley on "Methods of Measurement of Dielectric Characteristics at Commercial Frequencies," issued [by A.S.T.M.] separately.

Tests of Mica Products. Study of methods covering mica for capacitor manufacture and built-up pasted mica for general insulating purposes. Tentative methods prepared for grading natural mica and tests for pasted mica, see preprint, 1934 report of committee *D-9*.

Properties of Electrical Slate. Study of the properties of slate for use in electrical work. Consideration being given to methods for electrical quality and impact tests. No report available.

Finding Work*

An authoritative dissertation dealing in a practical way with the important problem of finding work, and keeping it after it is found. This article was written by Samuel S. Board, placement specialist of New York, N. Y., for the American Society of Mechanical Engineers. Because of its general interest and value it is republished here in full.

THERE are very few men out of work today who have not made the rounds of companies with which they are familiar, of friends, and of organizations which list jobs; many of them have tried the methods which other men have used successfully; and yet they have not been placed or they have taken wholly inadequate positions. There is no patent method which will reach the needs of all of these men. The techniques of finding work have been tried repeatedly, and while there may be variations in the end the same procedure must be adopted.

No claim is made for originality in connection with the suggestions which follow. They involve merely a restatement of the *whole* process which must be followed in finding work when it isn't easily available. By a careful check as to what you or any one else has done in attempting to secure work, you may find *some* point which you have overlooked or some little thing which is wrong and which is enough to make the difference between success and failure.

Some years ago a really able sales manager lost his job because of difficulties in the company for which he had worked and finally came to me to check over his procedure in securing a new one. He had tried for several jobs and had been turned down in favor of some one else each time. He realized that something must be wrong but had not been able to determine just what. A careful review of what he had done each time revealed the fact that he had passed the first interview with flying colors but had fallen down on the second. When asked how long this second interview usually lasted he replied that he stayed as long as the prospective employer seemed to want him to—2 hours, 3 hours, or even longer. This seemed to be the difficulty (why, will be explained later), and after he had shortened this interview to 20 minutes or slightly more, he secured the next job for which he applied. This may seem to be a small matter, but it is little things which frequently cause the difficulty. The following article, therefore, is presented so you may check *your* procedure against what might almost be called "standard practice." If you are going to read it at all, I should like to ask you to read it through, even though some of it may seem irrelevant to your particular situation.

Distinguishing Factors in the Engineer's Problem

Despite the fact that most elements in the situation facing the engineer seeking work are similar to those facing other men, there are some which differentiate him from other groups of the unemployed. All of these elements will be found separately confronting some other group, but it is the combination which is certainly distinctive.

One of the most important of these is the fact that the engineer is so often employed by the job. Of course, laborers and artisans and sometimes such semi-professional workers as accountants are employed in this fashion, but on the whole men of comparable grade and ability such as major and minor production executives, salesmen, credit men, purchasing agents, and so forth, work not by the job but for an indefinite period until business contracts, the organization changes, or they fail to grow with sufficient rapidity to keep up with the requirements of the work. This means that whereas the other professional or semi-professional men may give their attention in the main, to "making good" on the job, the engineer must usually keep his eyes open for the next job. During such a period as that between 1923 and 1929, this may be largely unnecessary, since the demand for men of real ability is greater than the supply, but even under such circumstances the engineer, especially the young engineer, may be out of work for a period of from 2 weeks to 3 months. Such a lapse is a tremendous economic loss when the total time is figured.

This problem is, of course, intensified during depressions. While many other types of workers are "carried" by their firms even when work is slack, the engineer is likely to be laid off as soon as the need for his services has passed, especially if he has been with the firm a comparatively short time. There is, on this account, an especial reason for his attempting to work out an orderly method of advancement and for his learning the technique of selling his services when a change is necessary.

For some reason—perhaps because they are more used to studying materials and processes than people—many engineers seem to have little understanding of the fact that there *is* such a technique. Even sales engineers fail to study this question from a sales standpoint. The importance of making it a study, however, cannot be overemphasized.

Back in 1928, the president of a good-sized Chicago company telegraphed my office that he would be in New York the following day and wanted to see 3 sales engineers out of which he would pick one. Three good men were corralled for him and were duly interviewed. Afterward, the one I myself had rated as best in experience and ability came in and said that he had the job. (Those were the days when employers did not feel that they had to negotiate for 6 weeks or 6 months before employing men.) Long experience had made me skeptical regarding the validity of any hiring on the basis of a $^3/_4$ hour interview so I asked the engineer how he got the job. He laughed and said, "Well, I discovered in the first 2 minutes that he was an enthusiast about small boats. I've handled and sailed them all my life, so we talked 40 minutes about boats and 3 minutes about the job, and I was hired."

Even though you may not think this employer was careful enough, the man *did* understand the principles of selling and applied them successfully. Many engineers either do not understand them or fail to use them when their own future is the subject of discussion.

A third distinguishing factor in the engineer's situation is connected with the cyclical variations of business activity. Frequent reference is made to the "business cycle" as if the variations were the same for all industries, when as a matter of fact the curve which is referred to is a composite of many curves which vary in periodicity and intensity. A great many engineers are employed in connection with the heavy industries and the building trades. While some of these, at least, have longer cycles, the intensity of the swing is greater and therefore the unemployment is more severe. Many engineers also are employed in the developmental side of business and such work is more likely to take place during business rises or when money is easily available. In mentioning this there is no intention of suggesting that engineers should not engage in such work but merely that these conditions should be reckoned with and an effort made to discount them.

This can be done in several ways. It is possible to specialize as to one's major oc-

* Reprinted by permission from the November 1934 issue of *Mechanical Engineering*. Copies of this article, reprinted in small pamphlet form, may be obtained from the publication sales department of The American Society of Mechanical Engineers, 29 West 39th Street, New York, N. Y., at the following prices: Single copies, 10c; 100 copies, $9.00; 200 copies, $15.00; 300 copies, $21.00; 400 copies, $24.00; 500 copies, $25.00.

cupation and yet maintain sufficient contact with other types of work so as to shift when the times demand it. Hobbies which may be entirely outside the technical fields have provided depression occupations for engineers. At least 2 engineers of my acquaintance assured me that they made quite satisfactory incomes during the picture-puzzle craze by cutting them out for the high-class shops on the jig saws that were a part of their home workshops.

A sounder method, however, would be, I believe, for men who have worked for the larger companies and on larger projects to search out smaller manufacturers when times get slow and give them the benefit of engineering knowledge, since small plants, if efficiently managed, can adapt themselves more easily to changed conditions than can the larger ones and can hire experts when they are available, without upsetting a general policy.

One Connecticut manufacturer told me that he saved 60 per cent of his fuel bill one year during the depression by putting 2 young mechanical engineers on a job ordinarily done by laborers and then getting them to show the others how to do it properly. This sounds almost fantastic, but his plant made money that year when other similar ones did not. Of course, the biggest difficulty in undertaking to make a job like this, when one is not obvious, is that of "selling" these small employers. Many of them are not so intelligent or progressive as the one mentioned, but it can be done.

The differences just reviewed between the problem of the unemployed engineer and that of another educated man are not really so large, but they should be considered in devising any real attack on the unemployment problem of the engineering group. Even though this is so the attack must be along the same general lines as should be followed by any man out of work. Essentially, the problem for the individual is the problem of salesmanship. He must first determine the value and uses of what he has to offer. Then he must find a market, and, finally, he must outline an advertising and selling campaign which will inform possible buyers of the value of his wares in such a fashion as to make them pay real money for them. This is a simplification of the procedure which will be outlined in the remainder of this discussion.

What the Engineer Has to Offer

As has been stated, the first step which must be taken in selling a man's services as in selling a product is to determine what he has to offer. Something of an analogy is offered in the development and marketing of cellophane. According to the information at my disposal this was one of a number of products developed by the du Pont laboratories to use up the nitrocellulose left after the War. The government took most of its share out to sea and dumped it after caching a certain amount for future emergencies; but the du Pont company, being a private concern, did not feel it could do this and set its technicians at work to find other uses for it. Cellophane was one of the results. Even after it was ready for production the laboratories and the sales force had to study its uses, alter its composition to meet new requirements, and determine its tensile strength and ability to resist moisture. If they had not done a thorough job on that phase of the marketing, the phenomenal increase in its use could not possibly have taken place. Now they even make women's dresses of it.

Let us pursue somewhat the same method in determining what the engineer has to offer. In the first place, nearly every trained man has 2 antithetical advantages in amounts which are in inverse ratio to each other. Either he has youth and is relatively inexperienced, or he is more mature and has more experience. I suppose there is a middle ground somewhere in the early thirties when he has both youth and experience in considerable measure but the exact point of balance is hard to determine and is not important. Young men do come to me though and complain that they cannot get work because they lack experience. Older men are discouraged because (they say) the world is looking for young men. Both are wrong. The young man can find certain work where experience is unimportant and the older men can find it where maturity and experience are assets. The mistake both make is in trying to reverse their positions.

In the main, I think it is safe to say that large corporations tend to look for younger men, while smaller companies or new businesses are likely to seek men of more maturity who can take responsibility rather quickly. However, if you are young, you can sell the idea of youth and enthusiasm and the desire to work under some one who knows what it is all about.

If you are older, you can emphasize the value of your experience, the importance of your past positions, and the maturity and seasoned knowledge which you can bring to the job.

If you must seek work outside your own field it will mean, of course, that you must break down your experience into functions performed, in order to discover those easily adaptable to other types of work. For example, a mechanical engineer may be thought of to the world outside of the engineering fraternity in terms of the construction and operations of machines and power plants, whereas, you know that a mechanical engineer may be a designer, an operating superintendent, a test engineer, a sales engineer, a manufacturing executive, a production engineer, a research worker, and a lot of other things that I may not know. Moreover, there are designers of turbines, of automatic machinery, of fine tools, of automobile and airplane engines, and an almost infinite variety of machines and products. All these different types of work involve variations in interest and ability which can be used in describing your abilities along other lines. I do not mean to infer, of course, that what you have done in the past limits what you may do in the future, but the experience and abilities you know you possess may at least be used as a means of transition and should be so used.

Many men who are forced to seek work outside their immediate field try to make, as they say, a clean break and secure something which is entirely unrelated to what they have done before. Even though this may be a natural reaction it is an expensive method, since it usually means taking a beginner's wage. However, if you are willing to take a job in which some of your former experience can be used you can obtain substantially more and then later on take another step farther away and continue that process until a satisfactory occupation is reached.

In any event the only common denominators between jobs are the activities which are involved in these jobs. Any man who can do fine work with tools in one line can probably do similar work with difficult tools in another line. A person who is used to assembling and interpreting data can, at least with some training, take up this activity in another field. A man who is used to handling workers in one type of factory will not have much trouble learning to handle people elsewhere. Have you thrived best where action was involved? See action in a new job. Some day a dictionary of work functions will be prepared and then the task will be simpler. Meanwhile we must interpret our own past activities in terms of new jobs, just as we would describe what a product would do.

Importance of Appearance

The next most important phase of the study we are making is that having to do with what compares to the appearance, fiber, form, and shape of a product. In other words we must be prepared to describe the physical and mental equipment, the appearance, and the personality of the man in question. It is much more difficult for a man to do this for himself than for him to describe and study his experience or his specific work aptitudes. Yet it must be done since no job specification is written without including some of these factors, and to determine whether we meet these qualifications we must have some idea as to just what specifications we can meet.

It is also important as a preparation for the interview by which we may attempt to sell our services. In any such interview, a good share of the impression we make will be governed by what is termed our personality. This includes general appearance, clothes, voice, language, timidity or aggressiveness, and responsiveness to ideas. Of course, there are some things in this category that we just cannot change and these are the points on which men are prone to dwell in their own thinking. After we are 20, for instance, we can't add to or detract from our height, and most of us haven't come to the point, even if some bandits and the ladies have, of employing plastic surgeons to alter our faces. We can, however, even with limited means, be sure that our clothes are suitable and in order, that we look well-groomed, that our expression is alive, our faces mobile, our voices resonant, and our bearing alert.

Some engineers seem to feel that paying attention to personal appearance smacks of the beauty parlor, but that is all tommyrot. Being sure your appearance is suitable is what counts. It wouldn't be safe to go out on many engineering jobs wearing spats and carrying a cane, but these accouterments are an advantage on some jobs. Neither is it suitable to apply for an office job looking like a tramp or to ask for work on a relief project looking like a million dollars. One of the most pathetic stories of the depression has to do with an instance of this. It seems that an elderly clerk, who had worked for years in the financial district only to be laid off in the early part of the depression, was

literally destitute. He and his wife were starving when some one told him about a relief job that he might get the next morning. By this time his clothes were rather shabby but his wife sat up all that night sponging and pressing his only decent suit so that he would be presentable. She did too good a job, however, because when he applied for the relief job he looked so prosperous that they would not believe that he needed help and refused to do anything for him.

You really must dress and act the part in applying for any job, and the first step in doing this is to appraise your usual appearance, your personal assets and liabilities. It is comparatively easy to compensate for or remove liabilities and it gives you so much more confidence if you are aware of your assets.

Making a Personal Appraisal

There is one great danger in this matter of personal appraisal and that is the possibility of its degeneration into introspection. This will be very likely to happen if you try to assemble all these facts you have been gathering in your head. It just cannot be done properly that way. While you are considering one set of facts, another will be disregarded, and *vice versa*. The only safe way is to organize it carefully on paper. In order to make this easier an account is given of just how this recording may be done.

Let us start with your experience. I should prefer to start with the personal qualifications just mentioned, but it is a little easier, apparently, for most men to start the other way. In listing your experience take it in the reverse order, starting with what you have just been doing and working backward. Put down what you did, the firm's name, the length of your stay, and the range of salary you received. Then break down the jobs and list the various activities involved—whether you hired men, laid out work, figured costs, did a certain kind of designing, or what not. If your experience has been diverse enough, you may find it desirable to rearrange these bits of experience and find out just how much time you have spent in each activity.

If you are younger or had an interesting and varied school experience, it may pay you also to go back and analyze that in the same way. Perhaps there were abilities uncovered then which you have not used since. The same procedure should be followed for your avocational and family interests. Try to remember your activities along all these lines in 1933, 1932, 1927, and 1925, for instance. Throughout this whole analysis a keen watch should be kept for trends in experience and avenues of growth. The possibility of finding these is one reason for arranging the data in chronological order.

Next, your personal characteristics should be described in as objective a way as possible, depending more upon what other people say about you than upon your own estimate. Of course, your mental assets can be gaged in some measure by your scholastic record and the recognition you have received since. It isn't wise to ignore your important liabilities, but emphasis should be kept on the positive side.

You should then have a pretty good picture of yourself and what you can do best. The next thing is to decide what types of work you would like in the future and under what conditions. There may not be much difference between some of them, but it makes it easier to grade them as to desirability, when possible, and put it all down on paper.

Of course, none of these may be possible immediately and they may not even exist as jobs. Men have come in to me and spent several minutes describing the sort of work that they desired and then I have had to tell them in the end that the job just did not exist as far as I knew. They have simply made a synthetic job out of their desires. You will be able to determine this for yourself if you will leave the personal question for a while and consider what functional types of work are open. Since we are concerned at the moment with engineers, I shall try to discuss the markets for the services of engineers even though this must be done in general terms.

Types of Work Open to Engineers

It is easy to talk about engineers as if they were a peculiar race of men, set apart somehow and separate from the undistinguished rest of mankind, but I refuse to treat them that way. To me they are much like other men. They have the same domestic problems, the same desire for power and for money, the same urge to serve their fellowmen that others have. They may have these in degrees which vary from the degrees which others have them but in general they are just people, despite their scientific training and the wizardry which they sometimes seem to others to possess. So, also, the work that they do does not vary greatly from the tasks that occupy other people. In fact, they enter all sorts of occupations and professions. I know men trained as engineers who are accountants, lawyers, salesmen, artists, politicians, and, I think I might add, ministers. Some of them have discarded engineering as a profession but many have merely combined it with other activities. Nevertheless, there are certain types of work in which engineers are ordinarily found, and, if we are to discuss at all adequately the opportunities for engineers seeking work, it seems the obvious thing to do to cover this better known ground first. I propose to do this on a functional basis instead of using the usual method of dividing the varieties of work according to the engineering degrees of the men who most commonly undertake these tasks.

Getting Things Done

Suppose we consider the engineer first as an operating man. He gets things done. Usually he will be found in command of at least a small group of men. Perhaps his greatest satisfaction comes from seeing the results of his labors—so many cars turned out each week, or so many barrels of gasoline, or a bridge farther along toward completion, a building built, a railroad kept running, or a communication system kept in operation. His is the brain that checks on the labor of others, that corrects mistakes and surmounts difficulties, that tells how and where and with what tools a task is to be done. In this group come primarily the civil engineers, the construction men, and the mechanical and electrical engineers—all of them types of engineers who have found it especially difficult to get jobs in the fields in which they customarily work during these hard years. We have not, except as the government has been pouring out funds, been building very much. Many of these men are in the so-called capital goods industries, in which the index of employment is still abnormally low.

If you are in this field of activity or have been and your genius is getting things done and in producing tangible goods, why not turn to the other operating fields and see if there are not more opportunities? Plants need to be run as well as constructed and in times past many men who have designed plants and built them have stayed to operate them. Moreover, with more stabilized prices and increased mechanization the operation of plants and factories should and will demand more technical skill on the part of those in authority.

Most engineers understand machines and are fascinated by them. There is no reason why they should not extend their field of usefulness into a great many industries in which the "rule of thumb" is still the governing principle. It is foolish for an engineer, if he is competent, to think that he needs to have experience in any particular industry to do the work necessary in that industry. A few years ago a manufacturer of a rather complicated machine, wanted a factory superintendent. It was specified, however, that any one applying for the position must have had casehardening experience, since that was an important part of the manufacturing process. A competent engineer of my acquaintance felt that he could handle the job even though he had not had such experience. Before applying for the position, however, he spent three days in the New York Public Library reading up on all the latest developments in casehardening. He found out so much about the problems involved that he secured the position in spite of competition with experienced men and even though he frankly confessed his lack of actual experience in the field. He did a good job, too. We are sometimes afraid of the bug-a-boo of specific experience. We ought instead to realize that a man with a trained mind who is not afraid to tackle new problems and is not too diffident about seeking information can bring a valuable and often fresh point of view to the solution of problems that have not been properly solved, because they are too greatly bound around with traditions of what has been done in the past.

There is one phase of an operating job, however, which bothers a good many engineers and to which they need to give close attention. That is the human factor. It simply isn't possible to treat men and women as you do machines. Allowance must be made for individual differences, for prejudices, for ambitions, and for fixed ideas. A certain amount of inspiration as well as consideration, must come from the man responsible for supervision. Scientific management, which is, I take it, principally the application of engineering principles to human productive activity, must sometimes go slowly and allow for the absorption of ideas, in order to save time and money in the end. The engineer's impatience with human frailties seems to be the greatest limiting factor to his usefulness as an operating man.

There is another factor in operating, how-

ever, which favors the engineer. Even though the introduction of machinery has reduced the number of workers in many industries, it has increased the need for maintenance engineers who must see that these machines run, are operated properly, and are kept in good condition. Just after I had finished a period of employment as a machine operator, a well-known psychologist told me that it would not be very long before all machines would be automatic and would be run by morons, meaning, of course, people with less than average intelligence. I was highly indignant at the time because I had come to realize by actual experience that, whereas the manual labor necessary is undoubtedly reduced by automatic machinery and the time necessary to learn the procedure may be cut down to a negligible period, understanding the operation of the machines and being able to act correctly in an emergency requires a high order of intelligence, at least of a certain kind. It also involves a thoroughly trained person to correct difficulties when they occur. Moreover, modern production processes are so closely interrelated that the overproduction of one part or the breakdown of one machine may upset the schedule of a whole factory or series of factories. Here, in the more accurate coördination of production, lies a large opportunity for the trained mind of the engineer. It may be necessary to sell this idea more thoroughly to manufacturers and perhaps you as an unemployed engineer can have a very definite part in so doing. It certainly can be done.

Research

We must proceed to discuss some of the other phases of work commonly done by engineers and perhaps the next one which should be mentioned is that of research. Business men have come more and more to appreciate the practical results of research even when it seems most remote from the work in hand and scholars engaged in research are coming to appreciate the fact that the pursuit of new knowledge may be profitable financially as well as intellectually. Surely, much progress has been made in a better understanding of the possibilities of research when one of the foremost leaders of industrial research announces that a part of his staff has been engaged for some time in trying to solve the riddle of why grass is green! This, in spite of the fact that there is no apparent connection between this field of research and the products produced by his organization.

Research today, as most of us know it, takes on a multitude of forms. It may involve the experimental design of new machinery, extensive microphotography, the careful analysis of new and old materials, the accumulation and sorting of information from a multitude of sources in order to determine which may provide a vital clue to an entirely new procedure. Many men haven't the patience for such work, they can't stand the inaction, or, most of all, they haven't the controlled imagination.

It is a mistake, however, to think that all such work is done in the universities or in the big corporation laboratories. Much valuable research has been done in lofts, in small shops, or in private laboratories. To discover these smaller enterprises requires something of the instincts of a ferret. They must be searched out, followed up patiently, and approached with caution. Much of this work is not profitable from a monetary standpoint or from the point of view of results, but if you have that type of mind and will apply the same techniques to the discovery of opportunities to be associated with such ventures as you would use in other research, they can be found and are probably not much more hazardous financially than a host of other occupations. Such work is entitled to be called professional from almost any aspect.

The Consulting Engineer

Of all the work that an engineer does, however, that of the consulting engineer is probably nearest to a completely professional status. Also, it involves some of the most varied abilities. The good consulting engineer must have the analytical ability of the research man, the operating skill and ability to handle people of the operating man, and the enthusiasm and the financial acumen of a good banker or controller. He must keep in touch with new ideas and yet have a comprehensive knowledge of what has gone before. Above all else he must have the ability to plan the expenditure of his own time. Does this sound like a large order? Well, it is.

Perhaps the good consulting engineer comes nearer to being a master of his field than any one else. Excellent engineers who can do splendid work as employees find themselves unwilling or unable to assume the responsibility of independent action. Others lack the ability to sell their services to prospective clients. It is likely to be either a feast or a famine. Either a consulting engineer is so busy that he cannot handle the work and finds it difficult to hire other men who will do it efficiently, or he has time on his hands and has to employ all the arts of a salesman to get enough business to provide him a living. Some engineers find the answer in supplementary occupations, such as teaching, the management of organizations, or through a regular consulting arrangement on recurring problems. The best consulting engineers I have known have been men who have worked for others on a variety of problems, frequently in various parts of the world, and then, after they have had the benefit of this experience, have settled down in some central location to make their experience available to whoever have problems to solve. They are men with standing and prestige who are recognized as authorities. Business in good times naturally flows to them. In poor times they live on their accumulated savings or go into other lines of work. Sometimes they tighten their belts.

It would be possible, and perhaps profitable at another time, to analyze the requirements of a consulting engineer's work more fully, but the present (the fall, 1934), when we are partly through a depression, is not a time when it is possible for very many to enter this field, and there are other possibilities for engineers which should be given more attention.

Sales Engineering

One of the principal fields of work for engineers outside of what may be called straight engineering is that of sales or sales engineering. Many engineers have tried to go into nontechnical selling without much success, but increasingly, products of a technical nature are demanding engineers to sell them, even some which may be classed as "consumer goods." There are large numbers of machines and basic materials—metals, chemicals, rubber, fabrics—which are used in manufacturing and which must be sold by men who can appreciate their uses and help adapt them to various mechanical situations.

Many men, especially engineers, say and feel that they cannot sell. Some, of course, cannot, but the main reason why the others feel that they cannot is because they think of selling as peddling, or as forcing on buyers things which they do not want and cannot use. True selling is almost the reverse and consists of so appreciating the problems, needs, and personality of the buyer as to be able to make him see, understand, and want the product being offered to him. If it is not desirable and useful in a given situation it should not be sold.

Let us analyze this statement a little further. In the first place, a salesman must study and understand the problems of the buyer. This involves learning as much about his needs as is possible ahead of time; then gathering by skilful questioning of the purchaser more information, including his own prejudices in the matter. Second, it is necessary to understand the buyer himself, to apprehend—there isn't any other word for it—his thoughts and thought processes. Third, the salesman must "get his ideas across" to the buyer convincingly and persuade him to make a decision; get him to "sign on the dotted line." This does not involve "high-pressure" selling necessarily. It merely means creating a sufficient desire and then letting the buyer take the initiative. If the salesman is interested sufficiently in people and is sufficiently interesting to them to get their good-will, the rest of the selling technique can be learned.

Many men think that it makes no difference what they select to sell, but my experience indicates that it makes a lot of difference to the beginner, at least, since, to sell convincingly, most beginners must understand, like, and believe in the product. There is a big field for engineers here, however. As competition becomes keener in this country and prices become better standardized, the art of selling will be more and more necessary, and those understanding it will be in greater demand. Pick your line, pick your company, and you can frequently sell them the idea of taking you on.

One more point regarding sales work should be discussed briefly; that is, the methods of paying salesmen. At the risk of being seriously challenged, I should like to say that most worthwhile selling jobs today pay a salary, or a salary and a commission. If a sales job does not do so, the employer is asking the salesman to take most of the risk. A drawing account is something of a compromise. The salesman is paid a commission but is allowed to "draw" a fixed sum every week or month which is deducted from the commissions he earns. If after a certain period he has drawn more than he has earned in commissions, he is supposed to make up the difference. The company does not always demand this if it is felt that the drop in earnings is

not the salesman's fault, but it is considered an obligation and therefore should be set at the start at an amount which is a little less than the expected earnings from commissions.

Many types of goods and services are sold on a commission basis and some men prefer this basis because of the larger percentage given but it is a particularly harassing method of pay for a man who is methodical in nature. Most companies selling staple articles or articles which involves large unit costs, such as machinery, prefer to pay their salesmen salaries which net them a smaller percentage on their sales if they are successful, but, of course, do not involve so much uncertainty.

It has been pointed out that a salesman needs to be careful about his appearance. He does not need to be unpleasantly aggressive, but he must be well dressed and persistent enough to get a hearing. He must understand people sufficiently to make himself liked and easily understood—persistent but not a pest, in other words.

Engineers in Business

In addition to the foregoing functions of engineering which are generally recognized there are opportunities in other phases of business also. Many engineers, especially industrial engineers, eventually transfer to financial positions, such as controllerships. Others secure places for themselves as technical advisers to banks and accounting firms. These positions are likely to be a step beyond consulting work instead of a prelude to it. Others, who are interested in people and their efficiency, go into the personnel field. Many purchasing agents are engineers. Lately, a number of mechanical engineers have entered the planning departments of retail stores in which the handling of goods from the receiving office to the customer is, in many cases, an engineering problem. There are also places for engineers in the editing of technical magazines and books, and many go into various phases of the civil service.

It would be impossible within the limits of this article to give detailed analyses from a functional standpoint of all these various business and public occupations into which some engineers go, and which do offer a wide variety of opportunity if properly investigated. There are numerous books describing them and if these are carefully studied the information can be obtained from them. There are certain of these occupations about which I shall attempt to comment briefly, however, because the information may not be obtainable elsewhere. One of these is banking.

After a good many years' study I am convinced that the only way for an engineer to become connected with a bank in the capacity of adviser on industrial problems is either to become acquainted socially with one of the bank officers, or, more properly, and I think more easily, for him to meet the bank officials in the discussion of a problem in which the bank is interested. Bankers who are impressed by an engineer's handling of an analysis or by his solution of an operating problem will, at times, seek his help with other problems, and, in order to avoid paying a heavy consulting fee, will take him on at a substantial salary. To be able to create this opportunity for himself a man must have a flair for finance because he must be able to talk the language of the banker and because the financial aspect of the problem is likely to play a considerable part in the work he is asked to do.

Purchasing is a distinct career which is usually entered early in life. There are, however, instances in which engineers have been able to secure such opportunities later. This is especially true when they have been engaged in industrial reorganization. In order to purchase successfully, a man must have an almost unlimited capacity for absorbing detail without being swamped by it, must be interested in and understand markets, must be able to understand but not necessarily to like people, although that is a help. His judgment and ability to decide promptly must be excellent and he must be able to make decisions without worrying about them. A purchasing agent can many times put a firm "in the black" or "in the red" simply by buying at the right time and in the right quantity.

Planning departments are likely to assume the aspect of boards of strategy. They have to do with the flow of goods and work in process, with plant layout, and, with questions of management policy. This field is a good example of special jobs in which engineers are finding places.

Another job is that of building superintendent. In smaller buildings this may not be far removed from the work of a janitor, but in larger buildings the problem of mechanical upkeep makes an engineering training desirable, so that both mechanical and structural engineers will be found carrying on this work with success.

Nothing has been said so far regarding strange or unusual jobs which engineers have undertaken. There are many of them, but such possibilities are discovered either by chance or by an analysis of the individual's special interests. What has been attempted is a review, from somewhat of a functional standpoint, of the occupations usually open to engineers, in the hope that those who are unemployed may find something they have overlooked.

EDITOR'S NOTE: Although this important article is being republished in full in Electrical Engineering, space limitations require that it be presented in two parts; the second and concluding part is scheduled for inclusion in the January 1935 issue.

A.S.C.E. Officers for 1935 Nominated. The complete roster of official nominees for offices in the American Society of Civil Engineers for the year 1935 has been announced. Arthur S. Tuttle of New York, N. Y., has been nominated for president. Mr. Tuttle is widely known not only because of his activities in the A.S.C.E., but also because of his important engineering experience, particularly with the board of estimates and apportionments of New York City, from which he retired in 1928 as chief engineer after 26 years of service. Continuing as consulting engineer, he also has recently served as New York State engineer for the Federal Emergency Administration of Public Works. For vice president, D. H. Sawyer of Washington, D. C., was nominated to represent Zone 2; and Henry E. Riggs, of Ann Arbor, Mich., to represent Zone 3. For directors, each representing a separate district of the A.S.C.E., the following were nominated: C. Arthur Poole, Rochester, N. Y.; Herman Stabler (A'04, M'13) Washington, D. C.; James L. Ferebee, Madison, Wis.; Charles B. Burdick, Chicago, Ill.; H. S. Morse, Indianapolis, Ind.; Ivan C. Crawford, Moscow, Idaho; and Theodore A. Leisen, Omaha, Neb. The tellers' report on the results of the ballot will be announced during the A.S.C.E. annual meeting, Jan. 16–19, 1935. Those elected take office immediately.

Outdoor Weathering of Metals and Coatings

A book has been prepared containing the papers and discussions presented as part of a symposium on the outdoor weathering of metals and metallic coatings, held at the 5th regional meeting of the American Society for Testing Materials, Washington, D. C., March 7, 1934. This symposium evaluates much of the performance data obtained from the extensive outdoor weathering tests carried out by the Society's committees *A*-5 on corrosion of iron and steel and *B*-3 on corrosion of nonferrous metals and alloys. The symposium is intended to illustrate applications of A.S.-T.M. corrosion test data in solving materials problems, but the authors of the 5 extensive technical papers did not confine them to data or official conclusions of the 2 corrosion committees.

The papers discuss the following subjects: outdoor test results on bare and metal-coated ferrous specimens; the harmony of outdoor weathering tests; influence of rainfall and smoke on the corrosion of iron and steel; early interpretation of test results in the atmospheric corrosion of nonferrous metals and alloys; and galvanic corrosion by contact of dissimilar metals.

An interpretation of corrosion test results necessarily introduces various viewpoints. The very considerable portion of the publication devoted to discussion thus gives a broader view of the field. Extensive contributions from technologists in England indicate interesting results of widespread test programs conducted there and comparisons with conclusions reached in this country.

Much of the data are given in concise form through charts and tables and appropriate illustrations enhance the utility of the book. Copies of this 113 page book can be obtained from A.S.T.M. headquarters, 260 S. Broad St., Philadelphia, at $1.25 per copy, heavy paper cover; $1.50 in cloth.

American Physical Society Annual Meeting. The annual meeting of the American Physical Society will be held at Pittsburgh, Pa., December 27–29, 1934. This meeting will be held concurrently with the Annual Science Exhibition to be located in the Mellon Institute Building, Pittsburgh, Dec. 27–30, 1934. This exhibit, which was announced in Electrical Engineering for September 1934, p. 1327, is sponsored by the American Association for the Advancement of Science and Associated Societies.

How to Use Electronic Tubes in Industry

A pamphlet entitled "Industrial Electronic Tubes" has been prepared, which presents a fundamental treatment of the operation and the application of electronic tubes in industry. The treatment is nonmathematical, starting with electronic phenomena and the mercury arc, passing to high vacuum tubes and the grid glow family, thence to photo-responsive electronic devices and cathode ray tubes and ending with the specific technique of a variety of applications. Throughout the pages the purpose is to show how the physical properties discussed can be put to practical use in industrial control. It is an illustrated 217 page zincograph pamphlet, prepared under the supervision of the educational department of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and offered by them for $2.25 (net).

As a supplement to this pamphlet a "Manual of Experiments" may also be purchased for 65¢; in this series of 24 tests, the apparatus needed, methods of set-up, procedure to be followed, and results to be obtained are fully explained. These experiments parallel the course of study which can be obtained from the larger pamphlet, and demonstrate the type and characteristics of the various electronic tubes described. The 2 may be used as a schedule in this subject of both classroom and laboratory work. It is stated that advertising and propaganda have been carefully avoided so that the material can be used as an accurate and unbiased text.

France Honors Early Menlo Park Worker. On April 6, 1934, Francis Jehl, curator of the "Edison Laboratory" in Greenfield Village, Henry Ford's museum at Dearborn, Mich., was honored by the French government when its representative, M. Leon Morand, consul at Detroit, bestowed upon the aged electrical engineer the title of Chevalier of the Legion of Honor. Mr. Jehl is reported to be the only survivor of the small group in Thomas A. Edison's research laboratory in Menlo Park, N. J., of 1878–79. He assisted Edison in the experiments that led to the invention of the first practical incandescent lamp. It is reported that following the successful production of the incandescent lamp and the Edison system, Mr. Jehl installed and started the testing department of the Edison Machine Works in New York City in 1881, and the following year was sent to Europe, where he assisted in starting the French Edison Companies' Lamp Works. He also pioneered in the installation of electric lighting equipment in other parts of Europe. The presentation by the French government of this honor to Mr. Jehl was followed by a brief address by ALBX DOW (A'93, F'13, and member for life) who spoke of his early association with Mr. Edison and Mr. Jehl. Mr. Jehl is a son of an officer of the Union Army, whose ancestors migrated from France to America in Colonial days.

Metropolitan Opera Installs Lighting Control

WHEN the opera season in New York opens on December 24, 1934, occupants of the Metropolitan Opera House will observe for the first time the results of the thorough remodeling and modernization program which has effected numerous improvements to the historic opera house. Most notable of the changes directly affecting the operatic productions is the installation of the most modern type of electronic tube control for both the stage and house lights. This new lighting equipment, employing electron tubes to control the reactor dimming system, was manufactured by the General Electric Company, and will place the control of all lighting effects at the finger tips of one individual. The presetting controller located in the "lighting pit" below the stage is shown here. A hooded opening in the stage floor near the footlights enables the operator to observe the effects produced. To the right of this board, and not shown here, is the master controller. From the lighting pit, each of the 156 circuits for the stage may be independently preset for 3 complete lighting scenes, so that the touch of a button will accomplish the scene-to-scene change of circuits. In addition, the 11 house circuits may be controlled from this point. The presetting controller provides for the individual control of each circuit, while the master controller enables the operator to govern all circuits simultaneously, either for dimming or for blackout, and to split the control into major divisions of color. The circuits are arranged to provide one color for the house and 4 colors for the stage, except for the footlights where 5 colors are to be used. The Metropolitan Opera House is among the large number of places in New York which may be visited during the forthcoming A.I.E.E. 1935 winter convention.

Engineering Education to Be Reorganized at Harvard

The board of overseers of Harvard University at its last meeting approved action previously taken by the Corporation providing a plan of reorganization of instruction in engineering in the University. This plan, which will become effective in 1935–36, provides that undergraduate instruction in engineering will no longer be given in the engineering school but will thereafter be undertaken solely by the division of engineering sciences in the college, although with the same equipment and under the same officers of instruction as formerly.

The tendency in recent years has been for the majority of students wishing to obtain undergraduate instruction in engineering at Harvard to secure it through the division of engineering sciences in the college rather than by registering as undergraduates in the engineering school, and the administrative change now to be made is in conformance with this tendency.

The engineering school will be continued on a strictly graduate basis, as the graduate school of engineering, with courses in the several branches of engineering leading to the degrees of master of science in engineering and doctor of science.

Pennsylvania Railroad Orders 57 Locomotives. Orders for 57 streamlined electric engines, reported to be the most powerful electric passenger locomotives ever built in the world, have been placed by the Pennsylvania Railroad. Costing almost $15,000,000, these new locomotives have been specially designed for high speed passenger service to be inaugurated between New York, Philadelphia, Baltimore, and Washington, early in 1935. They will be capable of making regular operating speeds of 90 miles per hour hauling standard trains. Twelve 57-inch driving wheels will drive the fully streamlined articulated engines along the tracks with full power of 4,620 horsepower at high speed. Each locomotive will be 79.5 feet long, of all steel construction, and will weigh 230 tons. They will operate on an 11,000-volt 25-cycle single-phase system, the current being supplied by overhead wires through a pantograph. The maximum starting tractive effort will be 72,800 pounds. Eighteen complete chassis will be built at the Pennsylvania Railroad's Al-

toona shops, and 25 chassis will be built by the Baldwin Locomotive Works at Eddystone, Pa. The General Electric Company, at Erie, Pa., will build 14 complete locomotives, including chassis and electrical equipment, and in addition will build electric propulsion and control apparatus for 9 other engines. The Westinghouse Electric and Manufacturing Company, at East Pittsburgh, Pa., will build the electric propulsion and control apparatus for 34 locomotives. These latter 2 groups of electrical equipment will be installed by the Pennsylvania Railroad in the 43 chassis built by it and the Baldwin Locomotive Works. In a previous order placed in July 1934, 28 electric passenger engines were ordered by this same railroad at a cost of over $6,000,000.

Lightning Storms in Northwest Studied

A report "Lightning Storms and Fires in the National Forests of Oregon and Washington" has recently been prepared by W. G. Morris of the Pacific Northwest Forest Experiment Station, Portland, Ore. One thousand copies of this report have been printed and are being sent to forest fire wardens in Oregon and Washington, national forest supervisors and rangers, electric power companies in the northwest, local weather bureau officials, and other interested persons.

In this report, lightning storms in Oregon and Washington, some of which caused 215 forest fires in a single day and traveled at speeds of 1 to 40 miles per hour have been mapped and described. From records taken since 1925 by 200 forest fire lookouts stationed on mountain tops in the national forests of these 2 states, the Pacific Northwest Forest Experiment Station has made the first comprehensive study of mountain lightning storms undertaken in this region. Findings of the study are: the time of day when lightning storms usually occur; direction, length, and rate of lightning storm movement; percentage of lightning flashes which strike the ground; frequency of lightning storms and fires in different parts of the national forest areas, and the relative number of forest fires set on various types of storm days.

Lightning on the national forests of Oregon and Washington causes 750 fires annually, more than $^1/_2$ of the total number. These storms cause enormous damage. Unfortunately, they occur over immense areas and the fires usually start in the most inaccessible places.

Definite zones of lightning storm occurrence have been mapped in Oregon and Washington. However, lightning storms do not follow repeatedly the same lane or track, as for example, certain valleys and ridges. The number of lightning fires per acre at high altitudes is no greater than at low altitudes on most national forests. Most lightning flashes in the mountains of this region are from cloud to cloud. A greater percentage of cloud to ground flashes or strikes occur on days when storms are widespread than on days when storms are localized.

A 500-Watt Loudspeaker

A new loudspeaker, shown in the illustration, has been developed which is so powerful that it can amplify the human voice one million times, and over flat country still air can be heard a distance of several miles. This loudspeaker is 500 times more powerful than the ordinary loudspeaker, and is intended primarily for outdoor use. The speaker, which was developed by engineers of Bell Telephone Laboratories, Inc., for the Western Electric Company, was recently used at reduced power by the U.S. Coast Guard at the International Yacht Races. The speaker has been designed so that speech projected from it is sharpened so as to penetrate other noise more easily, concentrating its power in the band from 400 to 4,000 cycles. Instructions and warnings can thus be given in many special applications. The amplifier is capable of delivering 1,000 watts of speech current to the loudspeaker, and the speaker of delivering 500 watts of energy to the air. Both the speaker and the microphone which is used with the system are of the "moving coil" type. The speaker and horn combined are 30 in. in diameter by 30 in. deep.

Unit Air Conditioner Association. The formation of a new association, the Unit Air Conditioner Manufacturers Association, New York, N. Y., to foster and promote unit air conditioners has just been announced. Preliminary figures indicate that the annual gross sales for last year of unit type of equipment were approximately $4,000,000, and it is estimated that the current year will see this volume exceeded by 50 per cent or more. It is the aim of the association to guide the development of the industry along the proper lines so that the advantages to be gained by public buying will enhance the continued development and use of air conditioning.

Large Transformer Order Placed. An order for 7 65,000-kva transformers was placed the latter part of October by the bureau of power and light of the city of Los Angeles, Calif., with the Westinghouse Electric and Manufacturing Company. This order is reported to amount to approximately $1,000,000, and to be the largest single order for transformers placed in the last 5 years. These transformers will be installed at the Los Angeles terminal of the 285-mile 287-kv transmission line from Boulder Dam. Six transformers arranged in 2 banks with one for standby service will step down the voltage to 132 kv. Each unit will weigh nearly 250 tons, stand 35 ft high, and occupy a floor space area of about 19 × 20 ft.

Standards

Radio Standardization Sponsorship to Reside Solely in I.R.E.

The sponsorship of the sectional committee on radio, which has been held jointly by the Institute of Radio Engineers and the A.I.E.E. since its inception in 1924, was considered by the standards committee of the A.I.E.E. at its October meeting, and it was recommended that the A.I.E.E. relinquish its joint sponsorship in favor of a sole sponsorship by the I.R.E. This action was approved by the board of directors and the suggestion transmitted to A.S.A.

Limit of Observable Temperature Rise

At the meeting the A.I.E.E. standards committee held on October 16, 1934, a question was raised relative to the exact meaning of "limit of temperature rise" as it appears in many of the A.I.E.E. standards. It had been suggested that an ambiguity existed. Was it the observable limit or the hot-spot limit to which reference was made? In the minds of the committee there was no question as to the limit referred to, but in order to eliminate any such question the clause will be reworded in all future editions and will appear as "limit of observable temperature rise."

Standards on Electrical Insulating Materials

A publication of considerable interest to the electrical industry has just been issued by the American Society for Testing Materials entitled, "A.S.T.M. Standards on Electrical Insulating Materials."

This 1934 edition includes in their latest approved form 21 standardized methods of test and 12 specifications. The method of testing molding powder used in manufacturing molded electrical insulators has not been published heretofore. During 1934, revisions were made in a number of the test methods including those covering the following materials used for electrical insulation: varnishes, solid filling and treat-

ing compounds, untreated paper, sheet and plate materials, varnished cloths and cloth tapes, laminated tubes and round rods, and electrical porcelain.

In addition, the following are covered by specifications or tests: flexible varnished tubing, rubber gloves, rubber matting, electrical cotton yarns, silk and cotton tapes, pasted mica, and slate.

Copies of this publication can be obtained from A.S.T.M. Headquarters, 260 So. Broad St., Philadelphia, at $1.75 per copy. Special prices are in effect on orders for 10 or more copies.

Test Code for Transformers

The "Test Code for Transformers," which was prepared under the auspices of the electrical machinery committee of the Institute and has been available in printed form for comment since October 1931, was ordered transmitted to the American Standards Association for action by the standards committee at its October meeting. The code will be considered by the sectional committee on transformers, together with revisions and additions suggested by the electrical machinery committee.

Test Code for Polyphase Induction Machines

There has just been received for action at the next meeting of the A.I.E.E. standards committee, a "Preliminary Report on a Proposed Test Code for Polyphase Induction Machines." This has been developed under the auspices of the electrical machinery committee and will probably be ordered published for general comment. Notice of availability of the report will appear in a later issue.

American Engineering Council

Census of Engineers

A profession-wide survey to show how engineers have fared through the hard times is being made by the U. S. department of labor in coöperation with American Engineering Council and as many of the engineering societies as are willing to participate. Unsigned confidential questionnaire returns from 100,000 individuals will give salary trends, types of employers, and duties over the past several years, plus educational background and other facts designed to give a true picture of the engineers' status. Compilation of returns early in the year will show how our people have adjusted to changing conditions and how many are unemployed or in minor jobs, awaiting placement in regular work. This is believed to be the most comprehensive nation-wide study ever made of a professional group. Results are expected to be of immediate practical application to the engineering employment program; will serve as a check against policies of engineering schools which may be turning out too many graduates in some fields and not enough in lines of current demand. The survey has resulted from negotiations by Council with Dr. Isador Lubin, commissioner of labor statistics, whose Bureau will do the job.

As a statistical backlog for present estimates, Council has made an intensive study of the distribution of engineers among the various industries as of the Census of 1930. 225,000 called themselves engineers, or one to about every 500 of population; one engineer to every 210 persons listed as gainfully employed. Membership of engineering and allied technical societies totaled 115,000 as of 1929 which makes the Census figure look large; it probably includes surveyors, draftsmen, and minor technicians. Arrangements are being made for a better classification in the next Census.

The breakdown by industries is none the less significant. In fact, the exceedingly small ratio of engineers in many industries is the more striking when it is remembered that the count of engineers is probably high. In forestry and agriculture, only 0.01 per cent of the employed are listed as engineers; in wholesale and retail trade, only 0.02 per cent; textile and clothing industries, 0.06 per cent. The figures range up to 3.51 per cent for public utilities. Although Federal work offers the most widespread opportunities at present, it is obvious that the real future of the profession still is in the field of private industry. In 1930, 11 per cent of the 225,000 were employed by governments (Federal, State, and Local); 24 per cent were on a consulting basis, doubtless mainly for private firms; and 65 per cent were employed by industry and commerce. The development of technology in backward industries is the main hope for the profession. Two charts which Council has made available tell the complete statistical story.

"Integration" of National Activities

The confusion of events affecting the future status of industry and trade has been gradually clarifying over the past several months. There is still much confusion in national policy because of the variety, scope, and varying leadership of governmental activities. If there is one word which may be made the keynote of immediate effort, it is the word "integration." In these activities engineers are playing and have played an important part. American Engineering Council during the past few months has been perfecting its organization plans to fulfill these new and increasing demands for Washington service.

Steps already taken by Council are following the same philosophy now being exhibited by the leaders in government, that is, we are working on the policy of integrating Council relations, both within and outside the engineering profession and then to relate the integrated whole to the challenging problems of the times. The executive committee and the executive secretary of American Engineering Council have been greatly stimulated by the enthusiasm and renewed purpose with which the present members of Council have supported its work in the past year. Through regular monthly meetings with the secretaries of the National Society members and with corresponding relations with local organizations, there is evident a strength of purpose which is deeply appreciated by those who have been elected to lead the affairs of Council. In this connection, the executive committee is planning to present for consideration of local engineering organizations a plan of membership, which they hope will increase the participation of engineers in national affairs, as well as provide less financial obligation.

Representative on Employment at Washington

Facilities to aid the placing of men are provided in Washington through the coöperation of the National Engineering Employment Committee to meet the needs of pending Federal plans giving early promise of employment of a large number of engineers, in addition to the thousands already in the Federal service. A special representative of the National Engineering Employment Committee is to be located in Washington. Col. C. H. Crawford has been selected to represent the 4 national societies of civil, mining and metallurgical, mechanical, and electrical engineers in an effort to aid the government in securing qualified men for engineering work.

Colonel Crawford's efforts will be devoted to the task of becoming acquainted with the government's present and future needs for engineers. He will be in direct contact with the employment committee and for the present all communications regarding opportunities for government service should be sent to the Engineering Societies Employment Service at 29 West 39th Street, New York, N. Y.

Unemployment Among Engineers

Unemployment of engineers has declined in the past year but still is no small problem. Council recently prepared a rough estimate based on telegraphic returns from the States which have been somewhat substantiated from Federal sources. Conclusion: present unemployment of engineers stands in the magnitude of 30,000.

The field for employment, present and prospective, of engineers in the Federal services, has been probed by a member of Council's staff, who has visited more than 70 government agencies in Washington within the past few weeks.

Council's canvass shows, approximately 15,000 engineers are employed by the regu-

lar and emergency units of the government whereas only about 4,000 were on the rolls before the present administration took office. Substantial numbers also are serving in subprofessional and nonprofessional capacities. A report of the findings for each agency with notes as to employment procedure is being considered for publication purpose: to advise individuals and societies where opportunities exist and where they do not exist; to serve as a guide which will save the time and trouble of seeking Federal placement in the wrong places and in the wrong ways.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Engineering Education Should Train 2 Types of Engineers

To the Editor:

I have been much interested in several papers on the subject of engineering education which have appeared recently in ELECTRICAL ENGINEERING and particularly in the discussions of 3 of these papers in the October 1934 issue, pages 1413–22. In the hope that the personal experiences of one who has passed through this process of technical training and adjustment to industry at a comparatively recent date may add something to what has already been said on the subject the following observations are offered for your consideration.

Having been interested in electrical science since early boyhood it was natural that I should select electrical engineering as a profession and I accordingly enrolled in the electrical engineering department of a well-known mid-western university in the fall of 1923. As the end of my sophomore year approached, however, I had begun to doubt the ultimate wisdom of my choice. It seemed to me that my personal interests and inclinations were more in the field of executive work in technical industry than in purely technical design or research work and that in order to fit myself properly for the work I wanted that I needed training not offered in the schedule of instruction I was following.

After thinking the matter over during most of the following summer I transferred at the beginning of my junior year to a course in business administration administered by the college of commerce. My idea in making this change was that the required courses in the new curriculum would provide the training missing from the regular engineering course and that by using an increased number of electives to take engineering courses I could fill in the engineering background that I wanted. One semester of this new course, however, was enough to convince me that the required subjects would crowd out too much of the engineering work which I still regarded as the fundamental portion of the training.

At the end of the first semester of my junior year I therefore transferred back to the college of engineering, this time to a course listed in the catalogue as "engineering physics." My selection of this course was based upon the fact that it included fundamental courses in electrical engineering together with advanced courses in mathematics, physics, and chemistry and also a number of electives which would permit me to fill in the so-called liberalizing courses that I wanted. Some of the courses which still could not be wedged into the regular schedule were included by securing permission to take more than the usual number of semester hours of work. This is the course in which I finally secured my degree and which incidentally is a course of instruction intended for the training of research engineers.

Following the completion of my university work 7 years ago I spent 2 years in a training course for junior executives conducted by the organization in which I am now employed. The last 5 years have been devoted to various staff positions.

As I look back over these experiences now 2 things seem to stand out quite clearly. First, that what I was really trying to do and did not quite realize it at the time was to make for myself just such a course of training as that described by L. W. W. Morrow in his paper "Industry Demands and Engineering Education" which appeared in ELECTRICAL ENGINEERING for April 1934, pages 518–22. What I was trying to get was a main stem of engineering and scientific training with the necessary economic and sociological training to fit myself for executive work in technical industry. If a course of this type had been offered, especially one that could have been adapted to the needs, abilities, and inclinations of the individual student as the course progressed I believe that I would have secured a great deal more benefit from the 4 years I spent in college. Second, that with all of the short-comings inherent in the way in which it was necessary for me to fit my university work to my needs I believe, after 5 years of experience, that the training I secured is better adapted to my purpose than a purely technical course in electrical engineering would have been.

Whatever may be the final form of the courses adopted by our leading technical schools it seems evident that a real need has been indicated by this group of papers and that a worth while improvement will necessarily follow.

The suggestion that "honors" courses be provided for the development of professional and technical engineers with the regular curriculum designed for engineers going into general industry seems to me to be an unfortunate choice of terminology. It seems to me to be not so much a question of ability between the 2 types of engineers as it is a question of providing the best possible training for both types. The events of the past few years indicate clearly that the need for problem solving ability in the sociological and economic fields is at least as great as it is in the purely technical phases of engineering work. The most constructive thing to do is to recognize frankly that there are 2 types of engineers of approximately equal importance to society and to provide schedules of instruction that will enable both groups to get the most out of their technical school training.

The most practical suggestion would seem to be for both groups to pursue the same schedule of instruction during the early part of the curriculum and for the individual student to make his choice between the 2 types of work at about the beginning of the junior year. In this way both courses could be developed as an integrated whole and there would be sufficient time during the first 2 years for giving the necessary information and advice to the individual student to enable him to make an intelligent and well-considered choice.

Very truly yours,

T. F. McMAINS (A'34)
(Chief Operator, Western Union Telegraph Company, Wichita Falls, Texas)

A New Stroboscope to Study Hunting of a Synchronous Motor

To the Editor:

The characteristic of the synchronous motor known as hunting is difficult for the average student to understand because it is hard to visualize what is going on in the machine. However, when the mechanical oscillation between the impressed voltage and induced voltage is converted into the oscillation of a beam of light, hunting becomes much easier to understand. By means of the following simple device this conversion is possible and the angular displacement of the rotor can be seen.

Referring to the diagram, M_1 is a small single-phase synchronous motor. M_2 is the synchronous motor which is to be tested for hunting. Both motors must have the same number of poles. A thin metal disk about 5 in. in diameter is attached to the shaft of M_1. A similar disk is mounted on a single-bearing shaft, the center line of which coincides with the center line of the shaft of M_1. The disks are mounted to run as close together as possible. The single-bearing shaft is connected through a flexible coupling to the shaft of M_2. A narrow radial slot about 1.5 in. long is cut in each disk. A light mounted as shown in the diagram and a shield to cut off undesirable light complete the stroboscope.

The motors run in opposite directions. When there is no hunting the radial slots

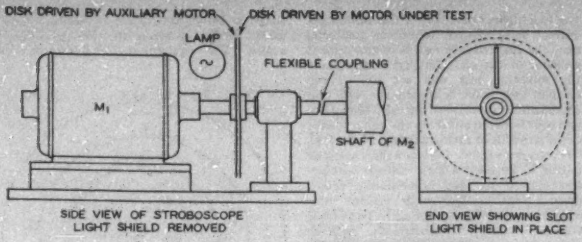


Fig. 1. Arrangement of stroboscope to study hunting

will pass each other at the same points each revolution. This allows a beam of light to pass through both disks when the slots pass. Because of the speed, this beam appears stationary and continuous to the eye. When the motor hunts, this beam oscillates through an angle which is approximately equal to the angular displacement in electrical degrees divided by the number of pairs of poles.

In addition to its use when studying hunting, this device shows some interesting facts when used to investigate the pull-in and pull-out torque characteristics of the synchronous motor. It also gives good results when used to determine the slip of an induction motor.

Very truly yours,

E. W. Winkler (A'30)
(Instructor in Electrical Engineering, University of North Carolina, Chapel Hill)

Reignition of an Arc at Low Pressures

To the Editor:

A recent paper by Mackeown, Bowden and Cobine ("Reignition of an Arc at Low Pressures," Elec. Engg., v. 53, 1934, p. 1081–5) describes experiments on a-c arcs at low pressures, and from the results draws certain conclusions about the mechanism of reignition and the transition from glow to arc. Though their theories may seem plausible in a qualitative way, a quantitative test reveals the necessity for additional assumptions so unreasonable as to throw strong doubt upon the correctness of their conclusions.

The results of the present investigations do not really disagree with those of Todd and Browne, (*Phys. Rev.*, v. 36, 1930, p. 732) who found a reignition voltage equal to arc voltage for a 90-amp arc between carbon electrodes at atmospheric pressure: for a low reignition voltage, it is necessary that the old anode-new cathode electrode shall have a temperature sufficient for considerable thermionic emission at current zero; with the low pressures, low currents, this condition was not realized as it was with the higher currents, higher pressure of Todd and Browne.

The intermediate voltage stage of discharge noted by the authors at low pressures may be a type of thermionic arc. It is well known that if the temperature of the cathode of a glow, on tungsten say, is raised the cathode fall decreases in a continuous manner from the normal value with no emission, to the low voltage of an arc when the saturation emission is equal to the total current flowing. The intermediate stages are stable, and may perhaps be classed as a form of arc.

Since the sparking potential in regions near the minimum is sensitive to cathode material and character of gas, the calculated curve used by the authors does not necessarily coincide at all with the true sparking potential for their experimental conditions. This is particularly true for the electrodes containing the rare earths.

The authors apparently hitch their cart before their horse when they invoke the high intensity field which may sustain the cathode *after* the establishment of an arc, to explain the lowering of the reignition voltage. It will be shown below that such fields do not exist in the glow which forms before the arc (clearly seen in Fig. 2 of the paper by MacKeown, Bowden, and Cobine, and probably also existent in all cases where the reignition voltage is high) and of course cannot be a factor in the reignition to a glow. Thermionic emission would lower the reignition potential below the normal sparking potential, and the glow voltage would be lowered to the same degree. At all pressures in Fig. 2, the glow voltage is constant at about 270 volts, both with the low current flowing to the left of A as well as when an arc exists during a part of the half cycle.

A quantitative test of the authors' theory of glow-arc transition may be made. Though unfortunately complete data are not available, still one may attain results of the correct order of magnitude using known characteristics of glows with other materials. Consider the oscillogram for one-centimeter pressure in Fig. 2. A normal glow exists, since the voltage remains constant with change in current, even up to the point at which the transition to arc takes place. The thickness of the cathode fall space is about 0.04 to 0.06 cm, so the average field is roughly 5,000 volts per centimeter; the field at the electrode surface will not be over twice as great, or 10^4 volts per centimeter. Now according to the theory of high field emission (see paper by Stern, Fowler, and Gossling, Roy. Soc. *Proc.*, A124, 1929, p. 699) in order to secure an emission equal to the emission of electrons by positive ion impact, a field over 2×10^7 volts per centimeter would be necessary. If high fields are to produce enough emission to begin to affect the glow, then surface irregularities must multiply the gross field by 2,000! Such a large multiplication is entirely unreasonable.

Consider now the other suggestion, that a spot of some impurity exists on the cathode, which yields more electrons than the rest of the cathode. Then, these electrons produce additional positive ions, which produce more electrons, but unless some new ionizing agent enters (high field emission) the process continues only until all the glow is concentrated upon the impurity. If a normal glow exists, the cathode fall is *lower* than before, so the field is weaker, and high field emission is still more improbable. If the current is large and the area of impurity small, an abnormal glow sets in, but the cathode fall is limited to the normal cathode fall of the body of the cathode; if it should rise higher, then all the current would be diverted away from the impurity.

The cathode fall in an abnormal glow is related to the normal fall by

$$V_A - V_N = \frac{A\sqrt{i_a}}{p}$$

where A is a constant, i_a the abnormal current density, and p the pressure. One may set a lower limit for V_N thus: V_N follows roughly the work function, which may be taken as 4 volts on the graphite and a lower limit of 1.5 volts on the impurity, which gives 100 for V_N. This is considerably lower than measured values of V_N for the alkalis. The constant A is probably about 100, and V_A is limited to 270. Thus for $p = 1$ cm

$$270 - 100 = \frac{100\sqrt{i_a}}{10}$$

from which $i_a = 189$. The current at the point of transition, from Fig. 2, is about 0.8 amp, so the diameter of the impurity is at least 0.075 cm. It is hardly conceivable that such an area of impurity could exist on supposedly pure graphite. Even if it did, the field would still be insufficient for cold cathode emission. The thickness of the cathode fall space, for such large current densities reduces to

$$d_a = \frac{B}{p}$$

where B has the value about 0.06, so $d_a = 0.006$. The field at the surface is thus about 10^4 volts per centimeter. Because of the reduced work function, the necessary field is reduced to about 5×10^4 volts per centimeter $\left(\frac{\varphi^{3/2}}{E}\right) = \text{constant}$). So one must postulate not only an unreasonably large spot of impurity, but also an irregularity upon it giving a field multiplication of 50!

A much more reasonable spot of impurity would consist of a few thousand, or at the most, a few million molecules. Only an extremely small part of the total current could be carried to such a spot, so the remainder of the cathode would be covered by a normal glow as in the absence of the impurity. With so small a spot, the thickness of the cathode fall space over it would not be the d_a calculated above, but almost the normal thickness for the rest of the electrode, so the field at the impurity would be only a little larger than over the adjacent

pure electrode. Thus one must assume coincident with the impurity an irregularity giving a field multiplication of 500.

Thus, the theory of glow-arc transition, which seems to fail in at least the case discussed above, and very likely in many other cases, reduces to a hypothesis which demands quantitative proof of its correctness before it can be accepted. Particularly valuable in extending the knowledge of the reignition of arcs between refractory electrodes at low pressures would be a determination of the sparking potential under the experimental conditions; an observation of anode drop and current density, so the anode (new cathode) temperature might be estimated; and an expansion of the time scale of oscillograms of the reignition region.

Very truly yours,

R. C. Mason (A'26)
(Westinghouse Research Laboratories, E. Pittsburgh, Pa.)

Arcover Caused by Absorption Current

To the Editor:

In the article entitled "Insulator Arcover in Air" by F. W. Maxstadt in the July 1934 issue of Electrical Engineering, p. 1062–8, a certain unexplainable phenomena is noted. Two electrodes with one centimeter spacing show a breakdown strength with air as the dielectric of approximately 30 kv and with a right cylinder of rubber in the field the breakdown strength was reduced to about 15 kv.

It is possible that this phenoma may be explained by the so-called "absorption current" of the rubber sample. This absorption current makes itself evident in the appreciable power factor displayed when a-c bridge measurements are made. It is also evident in the slow "soaking up" of charge after a direct potential is applied, often being measurable after some 15 min.

If the dielectric is a homogeneous material the charge due to absorption will be, after the potential has been impressed some time, evenly distributed throughout the mass. Assuming the charge to flow in from both electrodes during the period of absorption, the current flowing at the center of the dielectric will be zero and will increase as a linear function of the distance from the center of the material. From this analysis it is evident that the gradient is not constant during the absorption time but is a maximum at the electrodes and zero at the center of the dielectric. It is, however, probably constant after the charging process has ceased. Thus the required condition for a uniform voltage distribution in the insulation is not fulfilled and consequently the gradient over the surface cannot be uniform. If the gradient along the surface of the rubber cylinder anywhere exceeds the breakdown strength of the air small arcs will bridge the high gradient area. These small arcs are sufficient to ionize the air and cause complete breakdown of the gap.

However, if the potential could be raised very gradually, or, in other words, the absorption current limited, it will be possible to increase the potential difference across the gap to a higher value than if the absorption current were allowed to create gradients near the electrodes in excess of the critical gradient of the air. To verify this point the following test was set up: Three samples were made in accordance with the specifications established by Mr. Maxstadt and were found to impart to the gap a breakdown strength of approximately 14.5 kv at 60 cycles per second. When a direct potential of 15 kv from a high voltage battery was applied the gap immediately broke down. Next a 10-megohm resistor was placed in series with the line and a large high voltage condenser connected in parallel with the gap. The voltage across the gap was thus caused to rise very slowly when potential was applied. Under this condition no breakdown occurred at 15 kv. Thus the gradients at the electrodes were held below the breakdown gradient.

This is probably the explanation of why rubber, a high loss dielectric, or one showing a comparatively large absorption current will cause a gap to break down while glass or other low loss dielectrics will not under the same potential conditions.

Very truly yours,

Eric A. Walker
(Electrical Engineering Department, Tufts College, Medford, Mass.)

Graphical Solution of Star-Delta Transformations

To the Editor:

I read with interest the letter "Graphical Solution of Delta-Star Resistance Transformations" by W. W. Edson which you published in the October 1934 issue of Electrical Engineering, p. 1427.

In connection with the solution of equivalent delta-wye impedances (having the same ratio of resistance to reactance) your readers may be interested to know that an equivalent delta impedance may be found from known wye impedances by means of the simple diagram shown in Fig. 1. In this diagram A, B, and C are the delta impedances, and a, b, and c are the wye impedances. The equivalent delta impedances

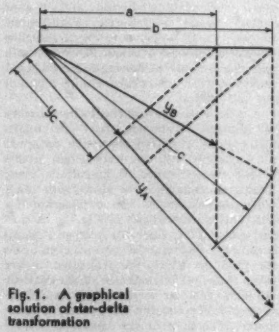


Fig. 1. A graphical solution of star-delta transformation

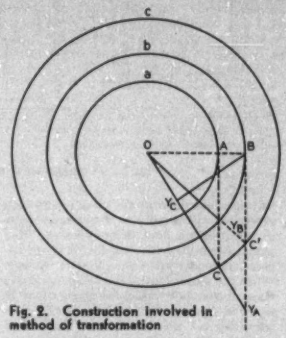


Fig. 2. Construction involved in method of transformation

$a = OA \qquad b = OB \qquad c = OC$
$y_A = OY_A \qquad y_B = OY_B \qquad y_C = OY_C$

in terms of the wye impedances are as follows:

$$A = b + c + y_A$$
$$B = a + c + y_B$$
$$C = a + b + y_C$$

As a matter of interest the construction and proof of this method follow.

Procedure

The procedure for this method (see figure 2) is as follows:

1. Let the smallest wye impedance be represented by a. Let the intermediate value of the 3 wye impedances be represented by b, and the largest wye impedance by c.
2. With a, b, and c as radii draw 3 concentric circles.
3. Draw line OB containing OA (radius of a) and OB (radius of b).
4. At points A and B draw tangents to circles a and b.
5. These tangents intersect circle c at C and C', respectively.
6. Y_A is the intersection of OC extended and tangent at B. Then if OY_A is denoted by y_A, the equivalent delta impedance $A = b + c + y_A$.
7. Y_B is the intersection of OC' and the tangent at A. Then if OY_B is denoted by y_B, the equivalent delta impedance $B = a + c + y_B$.
8. Y_C is the intersection of a normal to OC from point B and the line OC. Then if the intercept OY_C is denoted by y_C, the equivalent delta impedance $C = a + b + y_C$.

Proof

The well-known relationship between the equivalent delta impedance and the known wye impedance is:

$$A = \frac{ab + ac + bc}{a}$$

From similar triangles OY_AB and OCA

$$\frac{y_A}{c} = \frac{b}{a} \qquad y_A = \frac{bc}{a}$$

Therefore $A = b + c + y_A = b + c + \frac{bc}{a} = \frac{ab + ac + bc}{a}$

From similar triangles OY_BA and $OC'B$

$$\frac{y_B}{c} = \frac{a}{b} \qquad y_B = \frac{ac}{b}$$

Therefore $B = a + c + y_B = a + c + \frac{ac}{b} = \frac{ab + bc + ac}{b}$

From similar triangles OY_CB and OY_AB

$$\frac{y_C}{b} = \frac{b}{y_A} \qquad y_C = \frac{bb}{y_A} = \frac{bb}{\frac{bc}{a}} = \frac{ab}{c}$$

Therefore $C = a + b + y_C = a + b + \frac{ab}{c} = \frac{ac + bc + ab}{c}$

Very truly yours,

DAVID J. BALL (Enrolled Student)
(Rensselaer Polytechnic Institute, Troy, N. Y.)

Operational Calculus

To the Editor:

This communication proposes to correct a number of the inaccuracies in Prof. M. F. Gardner's paper "Operational Calculus" appearing in the October 1934 issue of ELECTRICAL ENGINEERING, page 1,339–47.

When it is said that "operational calculus applies to systems or situations where cause and effect stand in linear relation," one should not infer that it is inapplicable to nonlinear conditions.

The extent to which an operator may be handled as an algebraic quantity is restricted by and determined from its definition. An operator may be handled as a quantity in ways other than that suggested by the technique of the ordinary algebra; *e. g.*, "Introduction to a Form of General Analysis," by E. H. Moore, New Haven Mathematical Colloquium, 1906; "A New Foundation for General Algebra," by J. W. Young, *Annals of Mathematics*, 1927, series 2, volume 29, page 47.

When Leibniz adopted the $\frac{d}{dx}$ form in 1675, Johann Bernoulli was already using the D form.

The expansion of rational functions into terms having linear denominators was accomplished by L. Euler in 1775 ("Op. Anal.," volume 1, page 157), and by J. L. Lagrange in his formula for interpolation in 1795 ("Oeuvres," volume 7, page 286).

The determination of particular integrals by the method of partial fractions with the variable replaced by the operator D seems to have been first published by R. Lobatto in his "Théorie des Charactéristiques" in 1837.

Between 1840 and 1880, operation methods were considerably researched upon by C. Babbage, G. Boole, J. Blissard, J. Hammond, C. J. Hargreave, J. Herschel, H. M. Jeffery, E. McClintock, I. Todhunter, and others. For a comprehensive survey of work done, see a paper by S. Pincherle in "Encyklopaedie der Mathematische Wissenschaften," band 2, teil 1, page 761. The so-called "shift" theorem:

$$\psi(D)e^{hl}\phi(t) = e^{hl}\psi(D + h)\phi(t)$$

may for instance be found in a paper by C. J. Hargreave (*Philosophical Transactions*, Royal Society, London, 1848, page 31) where it is stated to have been already well known.

The formula evaluation of coefficients in expansions even more general than that of Heaviside's (1886) was provided by G. Mittag-Leffler in 1880 (*q. v.*, "Modern Analysis" by E. T. Whittaker and G. N. Watson, 4th edition, page 134).

The essential and distinguishing features of Heaviside's p operational calculus from the conventional D operational calculus lie in the p-integration:

$$p^{-1}\{\phi(t)1(_t)\} = \lim_{n \gtrsim \infty} \int_n^t \phi(t)1(_t)dt$$

(*q. v.*, "Treatise on Differential Equations" by A. R. Forsyth, page 57. "Electromagnetic Theory" by O. Heaviside, volume 1, page 392; volume 2, paragraph 239, page 59) and in the introduction of the unit function:

$$1(_t) = 0, \text{ 1 as } t \; 0 \lesssim$$

into the operand so as to avoid getting any but desirable answers when the ordinary D operational formulas are applied, with D replaced by p, and p^{-1} interpreted as the definite integral above.

Although Heaviside was well versed in Fourier analysis ("Théorie Analytique de la Chaleur" by J. B. J. Fourier, 1822; complex variable elaboration, by Cauchy, Dirichlet, Dini, etc.), no explicit evaluation of the unit function appears in his writings. The honor of determining the necessary and sufficient conditions under which this can be done falls to T. J. I.'A. Bromwich (London Mathematical Society *Proceedings*, volume 15, 1916; page 401; paper read Mar. 12, 1914):

$$1(_t) = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} \frac{e^{\nu t}}{\nu} d\nu, \; c > c_0 > 0$$

Hence, if:

$$\frac{Z(p)}{Y(p)} i(_t) = \phi(t)\, 1(_t)$$

and $i(_t) = 0$ for $t < 0$, then:

$$i(_t) = \frac{Y(p)}{Z(p)} \phi(t)1(_t)$$

Utilizing the D operational theorems:

$$e^{hD}F(t) = F(t + h)$$

$$\phi_0(D)\{\phi_1(t)\phi_2(t)\} = \phi_1(t + D_0)\phi_0(D_0)\phi_2(t)$$

and the explicit form of the unit function,

$$i(_t) = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} \left[\phi(t+D_\nu)\frac{Y(\nu)}{Z(\nu)}\right]\frac{e^{\nu t}}{\nu} d\nu$$

which is the contour integral solution of the Heaviside problem as substantially given by Bromwich, and his disciple, H. Jeffreys.

From the researches of Euler, as pointed out by Heaviside ("Electromagnetic Theory," volume 3, paragraph 526):

$$\frac{1}{p} f(t) = \int_0^\infty e^{-pz} f(x)dx = \int_0^t f(x)dx$$

Hence obviously:

$$\frac{Y(p)}{pZ(p)} \phi(t)1(_t) = \int_0^\infty i(_t)e^{-pt}dt$$

Thus, the so-called "Carson" integral equation (*Bell System Technical Journal*, Nov. 1922, page 43) was known to Heaviside at least before 1912. Why more extended use of this integral equation was not made by Heaviside is recognizable, first, because of his brilliant success in solving difficult problems by closed and open operational methods, and secondly, by finishing the half-quotation ("Electromagnetic Theory," 1899, volume 2, page 11) in J. R. Carson's book ("Electric Circuit Theory and the Operational Calculus," 1926, page 32).

"... are apt to take refuge in a definite integral, and call that the solution. It is certainly one form of the solution. But it may be just as hard, or harder, to interpret than the differential equation of the problem in question."

That the Heaviside-Carson integral equation is now meeting applicational success is because admittedly "a large number of infinite integrals of the type appearing in equation 9 have been worked out" (Carson, *Bell System Technical Journal*, Nov. 1922, page 48); equation 9 in the paper being that in question.

Although not entirely novel, the transform technique evolved in van der Pol's papers (1929 on) is very useful. Such technique has its purest form in symbolic analysis; *q. v.*, "Principia Mathematica" by A. N. Whitehead and B. Russell.

Very truly yours,

I. H. BARKEY (A'29)
(Technical Consultant, 2020 32nd St., Brooklyn, N. Y.)

Wine Makers and Bottle Makers—A Parable

[EDITOR'S NOTE: The parable which follows was part of a discussion by Professor Karapetoff of President J. Allen Johnson's address "An Insight Into the Workings of the Institute," both of which were presented at the A.I.E.E. North Eastern District meeting, Worcester, Mass., May 16–18, 1934. President Johnson's address was published in ELECTRICAL ENGINEERING for July 1934, p. 1039–46. In Professor Karapetoff's parable which follows, the specialists in any field are compared to the "wine makers," and the administrators in the same field are compared to the "bottle makers." In the Institute's organization, both "wine makers" and "bottle makers" will be found.]

To the Editor:

A certain country was noted for its wonderful native wines, both sparkling and mellow. Grapes were grown by small individual owners, and each specialist was proud of his product and of its distinct taste. For fermentation and aging, wine was poured into various casks, skins, bottles, jugs, etc., as the case might be. From time to time there was some talk about the containers being not always satisfactory and certainly not uniform. Gradually the makers of bottles and jugs organized an association to improve and to standardize their products, so as to provide the wine makers with better containers and thereby to assist them both in the production and marketing of the wines.

It so happened that while it was easy for bottle makers to become organized (their product being standard and comparatively easy to manufacture), the wine makers continued their individual production, at least for the choicest vintages, where intimate individual knowledge, skill, and professional pride were important factors. As

time went on, there was more and more talk about excellent bottles and less and less talk about the wines themselves, because the organized bottle makers had better publicity channels. In some cases fancy mass-production bottles began to be used for mediocre wines, thus discouraging best viniculturists.

To make the situation worse, the bottle makers conducted their activities as part of the wine making industry, and the wine makers were only invited from time to time as a favor to sit with them in their discussions. To make the camouflage complete, the bottle makers adopted for themselves the honorary degrees which the wine makers originally used to bestow upon their own distinguished confreres, such as master of fizz and doctor of fermentation, although the recipients from among the bottle makers did not even understand the meaning of the words. Every time an intricate technical problem in wine making arose, the bottle makers appointed an elaborate committee of their own men, with the final result that a bottle of a somewhat different shape was recommended as a remedy, even though the difficulty may have been of chemical or bacteriological nature.

The bottle makers' association grew and prospered. Not satisfied with bottles for wine, the association appointed representatives to sit on joint committees with makers of other kinds of containers, such as bathtubs and garbage cans, it being assumed that they had much in common. In the meantime less and less of exquisite rare wines began to be produced, and more and more of "vin ordinaire" of uniformly sour taste, sold in various fancy bottles. Finally the more discerning consumers from abroad ceased buying wine from this particular country, and warehouses became filled with empty bottles of all kinds of fancy shapes. Some of the wine growers went into other pursuits, some continued outside the association, and some began forming small professional circles of their own, very simple in external form, and devoted exclusively to real improvements in the quality of wines and general theory of grape culture and fermentation. Full membership was restricted to actual grape growers and wine makers; anyone interested as an amateur could become an associate member, but bottle makers were strictly excluded. In some circles, to be admitted one even had to prove that neither of his grandfathers was a bottle maker nor related to one.

In the end the cycle was completed and the wine growers again acquired the prominence due them, while the bottle makers' association became too top-heavy to continue to exist. Individual bottle makers found their proper modest function furnishing simple reliable bottles as specified by the wine makers. From the temporary flare-up, when the bottle makers came near ruining the wine industry by their overzealousness and naïve conceit, some of the puzzling old sayings originated, such as, "tell your troubles to the bottle makers," or "try a different-shape bottle."

Very truly yours,

VLADIMIR KARAPETOFF
(A'03, F'12, and Life Member)
(Professor of Electrical Engineering, Cornell University, Ithaca, N. Y.)

Designations of Photo-Electric Devices

To the Editor:

Attention should be drawn to the desirability of standardizing the designations of the 4 distinct classes of photo-electric devices. There are:

1. The vacuum-tube alkali-metal cells which operate with an external source of electromotive force. These are commonly referred to as photo-electric cells or as photo cells, alternatively as photo-electric tubes or photo tubes. These names are well understood.
2. The cells which change their resistance under the influence of light. These are well called photo-resistance or photo-conductance cells.
3. The cells containing an electrolyte and operating in connection with some voltaic action. These are photovoltaic cells.
4. The oxide-on-metal cells which without any external electromotive force furnish a current proportional to the incident luminous flux. These are variously called blocking-layer cells, barrier-layer cells, and barrage cells. These terms are objectionable in that they represent the selection of a name in accordance with a theory of the operation of the device rather than from a consideration of its obviously distinctive properties. They are also called photo-voltaic cells which is clearly a misnomer.

There is clearly a need for giving to this last class of cells a name which is both distinctive and descriptive. The most distinctive feature of these cells is that they will deliver a current proportional to luminous flux without the application of an external electromotive force. True, this is also true of the photo-voltaic cells, but they already have a distinctive name of their own and there is no chance for confusion. The oxide-on-metal cells constitute the only practical photo-electric devices in which the electromotive force necessary to produce the current is generated in the cell itself, under the influence of light. These cells therefore might be called "photo-emf" cells.

The presence of a true electromotive force in these cells has been questioned. This matter may be examined in the light of the following definition contained in the report on definitions of electrical terms of the sectional committee which the A.I.E.E. is sponsoring: "Electromotive force is the property of a physical device which tends to produce an electric current in a circuit." The answer is unambiguous. The question as to the allowability of forming a word partly out of an abbreviation will have to be answered by saying that the word so formed is understandable, practical, convenient and fits the case. It is an innovation, but engineers and scientists are usually not afraid of justifiable innovations.

At any rate there is need for a good name, whether it be this one or another, and it should be given and sanctioned before any of the present unsatisfactory terms becomes so firmly entrenched as to remain a burden on terminology for all time.

Very truly yours,

CLAYTON H. SHARP
(A'02, F'12, and member for life)
(Technical Consultant in Electricity and Light, White Plains, N. Y.)

Personal Items

W. R. SMITH (M'18, F'30) assistant chief engineer, United Engineers and Constructors, Inc., Newark, N. J., has been appointed chairman of the board of examiners of the Institute for the year 1934–35. Mr. Smith was born at Charleston, S. C., in 1885. In 1906 he graduated from Clemson Agricultural and Mechanical College, receiving the degree of B.S. in mechanical and electrical engineering. Following graduation he remained for a year as secretary and engineering assistant to the department head and then entered the apprentice course of the Westinghouse Electric and Manufacturing Company. From 1908 to 1913 he was employed by the Hartford Suspension Company, Jersey City, N. J., and from 1914 to 1922 by the Public Service Electric Company, Newark, N. J., where he was concerned with construction work, becoming field engineer in 1917. With the formation of the Public Service Production Company in 1922 he became superintendent of the electrical construction department and managing electrical engineer in charge of the electrical engineering department in 1924, accepting his present position in 1927. He has been a member of the board of examiners of the Institute since 1930, and is chairman of the New York Section. His

W. R. SMITH

E. L. MORELAND

A. A. KRONEBERG

HAROLD GOODWIN, JR.

F. D. KNIGHT

M. K. GOLDSTEIN

other memberships include the Illuminating Engineering Society, the Edison Electric Institute, and the Essex Electrical League.

E. L. MORELAND (A'11, F'21) of Jackson and Moreland, Boston, Mass., has been appointed chairman of the standards committee of the Institute for the year 1934–35. Mr. Moreland was born at Lexington, Va., and in 1905 graduated from The Johns Hopkins University, Baltimore, Md., with the degree of A.B. in mathematics and physics. Three years later he entered the employ of D. C. JACKSON (A'87, F'12, and past-president) and W. B. JACKSON (A'97, F'13) consulting engineers in Chicago, Ill., and Boston, Mass. He was made a partner of the firm in 1916. Upon his return from military service after the war the partnership with D. C. Jackson was formed. Among the projects of this firm have been the electrification of the Great Northern Railway through the Cascades and the electrification of the Lackawanna Railroad suburban service out of Hoboken, N. J. Mr. Moreland has been a member of the Institute's transportation committee since 1931, and of the standards committee since 1932. He has also served on the committees on power generation, 1929–31; electrical machinery, 1929–31; technical program, 1929–34; and Institute policy, 1933–34; and has recently been appointed Institute representative on the standards council of the American Standards Association.

HAROLD GOODWIN, JR. (A'11, F'23) consulting engineer, Wyncote, Pa., has been appointed chairman of the Institute's committee on transfers for the year 1934–35. Mr. Goodwin was born at Philadelphia, Pa., in 1888. In 1908 he received the degree of B.S. in electrical engineering from the University of Pennsylvania, and entered the employ of the Philadelphia Electric Company. He became superintendent of distribution in 1915, in which position he devised the 4-phase 2,300/4,600-volt system of distribution. In 1919 he entered power and transmission work with the General Electric Company, Schenectady, N. Y., and the following year became engaged in a power survey which was under the auspices of the U.S. Geological Survey. In 1922 he joined the staff of the engineering firm of Sanderson and Porter, New York, N. Y., and subsequently was connected with the Columbia Engineering and Management corporation. He now has offices in Philadelphia, Pa., and is associated with H. L. Doherty and Company, New York. He has served on the Institute's committees on membership, 1916–18; standards, 1923–25; electrical machinery, 1924–27; and associate dues and related matters, 1932–34. He has been a member of the board of examiners since 1925 and was chairman 1931–34, and has been a member of the committee on transfers since 1932.

F. D. KNIGHT (M'25) assistant superintendent, generating department, Edison Electric Illuminating Company of Boston, Mass., has been appointed chairman of the safety codes committee of the Institute for the year 1934–35. Mr. Knight was born at Limerick, Maine, in 1883. After a few years' experience with the General Electric Company at Lynn, Mass., he entered the University of Maine and received the degree of B.S. in electrical engineering in 1909. For 16 years he was connected with Stone and Webster, Inc., in enterprises in various parts of the country. Among these were the pioneer mercury turbine plant of the Hartford Electric Light Company and the first 1,400-lb steam plant of the Edison Electric Illuminating Company of Boston. Mr. Knight assumed his present duties with the latter company in 1925. He has been a member of the safety codes committee of the Institute since 1930, and is also Institute representative on the committee on low voltage hazards of the National Safety Council, on the electrical committee of the National Fire Protective Association, and on the National Fire Waste Council.

M. K. GOLDSTEIN (A'33) development engineer, J. D. Radio Company, Baltimore, Md., has been awarded the 1933 A.I.E.E. Middle Eastern District prize for best paper for his paper "Telemetering in Large Power Stations." Mr. Goldstein was born at Baltimore in 1909, and is a graduate of The Johns Hopkins University, class of 1930. He continued his studies with the aid of a scholarship and received the degree of doctor of engineering in 1933. He majored particularly in radio engineering, engaging in research on development, construction, and studies of duplex triple-grid tubes with particular reference to their intergroup shielding factors and effects of space charge modifications. During summers he has been employed as expert examiner in mathematics by the United States Government, and by the J. D. Radio Company. In 1933 he made an extensive survey of telemetering apparatus with particular reference to its use of thermionic and photronic devices upon which his paper was based. He is a member of the Institute of Radio Conferees, Institute of Radio Engineers, and Sigma Xi.

A. A. KRONEBERG (A'26) technical assistant to operating engineer, Southern California Edison Company, Ltd., Los Angeles, with his co-author L. F. HUNT (A'21) has been awarded the 1933 A.I.E.E. Pacific District prize for best paper for their paper entitled "Some Recent Relay Developments." Mr. Kroneberg was born at Ekaterinbourg, Russia, in 1899. He was educated at schools in Russia and after coming to the United States in 1923 entered the electrical engineering course at California Institute of Technology, where he was elected to Tau Beta Pi. Following graduation in 1926 he entered the training course of the Southern California Edison Company and became electrician at the Long Beach steam station. He was appointed to his present position in 1931.

L. F. HUNT (A'21) technical assistant to the operating engineer, Southern California Edison Company, Ltd., Los Angeles, has, with his co-author, A. A. KRONEBERG (A'26) been awarded the 1933 best paper prize of the Institute's Pacific District for the paper entitled "Some Recent Relay Developments." He was born in San José, Calif., in 1897. In 1919 he graduated from the University of Southern California with the degree of bachelor of science in electrical engineering. In 1928 he received the degree of electrical engineer from this institution. During the period 1916–19 he was electrician in charge for the University of Southern California, and in 1919 entered the graduate student course of the Westinghouse Electric and Manufacturing Company at East Pittsburgh, Pa. The following year he became a member of the supply engineering department of this company, engaged in relay design and application, continuing this work until 1922 when he undertook protection engineering for the Southern California Edison Company. In 1924 he became assistant to the chief electrical engineer of the company, and the following year became development engineer and technical assistant to the research engineer. Since 1930 he has been technical assistant to the operating engineer. He has designed many relays and relay schemes, the most recent of which is a carrier current system. He has also designed many high speed recording instruments. He is a member of Eta Kappa Nu and Sigma Alpha Epsilon fraternities.

S. W. HANNAH (Enrolled Student) service department, Hoover Company, Denver, Colo., with his co-author A. F. LOGAN (Enrolled Student) has been awarded the Institute's 1933 North Central District prize for Branch paper and has received honorable mention in the 1933 national awards for Branch paper for the paper entitled "The Measurement and Control of the Synchronous Machine Torque Angle." He was

born at Denver, March 30, 1911, and entered the University of Colorado at Boulder in 1929 as a holder of a scholarship. During his senior year, when the paper was presented, he was chairman of the Institute's University of Colorado Branch. In 1933 he received the degree of bachelor of science in electrical engineering with special honors, and received a fellowship in the department of electrical engineering for the year 1933–34. Mr. Hannah received the degree of master of science in 1934. He is a member of Tau Beta Pi, Sigma Tau, Sigma Xi, and Eta Kappa Nu.

Arthur Simon (A'03, F'13) engineering and patent consultant, Milwaukee, Wis., has had the honorary degree of doctor of science conferred upon him by Marquette University, Milwaukee. The citation stated "Arthur Simon—patent expert for Cutler-Hammer Co., in whose services he has been for 30 years—a citizen who has generously given his technical services to the public welfare, who by his own contributions to the science of electrical engineering—by his papers before local and national engineering societies, and by his service to the engineering profession, locally, nationally, and internationally, is entitled to the degree of doctor of science, honoris causa." Dr. Simon was a member of the Institute's committee on power transmission and distribution, 1923–25.

H. H. Barnes, Jr. (A'00, F'13) commercial vice president, General Electric Company, New York, N. Y., is serving as assistant chairman of the electrical section of a committee of business men in a drive to increase the membership of The Merchants' Association of New York. Mr. Barnes has been very active in committee work in the Institute, and is now serving on the Edison medal committee and on the committee on code of principles of professional conduct. He was a manager of the Institute 1910–13, and a vice president 1913–15.

E. C. M. Stahl (M'27) formerly assistant operating superintendent, Brooklyn Edison Company, Inc., Brooklyn, N. Y., has been appointed operating superintendent. Mr. Stahl is a graduate of Cornell University, and was with the New York Central Railroad and the Pittsburgh Transformer Company before joining the Brooklyn Edison Company 12 years ago. He became assistant operating superintendent in 1930.

P. H. Moon (A'24, F'34) assistant professor of electrical engineering, Massachusetts Institute of Technology, Cambridge, has designed and will be in charge of a 4-year course in illuminating engineering to be given at that college. Professor Moon was a member of the Institute's committee on the production and application of light 1931–33.

Frederick Creedy (M'30) formerly research assistant professor at Lehigh University, Bethlehem, Pa., has accepted an appointment as professor of electrical engineering at the University of British Columbia, Vancouver, Canada. Professor Creedy is a member of the Institute's committee on electric welding, on which he has served since 1930.

Victor Frederiksen (A'32) is electrical engineer for the National Electric Coil Company, Columbus, Ohio. This company was formerly the National Armature and Electric Works, Bluefield, W. Va., where Mr. Frederiksen has been located since 1926, and which, while continuing there is opening a new plant at Columbus.

Abram Hussey (A'06, M'18) superintendent of distribution, Brooklyn Edison Company, Inc., Brooklyn, N. Y., for more than 21 years, retired recently. Before coming to the Brooklyn Edison Company he was employed by the New York Central Railroad in connection with the electrification in the New York area.

C. W. Caldwell (A'32) formerly in the electrical engineering department of the University of South Dakota, Vermillion, has become instructor in electrical measurements at Purdue University, Lafayette, Ind. Mr. Caldwell has been serving as counselor of the University of South Dakota Branch of the Institute.

Paul Doty (A'04, M'12) formerly chairman of the Minnesota State Board of Registration, St. Paul, has been appointed regional reconditioning supervisor, Home Owners Loan Corporation, Atlanta, Ga. Mr. Doty is president of The American Society of Mechanical Engineers and a vice president of American Engineering Council.

T. R. Langan (A'13, M'30) northeastern district manager, Westinghouse Electric and Manufacturing Company, New York, N. Y., is a member of the electrical section of a committee of business men in a drive to increase the membership of The Merchants' Association of New York.

L. B. Bender (A'20, M'27) signal corps, U.S. Army, has been promoted from major to lieutenant colonel, and has been transferred from headquarters, fifth corps area, Columbus, Ohio, to Wright Field, Dayton, for duty in charge of the aircraft radio laboratory.

R. A. Belinge (A'28) valuation engineer, San Francisco, Calif., is with the United States Forest Service. He was formerly chief engineer, East Bay Cities Rate Department, Oakland, Calif., and has the rank of captain, signal reserve, United States Army.

Kiyosho Yamamoto (A'20) formerly director in charge of the manufacturing department, Sumitomo Electric Wire and Cable Works, Ltd., Osaka, Japan, has become managing director of the Sumitomo Aluminum Reduction Company, Ltd., Niihamacho, Niigun, Ehimeken, Japan.

L. J. Montgomery (A'18) who has been assistant general sales manager of the New York and Queens Electric Light and Power Company, Long Island City, N. Y., since 1917, has been appointed general sales manager.

M. O. DellPlain (A'08, M'12) president of the Northern Indiana Public Service Company, Hammond, Ind., since 1929, has resigned to become vice president of the Welsbach Street Light Company of America, Philadelphia, Pa.

I. A. Patten (A'28) assistant general superintendent of the Lynn Gas and Electric Company, Lynn, Mass., since 1930, has been appointed general superintendent. He has been with the Lynn company since 1911.

W. R. Strbuli (A'27) until recently with the substation department of the Long Island Railroad, Long Island City, N. Y., has joined the staff in charge of design and development of the Telephonwerke Albisrieden, Zurich, Switzerland.

E. R. McKee (A'30) who has been assistant professor of electrical engineering at Iowa State College, Ames, has accepted a position as professor and head of electrical engineering at the University of Vermont, Burlington.

J. D. Stacy (A'20) who was formerly in charge of the radio receiver division of the RCA-Victor Company at Camden, N. J., has accepted a position as capacitor design engineer for the General Electric Company at Pittsfield, Mass.

E. G. Cullwick (A'26, M'33) formerly assistant professor of electrical engineering, University of British Columbia, Vancouver, Canada, is now in the electrical engineering branch of the Military College of Science, London, England.

E. C. Milde (A'32) formerly an instructor in physics at Worcester Polytechnic Institute, Worcester, Mass., has accepted a position in the laboratories of the Atwater Kent Manufacturing Company, Philadelphia, Pa.

C. M. Underwood (A'31) formerly sales engineer, Raytheon Manufacturing Company, Newton, Mass., is senior welding engineer, United States Navy Yard, Washington, D. C.

C. H. Lydall (A'20) formerly representative in Chicago, Ill., of Merz and McLellan, London, England, is now North American representative with offices in London.

C. W. Dalzell (A'27) formerly a sales engineer for the Suburban Electric Development Company, Pittsburgh, Pa., is now with the Heyer Products Company, Inc., Belleville, N. J.

L. S. Cooper (A'29) formerly with the Hoffman Beverage Company, Newark, N. J., is an engineering assistant in the transportation department of the General Electric Company at Erie, Pa.

W. A. Black (A'12, M'30) formerly district manager, Allen-Bradley Company, Cleveland, Ohio, is electrical sales manager for the Fairbanks Morse Company, Cincinnati, Ohio.

James Dixon (A'02, M'13) formerly with the Reliance Electric and Engineering Company, Cleveland, Ohio, is now with the Crocker Wheeler Electric Manufacturing Company, Ampere, N. J.

C. D. Friday (A'30) who has been a postgraduate student at Ohio State University, Columbus, is assistant electrical engineer, bureau of yards and docks, Navy Department, Washington, D. C.

K. D. Engle (A'25) formerly with the Cornell-Dubilier Corporation, New York, N. Y., is now factory superintendent for the Micamold Radio Corporation, Brooklyn, N. Y.

Gordon Cavanagh (A'32) valuation and rate engineer who was with the North American Light and Power Company, Chicago, Ill., is now with the Illinois Power and Light Corporation, Monticello, Ill.

E. B. Heath (A'25) formerly of Pacific Palisades, Calif., has accepted a position in the department of engineering and mathematics of the San Bernardino Valley Junior College, San Bernardino, Calif.

J. R. Strong (A'01 and member for life) president, Tucker Electrical Construction Company, New York, N. Y., has retired from business and resides at Short Hills, N. J.

A. R. Nelson (A'22, M'29) Public Service Electric and Gas Company, Newark, N. J., has been appointed assistant superintendent of electrical distribution in the Essex County division of the company.

F. S. Kingston (M'30) Elizabeth, N. J., is president of the recently organized Kingston-Conley Electric Company of Jersey City, N. J., manufacturers of fractional horsepower motors.

P. W. Baker (A'16, M'29) formerly engineer in the small motor division, Wagner Electric Company, St. Louis, Mo., is now in the engineering department of the Kelvinator Corporation, Detroit, Mich.

M. F. Beall (A'32) Grand Rapids, Mich., is assistant to the chief engineer, Michigan Gas and Electric and Michigan Public Service companies, with general offices at Holland, Mich.

W. W. Woodruff (A'16) Swarthmore, Pa., is engineer of design and construction, Tennessee Valley Authority, and is now located at Chattanooga, Tenn.

Nathaniel Bishop (A'26) Bridgeport, Conn., has joined the radio sales engineering department of the General Electric Company in Bridgeport.

D. C. Green (M'26) president, Middle West Utilities Company, Chicago, Ill., has been named a temporary trustee of the company, which is in receivership.

F. M. Tait (A'94, F'12) president, Dayton Power and Light Company, Dayton, Ohio, has been elected a director of the Columbia Gas and Electric Corporation.

L. V. Banta (A'34) Bloomfield, N. J., is assistant to the sales engineer, Edison storage battery division of Thomas A. Edison Inc., West Orange, N. J.

C. M. Wolfe (A'27) formerly of Kingwood, W. Va., is now at the New Mexico State College of Agriculture and Mechanic Arts, State College.

C. F. King, Jr. (A'16) general engineer, Westinghouse Electric and Manufacturing Company, has been transferred from East Pittsburgh, Pa., to Philadelphia, Pa.

J. E. Davies (A'32) distribution engineer, Public Service Company of Colorado, has been transferred from Idaho Springs to Denver.

H. R. McKinney (A'33) U. S. Electrical Manufacturing Company, Los Angeles, Calif., has been transferred from the engineering to the sales department.

J. M. Lyons (A'28) assistant engineer, General Electric Company, has been transferred from West Lynn, Mass., to Schenectady, N. Y.

O. R. Fitz (A'33) Bayside, N. Y., is an engineering assistant with the New York and Queens Electric Light and Power Company, Flushing, N. Y.

M. W. Smedburg (A'33) formerly employed by the board of public utilities, Jamestown, N. Y., is working for the Tennessee Valley Authority, Knoxville, Tenn.

D. W. Yambert (A'16, M'21) is an engineer with the Dravo Contracting Company, Pittsburgh, Pa., and resides at Ada, Ohio.

C. M. Tolman (A'20, M'20) is an engineer with the Bartlett Hayward Company, New York, N. Y., and resides in Brooklyn, N. Y.

H. W. Morris (M'24) Washington, D. C., is with the bureau of public debt, accounts and audits, U.S. treasury department.

C. R. Shields (A'34) is a hydroelectric plant operator for the Western Colorado Power Company at Telluride.

J. T. Kelly, Jr. (A'12, M'22) St. Louis, Mo., is a salesman for the General Electric Company there.

Obituary

Frank Julian Sprague (A'87, M'97, F'12, HM'32, past-president and member for life) president, Sprague Safety Control and Signal Corporation, New York, N. Y., died October 25, 1934. Doctor Sprague was born at Milford, Conn., July 25, 1857. From 1874 to 1878 he attended the U. S. Naval Academy, and in 1882 attended the Crystal Palace Exhibition, London, to prepare a report for the Navy Department on electrical machinery, in which he recommended the use of direct-connected compound-wound dynamos for use on ships. In the spring of 1883 he resigned from the navy and for a year worked with Thomas A. Edison. The Sprague Electric Railway and Motor Company was organized by him in 1884, and in 1887 he undertook the building of the first extensive electric street railway, at Richmond, Va., on a 90-day contract. His success here led to contracts for 110 other railways. This company was merged with the General Electric Company in 1890, and in 1892 Doctor Sprague formed the Sprague Electric Elevator Company for the development and promotion of electric elevators. In 1895 he invented the multiple unit system of train control, which was applied 2 years later on the elevated lines in Chicago, Ill., for which project the Sprague Electric Company was formed. From 1903 to 1908 he served on the commission for the electrification of the Grand Central Terminal, New York. His automatic train control system was developed in 1906, at which time he formed the Sprague Safety Control and Signal Corporation. Doctor Sprague is credited with a number of other accomplishments, including the introduction of the constant speed motor, regenerative control, 3-point geared motor suspension, and, in 1926, the dual elevator, whereby 2 elevators operate in the same shaft. Doctor Sprague received the Elliot Cresson medal of the Franklin Institute in 1904, the A.I.E.E. Edison Medal in 1910, and the Franklin medal of the Franklin Institute in 1921. Stevens Institute of Technology conferred upon him the degree of doctor of engineering, Columbia University that of doctor of science, and the University of Pennsylvania that of doctor of laws. In October 1934, the John Fritz gold medal, the highest distinction bestowed jointly by the national societies of civil, mining and metallurgical, mechanical, and electrical engineers of the United States, was unanimously awarded him, presentation to be made at one of the sessions of the Institute's winter convention; Doctor Sprague received notification of the award only a few days before his death. For the period 1890–92 he served the Institute as a vice president, and was president for 1892–93. The committees on which he served were the Edison medal, 1911–16, traction and transportation (now transportation), 1914–16, and a special committee on the history of the electrical industry, 1932–34. A paper on the early developments in electric transportation was prepared by Doctor Sprague for the May 1934 issue of Electrical Engineering, and was published on pages 695 to 706. A biographical sketch of Doctor Sprague was given on page 791 of the same issue.

Martin L. Roper (M'24) assistant to superintendent of transmission, Pennsylvania Power and Light Company, Hazleton, Pa., died April 22, 1934, according to word just received at Institute headquarters. He was born at Brooklyn, Pa., July 23, 1883, and received the degree of bachelor of science in electrical engineering at Pennsylvania State College in 1906. After short periods of time with the Westinghouse Electric and Manufacturing Company as an engineering apprentice and with the Allegheny County Light Company, Pittsburgh, Pa., as a draftsman, he entered the coal mining department of the Delaware, Lackawanna, and Western Railroad at Scranton, Pa., and subsequently became district electrical foreman, being transferred to Kingston, Pa., in 1912. In 1921 he undertook a similar position with the Glen Alden Coal Company there, and later that year became general electrical foreman for that company at Scranton. Since 1930 he had been with the utility. Mr. Roper was a vice chairman of the Lehigh Valley Section of the Institute during the year 1933–34.

Warren Partridge (A'04, M'29) vice president, Utility Management Corporation, New York, N. Y., died October 30, 1934. He was born at Boston, Mass., January 10, 1875. After graduation in 1897 from the electrical engineering course at Harvard University he was employed by the Public Service Corporation of New Jersey at Newark as an inspector, division superintendent, and assistant chief engineer, until in 1909 he became general superintendent for the Springfield Power and Light Company, Springfield, Ill. Three years later he assumed the office of general manager of the Pennsylvania Public Service Company, Clearfield. From 1919 to 1925 he was a consulting engineer for H. D. Walbridge and Company, New York, after which he was with the J. G. White Management Corporation, serving as vice president of the Pennsylvania Electric Company and subsidiaries and the New England Gas and Electric Corporation and subsidiaries. Mr. Partridge was appointed a vice president of the Utilities Management Corporation about 4 years ago.

Charles W. Parkhurst (A'01, F'13) consulting engineer, Berwind-White Coal Mining Company, Philadelphia, Pa., died September 30, 1934. He was born at Hammonton, N. J., July 5, 1870, and was a graduate of Lehigh University, class of 1893, receiving the degree of electrical engineer. He was first employed in the electrical department at Cramps Ship Yard, Philadelphia, where he became assistant superintendent and had charge of the electrical installation on several ships. In 1897 he installed electrical equipment for a Pennsylvania Railroad ferry at New York, N. Y., and later that year designed some fittings for the slot conduit of the Metropolitan Street Railways Company of that city. Following short periods in the employ of the Union Iron Works, San Francisco, Calif., and the Siemens and Halske Electric Company, Chicago, Ill., as a designer of electrical equipment he became electrical engineer and superintendent of the electrical department of the Cambria Steel Company, Johnstown, Pa., where he had charge of the engineering, installation, and operation of all electrical equipment. At this time he was also a consulting engineer for the Citizens Light, Heat, and Power Company of Johnstown and the Pennsylvania Iron Mining Company of Vulcan, Mich. Since 1917 he had been consulting engineer for Berwind-White Company, and also for 6 years for Perin and Marshall, New York. Mr. Parkhurst had been reappointed this year as a member of the Institute's committee on applications to mining work, on which he had served since 1931. He was a past-president of the Association of Iron and Steel Electrical Engineers, and a member of the American Electrochemical Society and Tau Beta Pi.

George Washington Atkinson (A'15, M'25) of Springfield, Mass., construction engineer, procurement division, public works branch, United States treasury department, died September 15, 1934. He was born at Morocco, Ind., March 19, 1883. In 1908 he received the degree of bachelor of science in electrical engineering from Purdue University, and the degree of electrical engineering in 1911. From 1909 to 1917 he was employed in the supervising architects office, treasury department, Washington, D. C., where he was concerned with mechanical and electrical equipment for federal buildings. For 4 years following 1917 he was in charge of all electrical equipment at the Springfield Armory, and then became superintendent of power and maintenance for the Gilbert and Barker Manufacturing Company, Springfield, for 10 years. During the last 3 years as construction engineer he had charge of the construction of the postoffices at Palmer and Easthampton, Mass. Mr. Atkinson was at one time chairman of the Springfield Section of the Institute.

John Hugh McManus (A'10) special utility representative, Johns-Manville Corporation, New York, N. Y., died October 7, 1934. He was born at New York, June 8, 1879. From 1897 to 1904 he was employed by the Westchester Lighting Company, Port Chester, N. Y., after which he studied at Ohio State University and Pratt Institute. For 3 years following 1906 he was employed by the New York and New Jersey Telephone Company, Newark, N. J., and then entered the Johns-Manville organization as an electrical salesman.

Gomer Louis Evans (M'21) vice president, Wagner Electric Company, St. Louis, Mo., died September 10, 1934. He was born at St. Louis, November, 26, 1885. Following his graduation from the electrical engineering course at Washington University he entered the production division of the Wagner Electric Company, of which he subsequently became superintendent of production, assistant vice president, and vice president.

Membership

Recommended for Transfer

The board of examiners, at its meeting held November 27, 1934, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Campbell, Arthur B., chief engr., Seth Thomas Clock Co., Thomaston, Conn.
Coles, Edmund P., mgr., Gen. Elec. Co., Charlotte, N. C.

2 to Grade of Fellow

To Grade of Member

Bass, L. B., sales engr., Gen. Elec. Co., Oklahoma City, Okla.
Branson, Edward H., director of research labs., General Railway Signal Co., Rochester, N. Y.
Brown, Nelson E., asst. supt. of operation, Buffalo Gen. Elec. Co., Buffalo, N. Y.
Clark, Joseph, asst. engr., Brooklyn Edison Co., Brooklyn, N. Y.
Edwards, Manley W., elec. engr., Municipal Lt. & Pwr. Dept., Pasadena, Calif.
Foster, Clair V., proprietor and Mgr., North End Garage, Niagara Falls, N. Y.
Gillespie, Leigh R., telephone engr., Rochester Tel. Corp., Rochester, N. Y.
Gordon, Harry E., equipment engr., Rochester Tel. Corp., Rochester, N. Y.
Harper, Richard G., sales engr., Westinghouse E. & M. Co., Buffalo, N. Y.
Haslett, H. M., supt. of production, Porto Rico Ry. Lt. & Pwr. Co., Santurce, Porto Rico.
Hopkins, Ralph A., sales engr., Westinghouse E. & M. Co., Los Angeles, Calif.
Hubbard, Horace S., designing engr., Gen. Elec. Co., Pittsfield, Mass.
Hull, R. H., asst. prof. of elec. engg., University of Idaho, Moscow.
Huntington, Ernest K., elec. engr., operating dept., Rochester Gas. & Elec. Corp., Rochester, N. Y.
Irland, George A., asso. prof. of elec. engg., Bucknell Univ., Lewisburg, Pa.
Jones, Edward O., sales engr., Gen. Elec. Co., Buffalo, N. Y.
Langner, Frederick W., asst. to chief engr., Socony-Vacuum Oil Co. Inc., Olean, N. Y.
Macmillan, Campbell, research engr., motor dept., Gen. Elec. Co., Schenectady, N. Y.
Markowitz, Jesse, instructor, school of technology, College of the City of N. Y., New York.
Morrison, George, sales engr. and director, Commonwealth Elec. Corp., Welland, Ont. Canada.
Nimmo, William F., asst. mgr., elec. dept., Virginia Elec. & Pwr. Co., Norfolk, Va.
Oehler, John F., elec. engr., Bethlehem Steel Co., Lackawanna, N. Y.
Oetinger, Herbert W., asst. to vice pres., Duke Pwr. Co., Charlotte, N. C.
Phillips, Frank D., asst. designing engr., Gen. Elec. Co., Schenectady, N. Y.
Plummer, Ernest W., asst. supt. of meters, Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Reid, Charles R., asst. general supt., Shawinigan Water & Pwr. Co., Montreal, Que., Canada.
Runciman, Arthur S., supt. of transmission lines, Shawinigan Water & Pwr. Co., Montreal, Canada.
Scott, Lee R., elec. engr., Rochester Gas & Elec. Corp., Rochester, N. Y.
Stewart, Douglas C., asst. elec. engr., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Van Olinda, Frederick, division engr., Brooklyn Edison Co. Inc., Brooklyn, N. Y.
Vincent, Gilbert I., rate engr., Niagara Hudson Pwr. Corp., Syracuse, N. Y.
Walker, John R., asso. elec. engr., U.S. Bureau of Reclamation, Denver, Colo.
Zielinski, Henry H., resident engr., AEG, German Gen. Elec. Co., Schenectady, N. Y.

33 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election

of any of these candidates should so inform the national secretary before Dec. 31, 1934, or Feb. 28, 1935, if the applicant resides outside of the United States or Canada.

Aiken, C. B. (Member), Bell Tel. Lab., N. Y. City.
Ainsworth, V. A., Maritime Elec. Co. Ltd., Fredericton, N. B., Can.
Anderson, E. P., Portland Gen. Elec. Co., Portland, Ore.
Audlin, L. J. (Member), Niagara Hudson Pwr. Corp., Syracuse, N. Y.
Bedford, B. D., Gen. Elec. Co., Schenectady, N. Y.
Blake, W. J., Jr., Virginia Pub. Serv. Co., Alexandria.
Broverman, M., Gen. Elec. Co., Pittsfield, Mass.
Brown, L. K. (Member), N. Y. State Elec. & Gas Corp., Lancaster, N. Y.
Carpenter, J. W. (Member), Texas Pwr. & Lt. Co., Dallas.
Clark, G. A. (Member), Consumers Pwr. Co., Jackson, Mich.
Cone, W. S. (Member), 314 Montery Rd., S. Pasadena, Calif.
Crosby, C. L., Allis Chalmers Mfg. Co., Richmond, Va.
David, K. I., Pacific Pwr. & Lt. Co., Portland, Ore.
Davies, L. S., Provincial Mental Hospital, Essondale, B. C., Can.
Dunstan, A. M., Federal Pwr. Comm., Washington, D. C.
Elias, N. M., 333 Sixth Ave., N. Y. City.
Endres, M. L., Nat. Park Service, engg. div., Washington, D. C.
Fansler, B. I., Appalachian Elec. Pwr. Co., Roanoke, Va.
Farace, S. H., Phila. Elec. Co., Philadelphia, Pa.
Fassett, F. C., 100 Seward Ave., Detroit, Mich.
Finsterwalder, C. J., 22 Broadway Terrace, N. Y. City.
Fishwick, A., Illinois Bell Tel. Co., Chicago.
Fornhalt, W. H., Lehigh Univ., Bethlehem, Pa.
Priddle, C. G., Cleveland, Elec. Illum. Co., Cleveland, Ohio.
Frost, H. C., Defiance Spark Plugs Inc., Toledo, O.
Gibson, A. D. (Member), Buffalo Gen. Elec. Co., Buffalo, N. Y.
Hardgrave, T. W., Gibbs & Hill, N. Y. City.
Harris, C. F. (Member), Westinghouse Elec. & Mfg. Co., Rochester, N. Y.
Hathaway, F. B., Okla. Gen. Elec. Co., Oklahoma City.
Hess, H. M., Wayne Univ., Detroit, Mich.
Hogshead, C. C., Appalachian Elec. Pwr. Co., Roanoke, Va.
Hrivnatz, H. G., Houston Lighting & Pwr. Co., Houston, Tex.
Iber, A. K., Arma Engg. Co. Inc., Brooklyn, N. Y.
Johnson, E. A., Southern New England Tel. Co., New Haven, Conn.
Johnston, F. M., Houston Lt. & Pwr. Co., Houston, Texas.
Jones, M. (Member), Hamilton Hydro System, Hamilton, Ont., Can.
Jordan, W., Westchester Lighting Co., Mt. Vernon, N. Y.
Jorgenson, L. M., Kansas State College, Manhattan.
Kaspar, F. P. (Member), Okla. Gas & Elec. Co., Oklahoma City.
Kemp, C. G. R. (Member), c/o E. M. Gilbert Engg. Corp., Reading, Pa.
Kissel, J., Brooklyn Edison Co., Bklyn., N. Y.
Kneisly, H. L. (Member), c/o E. M. Gilbert Engg. Corp., Reading, Pa.
Kryter, R. J., Burline-Angus Co., Indianapolis, Ind.
Larkin, G. A., La Crosse Rubber Mill Co., La Crosse, Wis.
Lettine, A., 62 Berkley St., Valley Stream, N. Y.
Lind, H. M., Pacific Pwr. & Lt. Co., Portland, Ore.
London, J. B., Gen. Elec. Co., Charlotte, N. C.
Magee, W. G. (Member), Tide Water Pwr. Co., Morehead City, N. C.
May, M., 815 Victoria Bldg., St. Louis, Mo.
Mayer, E. E. (Fellow), 10 East 40th St., N. Y. City.
McGill, C. W., Edison Elec. Illum. Co. of Boston, Mass.
Merwin, J., Southern New England Tel. Co., New Haven, Conn.
Minichan, D. P., Appalachian Elec. Pwr. Co., Roanoke, Va.
Moore, W. B., Potomac Elec. Pwr. Co., Washington, D. C.
Moreland, H. D., Westinghouse X-Ray Co., Portland, Ore.
Murphy, P. J., Dept. of Public Works, Essondale, B. C., Can.
Pedersen, A. M., Hydro Elec. Pwr. Comm., Niagara Falls, Ont., Can.
Potts, J. C., Wright Aero Corp., Paterson, N. J.
Randall, R., Gen. Elec. Co., Oklahoma City, Okla.
Riebe, F. A., 804 S. E., 46th Ave., Portland, Ore.
Ruggles, L. LaF. (Member), Automatic Elec. Co., Chicago, Ill.
Sampson, C. C. (Member), Gulf Oil Corp., Houston, Texas.
Scott, J. A., Westinghouse Elec. & Mfg. Co., Rochester, N. Y.
Silver, C. T., Federal Pwr. Comm., Washington, D. C.
Simonson, M. L., Okla. Gas & Elec. Co., Oklahoma City.
Sinclair, L. B., Reading Co., Philadelphia, Pa.
Staples, E. B., Holtzer Cabot Elec. Co., Roxbury, Mass.
Streicher, W., 445 W. 153rd St., N. Y. City.
Summers, H. J., City Hall, Torrance, Calif.
Tabb, R. P. E., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Tedeschi, F., Westinghouse E. & M. Co., E. Pittsburgh, Pa.
Webb, J. M., United Management & Engg. Co., Indianapolis, Ind.
Winter, G. J., Westinghouse Elec. & Mfg. Co., Newark, N. J.
Wirz, A., Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Wolfertan, S. B. P. (Member), Canadian Gen. Elec. Co. Ltd., Montreal, Que., Can.

76 Domestic

Foreign

de Silva, S. R., Urban District Councils, Moratuwa, Ceylon.
Krishnaswami, S., Madras Govt., Hydro Elec. Dept., Karur, South India.
Robinson, D. M., Callender's Cable & Constr. Co. Ltd., London W. 12, England.
Sublet, F. J. A., Univ. of Melbourne, Victoria, Australia.
Subramanian, A. V., Maharajaha College, Pudukotta, South India.

5 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Adams, William C., 801 S. Lynn St., Champaign, Ill.
Babloozian, Levon M., 776 N. Cass St., Milwaukee, Wis.
Demeros, Andrew G., P. O. Box 787, East Pittsburgh, Pa.
Fracker, Henry E., Bell Tel. Labs., 463 West St., N. Y. City.
Gould, Albert S., 41 E. 42nd St., N. Y City.
Hansen, A. Fred, 2065½ W 30th St., Los Angeles, Calif.
Jordan, Henry, 7408A Christopher Columbus, Montreal, Que., Can.
Loscocy, William A., 14067 Cherrylawn Ave., Detroit, Mich.
Lynn, Harry H., 10 St. Paul Pl., New Rochelle, N. Y.
Macauley, John H., Elec. Dept., B.B. & C. India Rwy., Dohad, India.
Roisland, Kornelius, 356 W. 34th St., N. Y. City.
Rose, Edwin L., Dept. of Elec. Engg., Mass. Inst. of Tech., Cambridge, Mass.
Simpson, Sidney, Deputy Loco. Supt., Eastern Bengal R. R., Kanchrapara, Bengal, India.
Strong, Ernest A., Radio Station CJRW, Fleming, Sask., Can.
Stuntz, Hans, 106 Peck Ave., Newark, N. J.
Turnquist, F. A., 4 Birch Road, Wellesley, Mass.
Wagoner, K. S., 320 Wisconsin, Oak Park, Ill.

17 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

Der ELEKTRISCHE WIDERSTAND des MENSCHLICHEN KÖRPERS gegen TECHNISCHEN GLEICH- und WECHSELSTROM. By H. Freiberger. Berlin, Julius Springer, 1934. 146 p., illus., 10x6 in., paper, 9 rm. This report covers an extensive experimental investigation of the electrical resistance of the human body, carried out under the auspices of the Berlin generating station and various organizations of electricians. Careful measurements were made upon corpses and living beings, under conditions that reproduced those of the usual electrical accidents. In addition, previous work is reviewed, and the practical use of the conclusions is explained.

FIVE PLACE TABLE of NATURAL TRIGONOMETRIC FUNCTIONS to HUNDREDTHS of a DEGREE. Compiled by Amelia De Lella. New York, John Wiley & Sons, 1934. 10x8 in., paper, $1.00. These tables give the sines, cosines, tangents, and cotangents for every hundredth of a degree from 0 to 90. They are printed in facsimile typescript, clearly and legibly, upon a page of convenient size. The values correspond to those given by Briggs.

HEAT. By J. M. Cork. N. Y., John Wiley & Sons, 1933. 279 p., illus., 9x6 in., cloth, $3.00. This text aims to provide the advanced student with a survey of the field which includes recent developments as well as the older classical treatment of the subject. The presentation is brief, but complete, and references to original papers enable the student to investigate particular subjects further.

MECHANICAL VIBRATIONS. By J. P. Den Hartog. N. Y. and Lond., McGraw-Hill Book Co., 1934. 390 p., illus., 9x6 in., cloth, $5.00. This book is intended for use as a college textbook and also aims to meet the needs of practicing engineers. The theory is presented in an understandable form, and its practical application to water wheels, steam turbines, automobiles, airplanes, Diesel engines, and electrical machinery are discussed in some detail. There is a select bibliography.

MITTEILUNGEN aus den FORSCHUNGSANSTALTEN. Bd. 3, Heft 3 and 4, July and August 1934. p. 51-84, 85-110. Berlin, VDI-Verlag, illus., 12x8 in., paper, Heft 3, 3.80 rm.; Heft 4, 2.90 rm. These 2 numbers contain, as their chief contents, the report of an extensive experimental study of the resistance of steel to corrosion fatigue, and of methods of increasing this resistance by adding inhibitors to the corroding liquid. Other articles include one on a new electric railway car, another on the manufacture of an unusually heavy casting, and a third discussing the comparative merits of Strauss and Scherzer lift bridges.

PHYSIKALISCHE EIGENSCHAFTEN und FEINBAU von NATUR- und KUNSTHARZEN. (Kolloidforschung in Einzeldarstellungen, Bd. 11.) By R. Houwink. Leipzig, Akademische Verlagsgesellschaft, 1934. 228 p., illus., 12 rm. The first part of this book gives the results of an extensive investigation carried out by the author of the elastic and plastic properties of the natural and synthetic resins. In the second part of the data obtained are made the basis for a theory of the structure of resins, which explains the relation between structure and mechanical properties, the relation between structure and optical and roentgenographic properties, and viscosity is studied.

TEXTBOOK of APPLIED HYDRAULICS. By H. Addison. N. Y., John Wiley & Sons, 1934. 409 p., illus., 9x6 in., cloth, $5.50. This textbook contains, in part 1, a compact summary of the fundamental principles of hydraulics, and in part 2, a longer but equally condensed description of the practical application of these principles to engineering problems, turbines, pumping machinery, power transmission, etc. The book is of college grade, and especial attention has been given to the needs of readers whose work is not directly connected with hydraulics but who need to be familiar with hydraulic practice.

Engineering Societies Library

29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

General Cable Appointments.—George Sherry has been appointed general merchandise manager, and H. B. Tompkins general sales manager of the General Cable Corp. Mr. Tompkins was previously manager of supply sales, General Electric Supply Corp.

Holophane Co. Appointment.—A. D. Cameron has been elected vice president of the Holophane Co., Inc., 342 Madison Ave., New York. Mr. Cameron joined the organization in 1931 as manager and his new duties will be in particular relation to sales. His headquarters are in New York.

Okonite Executive Made President of NEMA.—Frank C. Jones, president of the Okonite Co., was elected president of the National Electrical Manufacturers Association at its last meeting. Mr. Jones became identified with the Okonite Co. immediately following discharge from military service after the World War, when he entered the factory of the company at Passaic. With his election as treasurer he was transferred to the New York office, subsequently being elected vice president and general manager. In 1932 Mr. Jones assumed the duties of president of the Okonite Co., when H. Durant Cheever, who had occupied that office, became chairman of the board. Mr. Jones has devoted considerable time to the activities of the National Electrical Manufacturers Association, concentrating particularly on its wire and cable work. He is chairman of the code advisory committee of NEMA and chairman of the supervisory agency for the wire and cable subdivision of the electrical manufacturing industry. He was formerly chairman of the wire and cable section and also of the paper cable group of NEMA.

Allis-Chalmers Introduces New Motor.—The new "Seal-Clad" squirrel-cage motors introduced by Allis-Chalmers Manufacturing Co., Milwaukee, are of open-type construction, with permanent coil protection. Hard, smooth, Bakelite shields are sealed over the stator coils giving protection against metallic dust, grit, oil, moisture, mild acids and other agents injurious to insulation. They are built in ratings up to 25 hp, 1800 rpm, and suited to a much broader range of application than the ordinary open motor. These motors have cast-steel frames, twistless and distortionless stators, silver-brazed, indestructible rotors, oil and dust-tight sleeve or anti-friction bearings.

New Contactor Line.—Ward Leonard Electric Co., Mount Vernon, N. Y., announces a line of a-c and d-c contactors that for several years have been used in their control assemblies and are now available as separate units. They can be used as control contactors for motors, for disconnect purposes in conjunction with suitable auxiliary switches, for electric ovens, various other electric control applications and for special control panels. High contact pressure with low operating and holding currents in the coil are among the features claimed for these contactors. Additional normally open or normally closed auxiliary contacts can be furnished when required.

New Weatherproof Safety Switches.—A new line of weatherproof, dust-tight type A safety switches in standard sizes from 30 amperes to 600 amperes capacity has been announced by the Electric Controller & Mfg. Co., 2708 E. 79th St., Cleveland, O. These switches use the same switch mechanism that is furnished with the standard EC&M safety switch which is of type A construction and should not be confused with the type C safety switches using lighter construction and without safety interlocks. Outstanding features of these safety switches are compactness, narrow width, light weight due to steel construction, semi-floating, double break V-blades, V-stationary contacts backed up with steel springs which guarantee full contact under heavy pressure.

Raytheon Acquires Charging Equipment Line.—The Raytheon Manufacturing Co., electrical equipment division, Waltham, Mass., announces the acquisition from the Square D Co., Detroit, of the latter's "RectiFilteR" business. RectiFilteRs are devices for changing alternating current to direct current, the conversion being effected with no moving parts. They consist of transformers, rectifying elements, choke coils, and condensers. In some cases meters, relays, switches, and other control equipment is included. RectiFilteRs are designed for operation from any a-c power circuit and by appropriate design of the transformers and rectifying elements can be made to deliver direct current at almost any combination of voltage and current. The Raytheon line includes standardized RectiFilteRs for broadcasting, theater, fire alarm, signal, telephone, and battery charging service. Among the various sizes are low voltage units rated at a few milliamperes to over 20 amperes and others delivering as much as 12,000 volts at 2 amperes.

Marine Radio Telephone Equipment.—A new type of radio telephone equipment which enables captains of fishing vessels, harbor craft and yachts to have telephone service at sea comparable with that on land is being shown for the first time at the Marine Exhibit, 80 Broad Street, New York. When within range of a coastal harbor telephone station providing this service, captains are able by means of this equipment to talk to their offices, their homes and in fact to almost any destination as easily as though they were on land. They merely pick up a telephone, located for example in the pilot house, press a button on the instrument and say "Marine Operator." Promptly a voice replies with the familiar "Number Please" and the call goes through as do millions of land calls daily. When the ship itself is called, a selective device rings its bell but not that of any other ship.

The equipment designed by Bell Telephone Laboratories for the Western Electric Co., consists of a telephone and a control unit, a cabinet which contains a 50-watt transmitter, a superheterodyne receiver, and a power unit. Crystal control keeps both transmitter and receiver on frequency at all times, eliminating tuning. One antenna serves for both sending and receiving. A bulletin on the new equipment has been published by the Western Electric Co., 195 Broadway, New York.

Trade Literature

Clip-On Ammeter. Bulletin, 4 pp. Describes the new Ferranti clip-on ammeter with a wide range of full scales and variety of frames, and with openings to take busbars up to $4^1/_2$ by $3^1/_2$ inches. Twenty-three of the more important features of the clip-on ammeter are emphasized. Ferranti Incorporated, 130 West 42nd St., New York.

Relays.—Bulletin, 12 pp., "Weston Relays." Describes a comprehensive line of sensitive toggle, polarized, power and time delay relays. Weston Electrical Instrument Corp., Newark, N. J.

Insulation Testing Equipment.—Bulletin 934, 12 pp. Describes dielectric strength test sets with potential ranges of 200 to 30,000 volts; insulation resistance meters and other instruments. Sound Engineering Corp., 416 N. Leavitt St., Chicago, Ill.

Circuit Breakers.—Catalog 5, 14 pp. Describes a new line of air circuit breakers, type HD (heavy duty). Previous desirable features, such as high speed of opening, simple construction and magnetic blowout action have been retained in the new line. In addition, the use of inverted brushes and secondary and carbon contacts is introduced in air breakers for the first time. The new breakers have exceptionally high interrupting capacities. Roller-Smith Co., 233 Broadway, New York.

Relays.—Bulletin GEA-1997, 8 pp. Describes instantaneous overcurrent relays for a-c circuits, Types PHC and PYC. Bulletin GEA-2006, 4 pp—auxiliary relays with mercury contacts for a-c and d-c circuits. Bulletin GEA-2009, 12 pp—directional ground relays for a-c circuits. Bulletin GEA-2012, 8 pp—transfer relays for current transformer tripping. Bulletin GEA-2014, 16 pp—current balance relays for a-c circuits. General Electric Co., Schenectady, N. Y.

Insulators.—Catalog No. 21. A comprehensive volume describing a complete line of porcelain insulators. Among recent developments noted in the new catalog are pintype insulators, now furnished with larger top and side grooves; a new one-piece insulator of exceptionally heavy proportions for use where breakage is frequently experienced due to shooting, etc. A new line of strain insulator fittings is also shown, as well as 3 new lines of bushings; improved suspension insulators are also listed. Ohio Brass Co., Mansfield, O.

Supplement to
1934 TRANSACTIONS

To give full continuity to the published TRANSACTIONS of the Institute, bridging the gap that otherwise would exist between the concluding number of the quarterly TRANSACTIONS (September-December 1933) and this present 1934 annual volume (the first in a re-established series of annual TRANSACTIONS) there are included on the succeeding 125 pages the following technical papers which were published during the closing months of 1933 and included on the January 1934 winter convention program:

1. **Power Limit of a Transmission System,** W. S. Peterson. Originally published in ELEC. ENGG., August 1933, p. 569–2.
2. **Power Limits of 220-Kv Transmission Lines,** Alex A. Kroneberg and Mabel Macferran. Originally published in ELEC. ENGG., November 1933, p. 758–66.
3. **Trolley Wire Lubrication Improved,** J. V. Lamson. Originally published in ELEC. ENGG., November 1933, p. 771–6.
4. **Power Limits of Synchronous Machines,** Edith Clarke and R. G. Lorraine. Originally published in ELEC. ENGG., November 1933, p. 780–7.
5. **Steady State Stability of Composite Systems,** S. B. Crary. Originally published in ELEC. ENGG., November 1933, p. 787–92.
6. **Transformers for Electric Furnaces,** H. O. Stephens and L. S. Schell, Jr. Originally published in ELEC. ENGG., December 1933, p. 822–6.
7. **Switching at Long Beach Plant No. 3,** A. A. Kroneberg, O. R. Bulkley, and W. A. Andree. Originally published in ELEC. ENGG., December 1933, p. 826–30.
8. **Fundamentals of Design of Electric Energy Delivery Systems,** J. Allen Johnson and R. T. Henry. Originally published in ELEC. ENGG., December 1933, p. 831–8.
9. **The 3-Phase Electric Arc Furnace,** Samuel Arnold, 3rd. Originally published in ELEC. ENGG., December 1933, p. 839–43.
10. **Electrodes—Carbon and Graphite,** Frank J. Vosburgh. Originally published in ELEC. ENGG., December 1933, p. 844–8.
11. **Induction Motors as Selsyn Drives,** L. M. Nowacki. Originally published in ELEC. ENGG., December 1933, p. 848–53.
12. **Corona Losses From Conductors of 1.4-Inch Diameter,** Joseph S. Carroll, Bradley Cozzens, and Theo. M. Blakeslee. Originally published in ELEC. ENGG., December 1933, p. 854–60.
13. **Cross Potential of a 4-Arm Network,** Anatoli C. Seletzky. Originally published in ELEC. ENGG., December 1933, p. 861–7.
14. **Switching at the Hudson Avenue Station,** C. M. Gilt, Originally published in ELEC. ENGG., December 1933, p. 868–75.
15. **Attenuation and Distortion of Waves,** L. V. Bewley. Originally published in ELEC. ENGG., December 1933, p. 876–84.
16. **Simultaneous Control of Voltage and Power Factor,** L. F. Blume and F. L. Woods. Originally published in ELEC. ENGG., December 1933, p. 884–9.
17. **Joint Use of Poles With 6,900-Volt Lines,** W. R. Bullard and D. H. Keyes. Originally published in ELEC. ENGG., December 1933, p. 890–8.
18. **Investigation of Rail Impedances,** Howard M. Trueblood and George Wascheck. Originally published in ELEC. ENGG., December 1933, p. 898–907.
19. **Counterpoises for Transmission Lines,** Charles L. G. Fortescue. Originally published in ELEC. ENGG., December 1933, p. 908–17.

For complete index see p. 1815.

Trolley Wire Lubrication Improved

Laboratory tests indicate that solid graphitic material for trolley wire lubrication is vastly superior to the graphite-grease now commonly used for that purpose. Tests under practical operating conditions now are being made on a 210-mile electrified portion of the Chicago, Milwaukee, St. Paul, and Pacific Railroad. This paper discusses briefly the general problem of trolley wire lubrication, and presents results of tests on both graphite-grease and solid lubricant.

By
J. V. LAMSON
ASSOCIATE A.I.E.E.

Univ. of Washington
Seattle, Wash.

OPERATION of an electrified railroad involves a certain amount of wear on the contact surfaces of the trolley wire and moving current collectors; this wear is dependent largely upon the type and amount of lubrication used on the contact surfaces. Such lubrication, early recognized as an important part of electric railroad operation, is the subject of extensive improvement resulting from an entirely new and different method of applying a solid lubricant. This paper outlines laboratory experiments devised especially for the study of contact surface lubrication, the results obtained, and some of the possibilities of the use of solid lubricant.

Summarizing the conclusions drawn as a result of these experiments, it appears that a solid graphitic material can be used to give effective trolley wire contact lubrication with its attendant reduction in the rate of wear and expense of worn part replacement. Such lubrication promotes longer wire life, which in turn avoids reduced wire cross section and mechanical breakages; it eliminates all forms of grease with its highly undesirable dirt; and current collection conditions are improved to the advantage of reduced communication interference, which ordinarily is caused to a certain extent by sparking at the collector contact.

Due to its very nature and method of application the solid type of lubricant is applied automatically on rough surfaces only, where needed, and all of that part that does wear away is deposited and distributed effectively on the contact surfaces instead of being dropped wastefully on the locomotive equipment as is graphite-grease. The rate of wear of the solid lubricant is sufficiently low to make a single application last several thousand miles; this feature makes road attention unnecessary, thereby forestalling the possibility of electrical injury or death to a man working on a pantograph that accidentally might become energized. When contact lubrication with solid materials wins favor in the field as it has in the laboratory, the possibilities of this method of lubrication will contribute toward the improvement of current collection on electrified railroads throughout the world. The results obtained in these laboratory experiments offered ample justification for an extensive service trial, which is now in progress with a form of this type of lubrication being used, to the exclusion of graphite-grease lubrication, on the 210-mile Coast division of the Chicago, Milwaukee, St. Paul, and Pacific Railroad.

Full text of a paper recommended for publication by the A.I.E.E. committee on transportation, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 3, 1933; released for publication Oct. 12, 1933. *Not published in pamphlet form.*

General

Ever since the advent of electric traction motors for the operation of trains, cars, and other vehicles that receive electric power through contact with a third rail or trolley wire, the design of current collectors and contact lines has been an important part of all systems of electric traction. Although many different forms of wheels, rollers, bows, and sliders have been in extensive use, the slider type of metal-to-metal contact at present is accepted as the most satisfactory device for current collection on fast, high-powered equipment; the scope of this paper is confined to a discussion of lubrication problems incident to the slider type of current collector.

Trolley wire lubrication is of interest to operators of all electrified railroads on which power is distributed by means of an overhead contact line, and this paper deals with the subject from their point of view. However, the results obtained in these experiments can be interpreted as applying to any exposed, sliding, or moving, metal-to-metal contacts that carry electric current.

A large majority of electric traction systems both in the United States and other countries use an overhead contact system with some form of sliding shoes mounted on bow or pantograph type current collectors which receive power for the operation of traction motors and necessary auxiliary equipment on electric locomotives and motor cars. On all these systems it is desirable for reasons of economy and operating efficiency to reduce the wear on trolley wire and contact strips to a minimum; it is with this object in view that the subject of contact lubrication has been given the consideration outlined herein.

Operating data covering trolley wire wear, contact surface condition, and locomotive movements were obtained from the Chicago, Milwaukee, St. Paul, and Pacific Railroad, which has hundreds of miles of main line road under complete electrical operation over a territory imposing practically every conceivable condition of speed, tonnage, track curvature, grade, temperature, and climate. This system made an excellent field for the study of wire wear and contact surface lubrication.

Need of Wire Lubrication

Trolley wire, being subject to wear, eventually becomes greatly reduced in cross section, with many attendant disadvantages such as decreased mechanical strength, electrical conductivity, and reliability. The inevitable delays and losses caused by the breakage of worn trolley wire have an economic bearing on the operation of any electrified railroad; and although the cost of such losses cannot be estimated accurately, it is logical to assume that they should not be overlooked. In the United States alone the regular operation of some 3,500 pantograph type current collectors, which slide in contact with trolley wire to the extent of more than 100,000,000 pantograph miles per year, involves a maintenance and replacement expense that depends directly upon the wear and tear on the trolley wire and contact equipment. Effective contact surface lubrication therefore is desirable where it prevents comparatively rapid wear of trolley wire and contact strips.

Wear tests conducted nearly 20 years ago by some of the electric railway equipment manufacturers conclusively demonstrated the value of using some form of contact surface lubricant for the reduction of wire and collector strip wear. When first adopted, the use of graphite-grease (a mixture of flake graphite and motor grease) as a contact lubricant held promise of solving many of the problems surrounding wire wear; however, experience has demonstrated it to be ineffective in many ways as a lubricant principally because of the method of application. It is also very dirty and somewhat hazardous. The graphite-grease adheres to the trolley wire, pantograph parts, and the tops of locomotives to such an extent that it interferes with workmen in their regular duties. Linemen, for example, find that greased trolley wire is extremely messy and awkward to handle when contact line repairs are made. The grease also adheres so tenaciously to the upper parts of the locomotives that cleaning and scrubbing the fouled parts is a problem of no small significance. When the grease drops on the walkways of the locomotive roofs it also greatly increases the possibility of a man slipping and falling from a dangerous height to the ground.

The graphite-grease normally is applied between 2 copper contact strips of a pantograph shoe as shown in Fig. 1; however its effectiveness is dependent upon the distance between the section of line in question and the locomotive terminal, where fresh lubricant is applied. Where the grease is rubbed on the wire, an effective lubrication results; but where the wire is remote from a locomotive terminal, the lubricant actually applied to the trolley wire is reduced in quality and quantity to a marked extent. In many cases the lubricant used with the graphite-grease filled shoe breaks down to the point where a layer of worn copper dust and grit covers the graphite-grease, stopping all lubrication.

The effect of terminal distance on wire wear is indicated in Fig. 2, which is derived from a study of over 500 wire measurements secured on the Rocky Mountain division of the Milwaukee railroad. The contact line consists of a pair of 0000 B. & S. gage copper trolley wires; d-c power is distributed over them at a potential of 3,000 volts. The section of line shown on the chart is part of a 440-mile division, which has locomotive terminals at the middle and at each end. Measurements showed that the trolley wire wear was a minimum at the terminals and a maximum midway between them.

Wear over curved track is somewhat less than that over tangent track due to the use of a chord type of overhead contact line, which has a tendency to sweep transversely across the moving pantograph shoes as a locomotive moves along the line. The graphite-grease which is usually clean and abundant near the extreme ends of the pantograph shoes thus is spread on the contact surface of the trolley wire over curved track resulting in a more effective lubrication at such points. The lubricant at the extreme ends of the shoes rarely is touched while a locomotive is on tangent track unless the trolley wire is out of alignment or the locomotive is subject to violent rolling.

Wire measurements taken on the trolley wire always should be supplemented by a lubrication mark. This mark is made by holding a page of an open notebook face upward against the contact surface of the trolley wire and moving it along the wire for a few inches. Near the locomotive terminals the abundant supply of graphite-grease on the wire transfers patches of thick black grease to the book, but at points a few miles away from the terminals a sharp black impression is left on the page of the book indicating that the contact surface of the wire is covered with a lubricating film of moderate thickness. At slightly greater distances from the terminals the clean white notebook page slides quite easily along the wire and picks up very little coloring from the smooth, glossy contact surface. Measure-

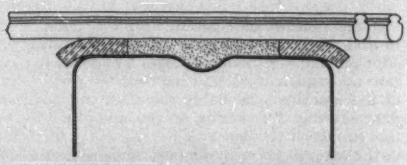


Fig. 1. Section of slider type pantograph shoe under 2 trolley wires. Space for lubricant is provided between the 2 contact strips

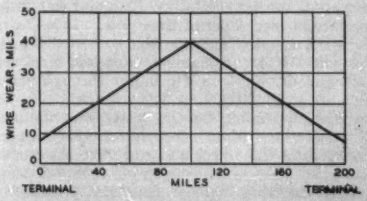


Fig. 2. Trolley wire wear on tangent track with graphite-grease applied at terminals, 50,000 locomotive passes

Fig. 3 (left). View of testing machine showing end of collector shoe and slider carriage; graphite-grease lubrication

Fig. 4 (right). General view of testing machine showing in the foreground the mechanism used to impart radial motion to slider carriage for simulating locomotive "roll"

ments taken at points midway between locomotive terminals showed the maximum wear on the wire; and when attempts were made to record lubrication marks in the notebook, the wire surface was found in some cases to be sufficiently rough to tear the surface of the page. Thus there were extreme conditions, ranging from an oversupply to a complete absence of lubricant within a distance of 100 miles.

Such observations indicated that there was much room for improvement in wire contact surface lubrication as the graphite-grease was applied wastefully without giving satisfactory results and it was therefore undesirable lubricant for the purpose.

Laboratory Test Machine Construction

Any experimental work on contact surface lubrication that could be accomplished in actual operation on a railroad, even on a large scale, might require a period of years to produce information of definite value. It appeared, therefore, that some other means, which would produce greatly accelerated results, would be required. The nature and importance of the problem warranted a sufficiently thorough study to justify the construction of a special test machine by means of which accelerated tests could be made under close observation and control. The relative effectiveness that different types of lubricant would give in laboratory experiments would provide an indication of the relative effectiveness and performance that might be expected of these lubricants under actual line conditions.

Such a test machine was designed and built at the University of Washington electrical engineering laboratory during the fall of 1931 and was in operation late in December of that year. It is illustrated in Figs. 3 and 4. The machine consisted principally of a wheel 46 in. in diameter mounted on a vertical shaft and driven by a d-c motor through a twisted belt. A ring of 0000 trolley wire or $^1/_4$-in. copper bus bar (depending on the tests) was mounted on the outer rim; when in operation this copper ring turned with the wheel and ran over the surface of a collector shoe which was spring mounted and held against the ring with a constant pressure. The standard upward pressure of $7^1/_2$ lb per shoe per wire, corresponding to 30 lb per pantograph, was adhered to throughout the experiments; likewise the standard current density of 200 amp per shoe per wire, or 800 amp per pantograph, was the same as that used on the Milwaukee 250-ton d-c locomotives operating on 3,000 volts.

For supplying the contact current, a motor-generator set was used; this was a 300-amp General Electric arc welding unit which furnished 200 amp at 6 volts continuously. A current of 200 amp was circulated from the positive generator terminal through a cable to brush holders bearing on the pulley of the wheel, into the wheel shaft and out through the metal spokes to the copper contact ring; from this ring it passed through the sliding contact to the spring mounted collector shoe and thence through a cable back to the negative generator terminal. The current path was practically a short circuit on the generator, which, however, had a very rapid voltage recovery and formed a violent arc whenever there was any separation at the sliding contact. The arc-welding type of generator selected for this purpose served to duplicate line conditions closely, as any amount of contact separation due to rough surfaces or skipping of the current collector shoe caused destructive arcing similar to that sometimes experienced in railroad operation. This characteristic would not have been available with a simple low-voltage electro-plating type of shunt generator.

The current collector shoe was mounted on a carriage that moved on a pair of slide rods with an irregular transverse motion maintained by a small motor driven gear mechanism to simulate the rolling action of a moving locomotive. The gear mechanism used to sweep the collector shoe carriage back and forth is shown in Fig. 4.

Preliminary Operation of the Apparatus

A fair amount of experimenting was done on the test wheel before the regular schedule of testing was adopted, and some minor changes were made to facilitate the regular work and improve the performance of the machine. Probably the most important refinement was the turning or machining of the contact surface of the wire ring to remove minute waves in the wire, to prevent skipping of the collector shoe at high speed, and to improve generally the smoothness of operation of the test machine. During the preliminary runs with graphite-grease as a lubricant,

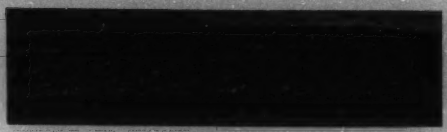


Fig. 5. Contact surface of trolley wire tested without lubrication

numerous failures of the lubricating film left the machine running without lubrication. The contact friction under these conditions was extremely high, and the current collection was subject to arcing and flashing which soon destroyed the contact surfaces. A view of the wire contact surface after a short run without lubrication is shown in Fig. 5, which clearly illustrates the rough nature of the contact surface and the burning and scoring caused by arcing and excessive friction. Conditions similar to those obtained without lubrication are brought about by failure of the graphite-grease lubricating film, an example of which is illustrated in Fig. 6. Such evidence as that exhibited in Figs. 5 and 6 bears out the contention that contact surface lubrication is highly important. Operation of any electric traction system without effective contact lubrication obviously would be destructive, unsatisfactory, and costly.

Test of Graphite-Grease

With graphite-grease used as a lubricant several test runs were made with the machine for the purpose of comparing the laboratory data with that obtained in actual railroad operation. Conditions maintained and observed during this test were as follows:

Constants

Rim speed	40 mph
Contact current	200 amp continuously
Roll frequency	24 cycles per minute
Collector shoe pressure	$7^1/_2$ lb

Periodical application of graphite-grease was made every 3 hours, which was the time required for the passage of 119 miles of wheel ring over the collector shoe. This is the practice followed in railroad operation.

Observations

Wheel turns or "passes"
Wire thickness
Readings taken every 50,000 turns (every 3 hr)

A turn is the same as a "pass" as used in railroad parlance and means that every time the wheel makes one complete revolution, any one point on the rim of the wheel makes a pass over the collector shoe. This would have the same effect as that which would be obtained if the wheel remained stationary and a locomotive collector shoe passed under it.

Wear on a trolley wire is essentially a function of the number of contact shoes or locomotives passing under it and for that reason wheel turns or revolutions are directly comparable to locomotive passes. Wear measurements on the current collector shoe were not recorded as they depend upon the miles of wire passed over the shoe; for a laboratory machine like the one used in these tests, this mileage is small and of little

Fig. 6. Contact surface of current collector shoe tested with graphite-grease between copper contact strips. Part of lubricant whipped out of shoe and surface of remaining lubricant became covered with copper dust

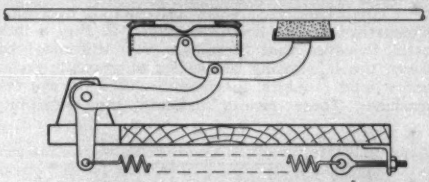


Fig. 7. Diagram of mechanical rigging used with auxiliary lubricator shoe; the lubricator shoe is at the right

consequence compared with the passes made by any one point on the rim of the wheel.

Results obtained during the graphite-grease tests were comparable to existing line conditions and indicated that the test machine could be used satisfactorily for determining comparative data on the effectiveness of solid and graphite-grease lubricants.

Test of Solid Graphitic Material

The collector shoe carriage was rebuilt to accommodate an auxiliary lubricator shoe for solid graphitic lubricant and the 2 shoes, current collector, and lubricator, were mounted on 2 levers each pivot-supported on the end near the current collector shoe (see Fig. 7). There was a set of these levers under each end of the 2 shoes. The pivot support was located in such a position that the lubricator shoe pressure against the wire ring was $^1/_2$ the current collector shoe pressure.

Before the auxiliary shoe with solid lubricant was tested, there was considerable doubt as to the ability of the solid graphitic material to withstand continuous service, for the lubricant was softer than most motor brushes and at times would be subject to severe abrasion and scoring. The first test, however, and all subsequent tests clearly showed the superiority of the solid graphitic material for exposed contact lubrication. Following these preliminary find-

ings a series of long test runs was made with the test machine, and a quantity of data was secured for the purpose of comparing the effectiveness of graphite-grease and solid graphitic material. The test conditions maintained and the observations made were the same as in the tests on graphite-grease, the lubricator shoe pressure being maintained at $3^3/_4$ lb.

Micrometer readings of the thickness of the copper wire were taken at 36 points on the wheel ring and the wear calculated from each measurement. The average wire wear then was determined and recorded graphically.

Results of the laboratory tests are summarized graphically on the chart of Fig. 8, which shows also the wire wear experienced in actual railroad operation under the most favorable conditions of graphite-grease lubrication near locomotive terminals. Curves representing laboratory findings should not be compared directly with data secured on the railroad because many variables, such as the type and flexibility of contact line suspension, weather and frost conditions, etc., enter into actual operation. Comparison of the 3 curves shown in Fig. 8 indicates, however, that there is a vast difference between the lubricating properties of graphite-grease and a solid graphitic lubricant as used on the test machine. These results indicate the possibility of improvement over the best conditions found in railroad operation. Without considering the curves of Fig. 11 as complete and final evidence, it is only logical to conclude that they indicate a distinct superiority of solid graphitic lubricant.

At the conclusion of the tests using solid lubricant the contact surfaces of the wheel ring and collector strip were of a rich bronze color and polished like a well kept commutator. The glossy surface could not be photographed satisfactorily, although the clearness of a reflected image is shown in Fig. 9.

A further test to prove the effectiveness of solid graphitic lubricant was designed to show its ability to repair a badly damaged and burned contact surface. This test was run when the wheel ring was in very poor condition following an extended run with graphite-grease, which had failed to maintain the contact surface in satisfactory condition. The auxiliary lubricator shoe was installed and the machine put back in operation with a rim speed of 45 miles per hour. The application of solid lubricant immediately reduced the mechanical friction of the contact to a low and constant value, the contact sparking was reduced, and the contact surfaces began to take on a polish.

Another test then was started in which the auxiliary lubricator shoe was tied down a small fraction of an inch with a string until it just cleared contact with the moving wire ring as shown in Fig. 10 at point *A*. Pressure on the current collector shoe was not altered appreciably. Lack of lubrication caused the contact surface to roughen at once, and the increased contact friction overloaded the test wheel drive motor until it finally stalled in a little more than 3 min as indicated at point *B*. The drive motor was a shunt machine with its armature current protected by a low external resistance as shown in the small circuit inset in the chart of Fig. 10. During this retarded condition the drive motor armature current more than doubled and its driving torque, of course, increased in like proportion tending to keep the wheel in motion. By the time the wheel had stalled, the fierce arcing and flashing caused by lack of smoothness at the contact had left the contact sur-

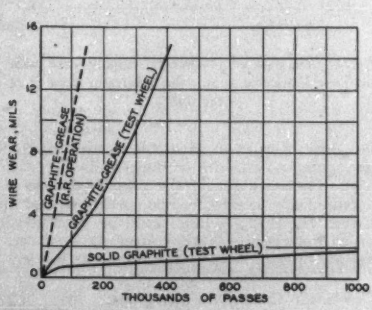


Fig. 8 (above). Comparison of contact line wear with graphite-grease and with solid graphitic lubrication

Fig. 9. Polished contact surface of wheel ring after extensive test with solid lubricant; watch is for reflection only. A similar polish was imparted to the contact shoe

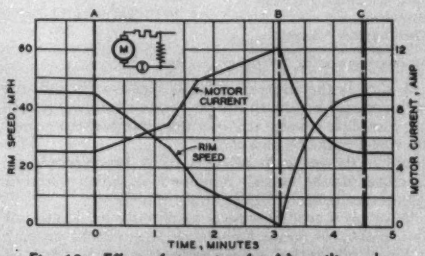


Fig. 10. Effect of removing (at A) auxiliary shoe of solid graphite lubricant while test wheel was rotating, and replacing it (at B) after the resulting increased friction had stalled the wheel

The small diagram shows the connections of the driving motor where I is an ammeter

face in an extremely rough and burned condition, apparently beyond repair.

At point *B* the string that held the auxiliary lubricator shoe clear of the wheel ring was cut, allowing the auxiliary shoe again to rub against the contact surface of the wheel ring. A small amount of the solid lubricant was rubbed into the surface of the wheel ring by the roll motion of the collector shoe carriage, and the wheel started and accelerated to normal smooth running conditions in 75 sec. The contact surfaces again began to assume a polish, and the solid lubricant on the auxiliary shoe rode smoothly against the wire without being worn after the first few turns of the wheel. This test illustrates the property of a solid lubricant to feed its graphite material automatically onto a rough surface requiring lubrication and to conserve the lubricant when running on a smooth surface. The test illustrates also the very important property of a suitable solid lubricant to repair quickly a badly damaged contact surface. Numerous repetitions of this experiment always developed results similar to those shown in Fig. 10.

Road Tests of Solid Graphitic Material

Wear on the solid lubricating material used on the auxiliary shoe was practically negligible during the laboratory tests; however, no information was available at the conclusion of these experiments to predict the probable life of such a shoe when used on a locomotive pantograph in main line road service. To complete the study of the solid lubricant several different types of auxiliary shoes were built, installed on the Milwaukee locomotives, and run over the Coast division between Tacoma and Othello, Wash., a distance of 210 miles. The auxiliary lubricator shoes were applied to pantographs of locomotives in both freight and passenger service and gave consistently good results. One auxiliary shoe wore away only $^1/_8$ in. of its solid lubricant during operation under more than 800 miles of trolley wire.

Transformers for Electric Furnaces

Important features that should be considered in designing transformers, for supplying power to electric furnaces, are pointed out in this paper. The extremely high secondary currents and low secondary voltages, together with the wide variation in voltage required by many furnaces, demand special design considerations in both the transformer and its associated equipment.

By
H. O. STEPHENS
MEMBER A.I.E.E.

L. S. SCHELL, JR.
ASSOCIATE A.I.E.E.

Both of the General Electric Co., Pittsfield, Mass.

FACTORS that differentiate the electric furnace transformer from the usual power transformer are outlined briefly in this paper. The low secondary voltages with their high currents and the large tap range require special design consideration. The important advantages of the conservator transformer would appear to justify its more general use for electric furnaces.

Reactance requirements of furnace transformers are frequently different from those of the usual power transformer, and a separate reactor with taps may be required; this may be mounted either externally or within the transformer case. Strictly straight-line volt-ampere characteristics of reactance, while desirable, are not absolutely necessary; and if iron core reactors are used, the permissible deviations from straight-line volt-ampere characteristics should be specified.

To supply the wide range of voltages required by many furnaces, a method of delta-Y switching with taps in both the transformer and reactor may be used. The advantage of providing this as an integral part of the transformer should not be overlooked. When many tap changes during a heat are desirable the advantages of the "load ratio control" transformer should be carefully considered.

Design Features

The chief feature that differentiates electric furnace transformers from the usual power transformers is the very low secondary voltages and the very high secondary currents required. Another important difference is that while the usual power transformer must deliver power at the point of use at a substantially constant voltage, many electric furnaces require that for most efficient operation definitely varying voltage be supplied during the load cycle.

Full text of a paper recommended for publication by the A.I.E.E. committee on electrochemistry and electrometallurgy, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 5, 1933; released for publication Oct. 23, 1933. *Not published in pamphlet form.*

The very high secondary currents present a serious problem in the design of large furnace transformers. The low voltage winding must be subdivided into several multiple coils, and the coils and connecting leads must be arranged so that the reactance of each is substantially the same. In the larger sized transformers in the medium primary voltage range, this result can be accomplished best by the use of an interleaved arrangement of windings.

Furnace transformers usually require a number of taps for varying the secondary voltage. Since there are only a few effective turns in the low voltage windings, and since the currents are so high, it is generally necessary to place the taps in the high voltage winding; overwinding it so as to give the required voltage range in the secondary. This means that since the primary turns are varied for each secondary voltage, the flux density in the core varies for each tap connection. The highest secondary voltage determines the size of core, and the lowest determines the total primary turns. Therefore, the range of secondary voltage has a large effect on the total weight and cost of the transformer.

The secondary voltage range also influences the reactance characteristics of a transformer. In a well designed transformer the reactance varies inversely as the square of the secondary voltage. In the usual design it is not desirable to allow a reactance in excess of 15 per cent. A large tap range then may mean that the lowest secondary voltage influences its coil arrangement. A minimum tap range means a minimum sized transformer.

Arrangement of the coils should be such that the primary taps can be located so as to affect the reactance of each of the multiple coils in the low voltage winding substantially equally. A common method of accomplishing this result is shown in Fig. 1. Each group of the high voltage winding is wound for full voltage, and all groups are connected in multiple. The taps are taken from the center of each group, and all corresponding taps are connected in multiple and brought to a single ratio adjuster for quick changing. In Fig. 2 is shown a very high current furnace transformer with the secondary coils arranged in multiple and Fig. 3 shows the high voltage side of the same transformer with the multiple connected taps from each group of the winding. This arrangement insures that the reactance of each of the multiple coils of the low voltage winding will be as near alike as it is physically possible to build them.

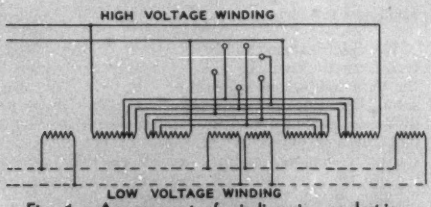


Fig. 1. Arrangement of windings in an electric furnace transformer so that taps in the high voltage winding affects the reactance of each coil in the low voltage winding approximately the same

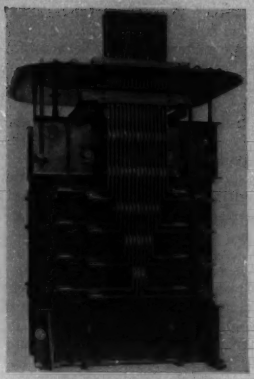
A criticism that might be directed against the type of transformer shown in Figs. 2 and 3 is that the bars leading from the bottom coils are several feet longer than those leading from the top coils and that this might cause sufficient difference in the reactance of the various circuits to cause serious unbalance in the current in the coils, thereby resulting in an increased copper loss and nonuniform heating in the coils. With suitably interleaved bars properly arranged this objection is of no practical importance as is shown by the following calculations and tests:

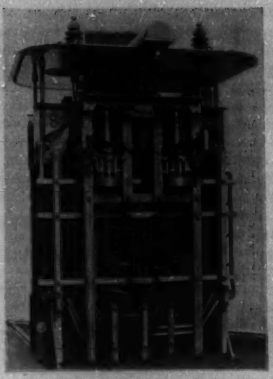
Transformer winding impedance	3.68%
Average impedance of bars	0.27%
Impedance of shortest pair of bars	0.19%
Impedance of longest pair of bars	0.33%
Total impedance of transformer, average	3.94%
Total impedance of longest circuit	4.01%
Total impedance of shortest circuit	3.87%

Maximum variation in impedance from the average is 0.07 per cent, which is less than the possible mechanical variations in the build of the coils and insulation. This would not cause an observable increase in the copper loss, and the expected difference in temperature rise above surrounding oil between the coil with maximum reactance and the coil with minimum reactance would be less than 1 deg C. Tests by means of thermocouples on the various coils showed the observed temperature differences to be no greater than the probable errors of observation. The observed rise of the top coil above the surrounding oil was 15.8 deg C and of the bottom coil 15.1 deg C.

Transformer tanks, covers, and coil clamping structure generally are made of steel. With currents of many thousands of amperes to be brought out, it can be appreciated that great care must be exercised in arranging the bars and leads from the windings and bringing them through the cover so as to avoid excessive losses and heating in the surrounding magnetic materials due to leakage flux from the bars. To do this it generally will be necessary to keep the bars subdivided in accordance with the transformer coil arrangement and interleaved so that the currents in adjacent bars are of opposite polarity.

Most large arc furnaces operate from 3-phase power; it is common practice to supply this power by means of one 3-phase transformer with the low voltage winding arranged for delta connection. Many years ago it was not uncommon for furnace engineers to request that the delta connections be made within the transformer case bringing out terminals so that the furnace operator would have only simple connections to make to his furnace flexible leads. Such an arrangement for furnaces of any considerable size would result in prohibitive losses in the tank and cover of the transformer. Consequently, it is now common practice to bring the interleaved bars through the cover from each phase of the transformer, the purchaser forming the delta external to the transformer in the most suitable place. Where there is a considerable distance between the transformer and the furnace, it is good practice to





Figs. 2 (left) and 3 (right). Assembled core and coils of an electric furnace transformer rated at 25 cycles, 5,000 kva, 13,200/130 volts; (left) low voltage side and (right) high voltage side

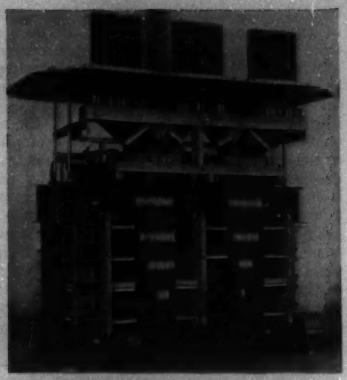


Fig. 4. Assembled core and coils of a 60-cycle 6,600-kva 44,000/170-volt furnace transformer, from the low voltage side; note arrangement of bars

carry the interleaved arrangement of bars just as they come from the transformer as near to the furnace as possible before forming the delta. In spite of the greater total current to be carried by the bars, this arrangement will result in no increase in bar copper, and generally less bar loss and almost complete freedom from losses and heating in adjacent magnetic material. Figure 4 shows a good internal arrangement of bars on a 3-phase furnace transformer.

Water cooled transformers generally are to be preferred for large furnaces, first, because of the saving in initial cost and required space, and second, because an adequate supply of cooling water generally has to be available for cooling the furnace electrode holders and the provision of water for cooling the transformers does not present an additional problem. When the water supply is of doubtful purity, self-cooled transformers should be used.

Furnace transformers often are installed in dirty locations where there is much dust, often of conducting material. It is important that the transformers be well sealed so that this dust cannot enter them. The large number of low voltage bars that must be brought through the transformer covers presents an opportunity for many small dust leaks unless properly designed. Stuffing boxes around each bar give effective protection against the entrance of foreign material.

Because of the difficulty and expense of making the many low voltage bar leads oil tight, oil conservators have not been used generally for furnace transformers. However, it would appear that furnace transformers need the protection afforded by the oil conservator more than the average transformer for the following reasons: (1) The conservator insures absolute immunity internally to dust and dirt; (2) furnace transformers in general are likely to be operated at relatively high load factors, and the conservator is particularly valuable in preserving the oil and preventing sludging; (3) the short periods of shut down between loads cause a considerable amount of breathing which presents an opportunity for bringing moisture into the tank; (4) the long periods of idleness during periodic relining of the furnace give further opportunity for moisture absorption. The oil conservator perfectly protects from all of these conditions. Suitable bus bar bushings have been designed and several furnace transformers have been built with conservators. It would appear that the advantages to be gained are important enough to justify more general use of the oil conservator on furnace transformers.

Reactance Requirements

The arc furnace has a characteristic peculiar to all electric arcs in that the resistance of the arc decreases as the current increases. The arc therefore is unstable unless sufficient constant impedance is placed in series with the supply voltage. There is usually a considerable amount of reactance in the furnace and its connections, in the furnace transformer, and in the supply circuit; and for large arc furnaces this reactance usually is adequate for stabilizing the arc. For smaller furnaces it often will be found necessary to provide additional reactance by designing the transformer with high reactance, or by adding a separate reactor in series with the transformer, or both. It is generally not desirable to build transformers with an inherent reactance greater than 10 to 15 per cent and this value, once selected is fixed; with a separate reactor, taps can be provided to vary the reactance as desired.

The total reactance in series with the circuit determines the power factor. It is desirable to keep the power factor high, but in general little is to be gained by maintaining it above 95 per cent. From

Fig. 5 it may be observed that with a total reactance of 30 per cent the power factor will be above 95 per cent, and the possible short circuit current with an arc resistance of zero (for example, when the electrodes are in contact with the metal) and ignoring all other resistance in the circuit, will be $3^1/_3$ times normal. This figure is based upon the assumption that the volt-ampere characteristic of all reactance in the circuit is a straight line, which is true with the exception of what may be obtained by means of an iron core reactor. From a practical operating standpoint it is of little moment whether the maximum possible short circuit current is $3^1/_3$ times or $3^2/_3$ times normal. Assume, for example, that the total reactance at normal current is 30 per cent and that of this, 15 per cent is supplied by the transformer, the furnace, and the circuit, while 15 per cent is supplied by an iron core reactor. Assume that the characteristics of the reactor are such that $3^2/_3$ times normal current may flow during a short circuit. Then at $3^2/_3$ times normal current there will be a total reactive drop across the transformer, furnace, etc., of 55 per cent, and across the reactor of 45 per cent. Characteristics of such a reactor are shown in Fig. 6; this particular reactor may be said to have an 18-per cent deviation from straight line volt-ampere characteristics at $3^2/_3$ times normal current. This is important because the permissible deviation from straight line volt-ampere characteristics determines the core density that the manufacturer must use in iron core reactors and affects their size and cost. Therefore, if iron core reactors are specified, the permissible deviation from straight line volt-ampere characteristics must be specified. If air core reactors of the current limiting type are specified, their characteristics always should be straight lines and no further consideration need be given to the subject of deviation.

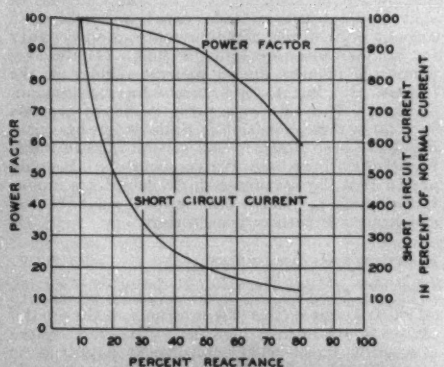


Fig. 5. Effect of series reactance on the power factor and short circuit current of a furnace circuit, straight line reactance characteristics assumed

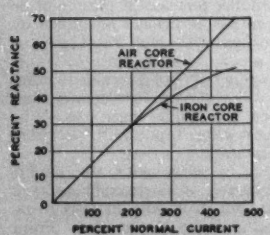


Fig. 6. Characteristic curve of an iron core reactor showing deviation from that of an air core reactor

Delta-Y Switching Arrangement

Most furnaces require a variable voltage for their operation. This is particularly true of the arc furnace for melting cold steel scrap, which usually requires a much higher voltage during the melting down period. Transformers for such furnaces commonly are provided with switches for connecting the high voltage winding in either delta or Y. At the start of a heat the high voltage winding is connected in delta, and after the melt is well under way it is connected in Y so as to give about 58 per cent voltage on the furnace for the refining period. If the Y-delta switches are mounted separately from the transformer, considerable wiring is required and only 2 voltages are available; they can be made an integral part of the transformer, and the very obvious advantages of doing this should not be overlooked in preparing specifications. These switches are available for various combinations of connections, but the majority of furnace transformers in the past have used a 4-position switch. Two delta tap voltages and two Y tap voltages usually are specified. By means of terminal board connections between the taps in the transformer windings and the switch, and also between the taps in the reactor winding and the switch, a choice of several transformer voltages and several values of reactance may be made available. If the reactor is required in the Y connection as well as in the delta connections, the switching arrangement will be complicated unless a 2-winding

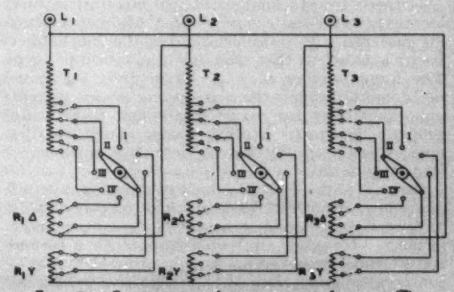


Fig. 7. Connections between transformer (T) 2-winding reactor (R) and delta-Y switch for 2 delta and 2 Y positions. Positions I and II are for delta connections; III and IV, Y connections

reactor is used, one winding for the delta connections and the other for the Y connections, each of which may be provided with taps as required. The Y tap connections need not correspond to the delta tap connections, and an exceedingly flexible choice of reactance is thereby available. In Fig. 7 is shown a diagram of such a delta-Y switch arrangement.

These switches may be operated by a motor mechanism with control button and position indicator on the operator's control panel, or they may be hand operated with a handwheel located on the panel or on the transformer. The motor operated switch, however, is preferred. In all cases the control should be interlocked with the primary oil switch as these delta-Y switches are designed for operation only with no voltage applied to the transformer.

It is permissible to shut down most furnaces for short periods during the heats to change taps. For that reason "load ratio control" transformers designed for changing taps without interrupting the load have not been used extensively. However, if any advantages can be obtained in the operation of furnaces by changing the voltage without interrupting the load, or if more than the 4 operating voltages obtained by the delta-Y switching are required, then "load ratio control" transformers should be considered to determine if their extra cost is justifiable.

Switching at Long Beach Plant No. 3

A study of the connections and methods of operation of the Long Beach steam plant No. 3, part of the system of the Southern California Edison Company Ltd. gives considerable information on desirable methods of switching at modern large generating plants. This paper, part of a symposium on switching at modern large generating plants, presents the problems for one plant.

By
A. A. KRONEBERG
ASSOCIATE A.I.E.E.
Southern Calif. Edison Co. Ltd., Los Angeles, Calif.

O. R. BULKLEY
ASSOCIATE A.I.E.E.
Southern Calif. Edison Co. Ltd., Los Angeles, Calif.

W. A. ANDREE
ENROLLED STUDENT A.I.E.E.
Stanford Univ., Calif.

SWITCHING problems encountered in the operation of the system of the Southern California Edison Company Ltd. and particularly of the Long Beach steam plant No. 3 are presented in this paper. Improvement in system stability is obtained by speeding up switching through the purchase of the fastest available switches and the changing of certain details on existing switches. The magnitude of short-circuit currents is controlled through the sectionalized operation of the system interconnections. Special attention also is given to methods of regaining stability after synchronism has been lost. Results of extensive klydonograph investigations indicate that switching surges can be reduced if the transformer banks are energized and deënergized from the low voltage side. Synchronizing by means of 220-kv circuit breakers is being accomplished at Long Beach steam plant No. 3 and other points on the system.

Protection of generators, transformers, busses, and transmission lines is described in this paper with particular emphasis on problems of line protection. Brief descriptions of methods of frequency control and of insuring continuous power supply to auxiliary equipment at the steam plant also are included. In conclusion trends are indicated toward future simplicity in the design of switching equipment and arrangement. For example, the practice of high voltage synchronizing permits the elimination of low voltage oil circuit breakers, and the development of quick starting turbine-generators to insure continuous auxiliary power supply removes the need of a shaft driven auxiliary generator. Auxiliary power ordinarily can be obtained through stepdown transformers from the terminals of the main generators or from low voltage system interconnections. The greatest change which is indicated for the future is in the high voltage interconnection with the system, whereby the development of high speed single line protection will reduce installation costs, improve reliability of service, and facilitate control of short-circuit currents.

General Description of System

The system of the Southern California Edison Company Ltd. consists essentially of a 220-kv backbone, as indicated by Fig. 1. This backbone, composed of 3 transmission lines, extends from the Big Creek hydroelectric development in Central California to the load center of the company with the Long Beach steam plant at the south end of the lines. Hydroelectric capacity totaling 398,000 kw is located

Full text of a paper recommended for publication by the A.I.E.E. committee on power generation, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 13, 1933; released for publication Nov. 3, 1933. *Not published in pamphlet form.*

at Big Creek and 200,000 kw of steam generating capacity is tied directly to the 220-kv transmission lines at Long Beach. Seven substations are located along the 220-kv backbone with transformers stepping voltage down to 66 kv, which is the sub-transmission voltage used on radial feeders from the major stations. Some 92,000 kw of stream flow hydroelectric capacity is scattered over the system and tied to the lower voltage networks.

The Long Beach steam installation is composed of 3 plants. Plant No. 1 was started in 1911, has 6 units ranging from 6,000 to 20,000 kw, and a total capacity of 70,000 kw. The generators are operated in parallel on an 11-kv bus and 3 transformer banks are used for interconnection with the 66-kv busses of plant No. 2. Plant No. 2 was started in 1925, has 2 units of 42,500 kw and one rated 60,000 kw for a total capacity of 145,000 kw. The generators in this more modern plant are operated as units with their transformers to a 66-kv bus.

Plant No. 3 was started in 1928, and is at the present time composed of 2 100,000-kw generators, wound for 16,500 volts and connected as units with their transformers. These 2 units are operating in parallel on a 220-kv bus, as indicated by Fig. 2. Some of the outstanding features of the Long Beach steam plant No. 3 of the Southern California Edison Company Ltd. are as follows:

1. All high voltage busses, switches, and transformers are located outdoors. Generators and transformers are arranged on the unit plan, and a double bus structure and duplicate switches are provided for each line and generating unit.

2. Methods and apparatus for accurate frequency control and for insuring continuous power supply to auxiliary equipment have been developed in the course of operation of the Long Beach steam station.

3. The outstanding feature is the magnitude of the ultimate installation and its interconnection with the system. With an ultimate capacity of 800,000 kw planned for the Long Beach steam plant, serious consideration had to be given to control of short-circuit currents. The rapid growth of the system of the Southern California Edison Company Ltd. in the period of years from 1923 to 1930 when the peak load increased from 295,000 kw to 583,000 kw created similar problems which had to be solved with a minimum of expenditures.

During periods of abundant water supply for the operation of hydroelectric plants the steam station becomes a peak and standby plant. During low water periods, the steam station becomes a base load plant.

Since the existing installation in Plant No. 3 is composed of 2 generating units and 2 transmission lines there are few switching problems encountered in its operation. The sections of transmission lines between the Long Beach steam station and Lighthipe, LaFresa, and Laguna Bell substations are so short that the switching problems of the whole group should be considered, especially since the bus and switching arrangement in all of them is essentially the same.

Stability

Stability of operation during short circuits on any system depends to a very large degree upon the speed of switching. This fact is well recognized by the industry and every effort is being made to build faster switches. The policy of the Southern California Edison Company Ltd. is to buy the fastest available switches for future installations and an extensive program of speeding up the switches on existing facilities is under way. Deion grids are being adapted to old Westinghouse oil circuit breakers, stronger trip coils are made to replace the original ones. In some instances the opening time of old 220-kv oil circuit breakers was reduced from 20 to 8 cycles by using 25-amp (d-c) trip coils instead of 5 amp ones, by shortening the travel of the tripping plungers, and by moving the tail stop springs to aid in tripping instead of closing.

Restoring Operating Conditions

Hand in hand with the problem of maintaining stability on the system comes the problem of restoring normal operating conditions after synchronism has been lost. When instability occurs as an aftermath to a short circuit, it is usually the hydroelectric plants that are out of step with the balance of the synchronous machines. In a case of this kind the operators at either Lighthipe or Laguna Bell substation sectionalize their 220-kv busses, separating the steam station from the system with as much load as the former can carry. After

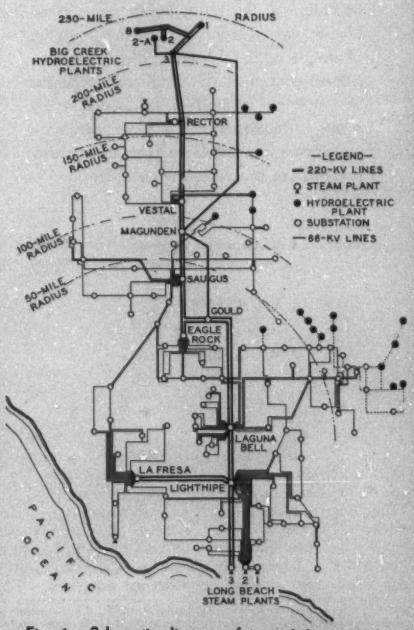


Fig. 1. Schematic diagram of transmission system of the Southern California Edison Company Ltd.

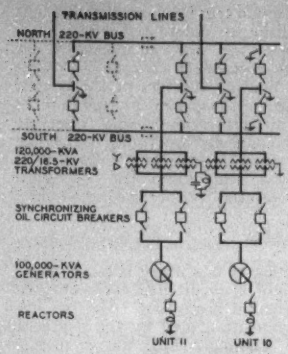


Fig. 2. Single line wiring diagram of the main circuits of Long Beach Steam Plant No. 3

normal speed and voltage have been restored on the 2 separate sections of the system, the operator at the point of separation parallels his busses with the aid of a synchronoscope. The exact point of separation is established beforehand and is determined by generating capacity on line at the Long Beach steam station and loads on transformer banks at the nearest 220-kv substations.

Control of Short-Circuit Currents

The short-circuit kilovoltampere control was necessary on the system of the Southern California Edison Company Ltd. because of the large amount of synchronous condenser capacity required for power factor correction and voltage control. The total system generating capacity of 950,000 kva and some 550,000 kva of synchronous condenser capacity gave a total of 1.5 million kva of synchronous machinery which must be considered under short-circuit conditions. Over one-half of this capacity is concentrated at the 5 major distributing points located within a radius of 20 miles. Within this area short-circuit control became a real problem. It was met by sectionalizing the 66-kv system in the area into 4 major groups, interconnected only through the 220-kv system. Sectionalizing of the 66-kv system which previously operated as a closed loop was accomplished easily since each key station was already equipped with a flexible double bus structure and a pair of oil circuit breakers per line. It was largely a matter of proper line and load selection for each group. This arrangement proved to be very satisfactory in line loading, voltage regulation, relay protection and reduction of short-circuit kilovoltamperes to within the rating of the old circuit breakers.

A study of this method of operation reveals the following:

1. Almost any degree of short-circuit control can be obtained by simply operating a number of small interconnections instead of large concentrated blocks of power.

2. Group operation of the 66-kv system has eliminated the heavy short circuits that formerly caused instability of the 220-kv system and thereby has greatly improved the quality of service.

3. Oil circuit breaker failures have been practically eliminated and the cost of overhaul and maintenance reduced to a minimum.

4. Group operation has simplified dispatching to such an extent that it is possible to dispatch all operations through the medium of switching centers in each group, thereby reducing delay in restoring service following an interruption.

5. Considerable improvement was obtained in the performance of protective relays.

Switching Surges

The installation of reactors or impedors in neutral connections to ground of star connected 220-kv transformer windings was part of the program of limiting fault currents. A General Electric impedor was connected in the neutral of the second unit at Long Beach steam plant No. 3 (unit No. 11). Reactors were similarly connected in the neutrals of 2 75,000-kva banks at LaFresa and one 75,000-kva bank at Laguna Bell. Klydonographs were connected to the 220-kv lines and across one of the reactors at LaFresa in order to investigate the magnitude of lightning surges. So little lightning disturbance has been experienced that the main interest in the results obtained has been in switching surges. It became apparent at once that transient waves of voltage occurred that considerably exceeded the rated voltage of the transformer windings, particularly at the neutral ends. A very considerable reduction in surge value resulted when transformer banks and lines were switched in such a manner as to always open a parallel on the 220-kv side and effect the energizing or deënergizing on the low voltage side. A similar investigation was made at the Long Beach steam station. The results of klydonograph investigations together with recorded rushes of ground current when transformer banks were energized from the high voltage side prompted the adoption of a policy to reduce to a minimum switching operations involving energizing of transformers from the 220-kv busses.

Synchronizing

The 2 100,000-kw units at the Long Beach steam plant are equipped with fast closing synchronizing circuit breakers between the generators and the transformer banks. Installation of these low voltage breakers was made necessary by the difficulty of obtaining potential for synchronizing on the 220-kv side. Potential transformers for 220 kv would have been too expensive and impractical, while potential devices connected to condenser type bushings at the time were new and untried. Potential networks composed of a small transformer and a network of resistance, reactance, and condenser which are connected to a 4,000-volt tap brought out of the condenser type bushing were first used to obtain voltage readings on the 220-kv lines. Over 2 years of satisfactory operation indicated that they could be used on the transformer 220-kv breakers to obtain synchronizing potential at a relatively small cost.

A series of tests was conducted at the Long Beach steam station late in 1930 to determine the feasibility of synchronizing large turbine-generators by means

of slow closing 220-kv oil circuit breakers. The results of the tests were very satisfactory and as a consequence potential devices were installed on all circuit breakers and all synchronizing was subsequently performed on the high voltage side of the transformer banks.

Experience in synchronizing by means of 220-kv oil circuit breakers obtained during the last few years indicates that in future installations of generating units composed of one generator and its transformer bank the 2 may be tied together with no low voltage breaker between them. As previously described, the operators at Laguna Bell or Lighthipe sectionalize their 220-kv busses during cases of loss of synchronism. When normal conditions are restored on the separate sections of the system they must be paralleled with minimum of time lost. The operator has no direct control over the speed of the 2 sections and must issue orders to the faster group to lower its speed to that of the slower one and then parallel his busses whenever the 2 sections are operating at approximately equal speeds and are nearly in phase. The success of this operation depends largely on the good judgment of an operator.

Protection of Generators and Transformers

Both generators and transformers at the Long Beach steam plant are equipped with standard types of differential protection. Percentage differential type relays are used with both generators and the transformers of unit No. 11 while standard overcurrent relays are used with the bank of unit No. 10. The transformer differential relays trip all high and low voltage oil circuit breakers of the unit, and the generator field circuit breaker. A differential operation of the generator relays trips the low voltage breakers, the field breaker, a breaker in neutral connection to ground, discharges tanks of carbon dioxide into the enclosed ventilating system of the generator, and trips the motor driven air blowers. An atmosphere of 25 per cent carbon dioxide can be maintained for 30 min. No overload protection is used with the units to avoid tripout on loss of synchronism. Past experience indicated that overload relays invariably operate on loss of synchronism and since separation is made at the substations it was desired to keep the units on the line during out of step conditions.

The differential protection of transformers is not sensitive enough to detect insulation failure between turns. In several instances failures of this kind caused considerable damage before a sufficient number of turns were short-circuited to cause a differential operation. Two methods of short-circuited turn protection are used at Long Beach. The low voltage windings of unit No. 10 transformers are composed of 2 coils connected in parallel. The currents of both coils of the winding are balanced in a percentage differential relay. Short-circuited turns in the transformers of unit No. 11 are detected by coils inserted between the windings and the core so that their axis is at right angle to the axis of the windings. These detector coils operate a current differential relay. Both arrangements of short-circuited turn protection trip the same switches that are tripped by transformer differential relays.

Since turbine-generators have an inherently low zero phase sequence reactance it was found advisable to install current limiting reactors in the neutral connection to ground of the generators, and in order to provide adequate protection against faults to ground on the delta connected low voltage side of the transformers, overcurrent relays were connected in the neutrals. These relays also trip the same breakers as the differential transformer protection.

Protection of Busses

Each bus or section of bus where busses are sectionalized by means of oil circuit breakers is equipped with 3-phase differential protection. The bus differential type of protection used by the Southern California Edison Company Ltd. has a perfect record of 100 per cent correct operation. It consists of parallel connection of current transformers in each phase of incoming and outgoing feeders and an overcurrent relay with a very low time and current setting. Any type of short circuit or fault is detected by such an arrangement and all oil circuit breakers connected to the bus are tripped. Unless both busses are involved, no interruption to service results. Differential protection is unquestionably the best method of protection in existence but unfortunately the very nature of its connections limits its application to equipment located at one station. The problems of line protection would not exist were simple differential protection applicable to widely separated terminals.

Protection of Transmission Lines

Double circuit transmission lines are used for 220-kv transmission as well as for the more important 66-kv feeders. It was possible then to obtain high speed of clearing faults through the use of balanced line protection. A current balance type of relay is used with each pair of lines and it is connected to detect unbalance of residual (or ground) currents in the lines. In addition to balanced protection each line is equipped with a separate residual overcurrent relay which is operative whenever one of the transmission lines is taken out of service. The inadequacy of the latter has been illustrated by several cases of system disturbance which resulted when short circuits occurred on single lines.

The use of residual currents for both the balanced and single line protection is due to the fact that in past years nearly 90 per cent of all line faults were single conductor to ground resulting from insulator flashovers. A relay system initiated by residual currents is considerably more sensitive to this kind of fault than are relays operated by phase currents. Efforts have been directed toward the development of additional protection to take care of multi-phase short circuits and some reliable form of single line protection.

Installation of instantaneous 3-phase overcurrent relays on all 220-kv and 66-kv lines at major substations of the company is under way at the present

time in order to provide protection against short circuits not involving ground return currents. The application of this type of relay is limited as it has a definite current setting and no time characteristic. The little experience gained so far shows that these relays provide adequate protection against severe 3-phase and phase to phase short circuits. The undesirable sequence relaying is still present however and will not be completely eliminated until an adequate high speed single line protective scheme is perfected. The ideal high speed single line protection would be one nearest approximating the simple differential protection of busses and equipment, that is, one that balances the output of the line against the input. Numerous pilot wire and carrier current protective devices have been recently proposed and a number of them are on trial at various stations of the company. It is too early to draw conclusions from these trial installations. Suffice it to say that when a reliable and relatively simple single line relaying system is perfected it will eliminate the problem of protection as a factor in the design of high voltage transmission.

Frequency Control

Strict requirements of a constant frequency for the sound motion picture industry and the appearance of electric clocks on the market prompted the development of equipment for accurate speed regulation on the system of the Southern California Edison Company Ltd. The problem was complicated by nature of the company's load, sudden swings of some 10,000 kw being a rule rather than an exception. Equipment has been developed that controls the speed of the system within a fraction of a cycle and compensates automatically for any deviation which may creep in so as to maintain an average frequency of exactly 50 cycles over longer periods of time. The general method of frequency control is to operate all but one of the power plants at constant load (blocked) and have one plant or generating unit operating under automatic frequency control. When a sufficient change in load on the regulating station takes place manual readjustment of loads on other stations is performed to operate as near to best efficiency as permissible under these conditions.

Auxiliary Power

An important item in the operation of steam stations is a reliable supply of power for auxiliary equipment. This power is normally supplied from a small generator coupled to the shaft of the main generating unit. Operation of plant No. 2 during sustained heavy overloads showed that when the speed of the main turbine-generators dropped so did the frequency and voltage of the auxiliary system with consequent disturbance of functions of pumps and other auxiliary apparatus. In order to insure adequate auxiliary power supply during emergencies 3 quick-starting turbine-generators were installed in plant No. 2 and plant No. 3. These turbine-generators can be started from standstill and thrown on the line in 13 sec. The switching over of the auxiliary load from the normal source of supply to the emergency turbine-generator is done automatically from one control button. During the switching operation the auxiliary power busses are deenergized for less than 0.5 sec. The motor driven exciters of the main generators are also equipped with steam turbines which have a governor setting slightly below normal speed, thus insuring continuous excitation for the main generators.

Conclusion

In concluding it will be well to indicate some of the trends in the design of the steam station and its interconnection with the system. As a direct result of the practice of high voltage synchronizing the elimination of low voltage oil circuit breakers was made possible. The development of quick starting turbine-generators to insure continuous auxiliary power supply removes the need of a shaft driven auxiliary generator. Auxiliary power can be readily obtained through stepdown transformers from the terminals of the main generators or from low voltage system interconnections. The greatest change by far would be in the high voltage interconnections with the system. In the original plans the ultimate 800,000-kw steam plant was to be connected to the Lighthipe substation through 4 220-kv transmission lines and pairs of lines from Lighthipe were to feed LaFresa and a future substation to the east of Lighthipe. The development of high speed single line protection will make it possible to loop the 2 future lines through LaFresa and the future substation, thereby saving the cost of installation of 4 line positions on the Lighthipe 220-kv busses, providing for reliability of service and facilitating control of short-circuit currents. The busses at the Long Beach steam plant No. 3 will be sectionalized with 2 generating units and a transmission line to each section. Such an arrangement will permit operation of the 220-kv system in a manner similar to the one used on the 66-kv system of the company. It will be possible to operate Long Beach as 4 separate steam plants of 200,000-kw capacity interconnected through several transformer banks in series. Thus the transmission lines and transformers will be operating in parallel to the load and in series to a short circuit.

References

1. 100,000-Kva Edison Steam Unit. *Elec. West*, v. 61, 1928, p. 272–7.
2. Long Beach Steam Plant No. 3 of the Southern California Edison Company Ltd., R. Wilcox and G. A. Fleming. Stone & Webster Jl., v. 41, 1931, p. 887–92.
3. Automatic Frequency Control, T. F. Robertson. *Elec. World*, v. 94, 1929, p. 267–70.
4. On Line in Thirteen Seconds, F. G. Philo. *Elec. World*, v. 96, 1930, p. 110–3.
5. Control of Short Circuit Kva, H. W. Tice. Presented at the Los Angeles, Calif., meeting of the engineering section, Pac. Coast Elec. Assn., 1932.
6. Master System Planning, N. B. Hinson and H. W. Tice. *Elec. World*, v. 97, 1931, p. 944–6.
7. Decentralized Dispatching Improves System Operation, H. W. Tice. *Elec. West*, v. 63, 1929, p. 384–8.
8. Synchronizing With 220-Kv Breakers, O. R. Bulkley and A. A. Kroneberg. *Elec. West*, v. 71, 1933, p. 24–5.
9. Development of a Relay Protective System on the Lines of the Southern California Edison Company Ltd., E. R. Stauffacher. Trans. A.I.E.E., v. 50, 1931, p. 80–8.

Fundamentals of Design of Electric Energy Delivery Systems

Fundamental economic factors involved in the design of systems for delivering electric energy to typical urban load areas are discussed and analyzed in this paper. The fundamental principles presented already have been applied in a practical way in the design of a radial system recently built in Buffalo, N. Y. Engineering studies upon which the selection of that system was based led to the conclusion that for areas of load densities too low to justify a low voltage network, a properly designed radial system is likely to be the most economical and satisfactory system.

By
J. ALLEN JOHNSON
FELLOW A.I.E.E.

R. T. HENRY
FELLOW A.I.E.E.

Both of the Buffalo, Niagara & Eastern Pwr. Co., Buffalo, N. Y.

DELIVERY of electric energy to consumers from a generating or receiving station within a load area embraces 3 steps, namely, subtransmission, substations, and distribution. In considering the cost of such delivery, all of these steps must be included; and in applying the fundamental principles involved in the design of a delivery system, a proper economic balance should be established among these 3 elements for best over-all results.

Development of automatic equipment, eliminating the need of operators in substations, has opened the way for the attainment of an ideal balance of cost of these 3 elements, thus making possible a rational design for minimum over-all delivery system cost. At one extreme may be found relatively short subtransmission lines, large substations, and long distribution feeders. At the other extreme the subtransmission lines may be carried clear to the distribution transformers, eliminating the substations and distribution feeders entirely as is done in the low voltage network system. Between these 2 extremes an infinite number of combinations is possible. As the subtransmission lines are extended further toward the consumer the substations become smaller and closer together and the distribution feeders shorter. For every value of load density there is probably one theoretically most economical combination. Practically, the requirements usually may be handled economically by 2 such combinations: a low voltage network for high density commercial sections, and a system of small substations with relatively short 2.3/4-kv distribution feeders for the remainder of the area.

For the 2.3/4-kv distribution system 2 alternative connection schemes are available: the network scheme, and the radial scheme. From an analysis of comparative costs, advantages, and disadvantages of each, the conclusion is reached that for large areas, at least, the radial scheme besides being less costly is more flexible and economically adaptable to growth and changes in load conditions.

Proper application of these fundamental principles results in the simplification of substation design, with consequent reduction of cost. In this connection, the "firm rating factor" also is important in determination of system design; the use of small units increases this factor and thereby tends to reduce cost.

Practical application of the fundamental principles discussed is illustrated by the radial system recently designed and built in Buffalo, N. Y., this type of system having been selected after comparisons with alternative intermediate voltage network systems had been studied for the same load area. The general conclusion reached as a result of those studies is that for areas of load densities too low to justify a low voltage network, a radial system properly designed in accordance with the principles outlined is likely to be the most economical and satisfactory system.

Distribution Terms Need to Be Defined

In these critical times it seems particularly necessary, if misunderstanding and misinterpretation by critics of electric power companies are to be avoided, to define meticulously the terms used in any statements made by the engineers of those companies. The term "distribution" especially is one that has been used somewhat loosely. Specifically, this term is applied to that part of the electrical system lying between the outgoing terminals of the distribution substations and the ingoing terminals of the consumers' premises. In its broadest aspect, however, distribution embraces the entire plant and process involved in the transportation of electric energy from the point of its production to the points of its use. In the modern large power system

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23-26, 1933. Manuscript submitted Oct. 20, 1933; released for publication Nov. 13, 1933. Reprinted for the Buffalo Niagara and Eastern Power Corp.

this process ordinarily takes place in 3 distinct steps, namely:

1. From generating stations to large receiving stations located in the area to be served. This step variously is called "high voltage transmission," "main transmission" or just "transmission." The receiving station sometimes is called a "terminal station"; sometimes a "type *A* (to *Z*) substation," a "main substation," a "transmission station," a "transmission substation," or by some other name particularly appealing to the individual concerned.

2. From the receiving station to the distribution substations. This step, originally called "transmission" before the advent of high voltage transmission, now usually is called "subtransmission."

3. From the distribution substations to the consumers. This step is that specifically known as "distribution."

In view of the lack of standardization of terms to designate the several parts of the process and system as indicated, perhaps power system engineers have only themselves to blame if some of their critics persist, as they seem to do, in misunderstanding the fact that the distribution substation and the transmission substation are 2 distinct and separate entities and not one and the same. When (and if) such critics finally do recognize this fundamental fact perhaps then they will desist from their present practice of implying that the entire cost of "electricity" is the "gateway" cost plus the "distribution" cost, and in their speeches and publications will take some account of the influence of "subtransmission lines" and "receiving stations" on the cost of electric service.

During the last few years leading power system engineers, recognizing the existing confusion of thought and nomenclature, and reflecting the current shift in emphasis and point of view from generation to distribution, have been thinking not in terms of generation, transmission, and distribution, but in terms of "load area" systems and the "bulk power" system; that is, in terms of delivery within, and supply to, given load areas. The individual load areas are geographical subdivisions which for natural, economic, political, or other reasons are served conveniently from a given point of supply. The bulk power system is the combination of receiving stations, transmission lines, and generating stations used to supply bulk power to the load areas. That is to say, the bulk power system is the modern interconnected substitute for the uneconomical and outmoded isolated generating station.

Within any individual load area the process of the delivery of electric energy embraces the process of subtransmission as well as that of distribution. In most cases both of these are necessary. How much of the process of delivery should be assigned to each is a matter of economic determination, and hence may vary greatly with the state of development of the art. The purpose of this paper is to point out some of the fundamental economic factors involved in the design of load-area delivery systems as affected by recent advances in the art.

The following nomenclature will be used:

1. A "load area" is a geographical area, usually determined for natural or economic reasons, that is supplied with electric power as a unit and in general mainly from a single receiving point or station.

2. The "bulk power system" is the combination of receiving stations, transmission lines, and generating stations used to supply energy in bulk or wholesale quantities to load areas.

3. "Generation" means energy production plant and process to and including the generator voltage bus or equivalent point.

4. "Transmission" will include step-up transformation at generating stations and transmission lines thence to load area receiving stations.

5. A "receiving station" will indicate a station receiving energy for delivery throughout a load area. Since it replaces a generating station it is a part of the bulk power system.

6. "Delivery" will mean the entire plant and process involved in the transportation of energy from a receiving station to consumers within a load area.

7. "Subtransmission" will mean the plant and process involved in the transportation of energy from a receiving station to distribution substations within a load area. It is thus a subdivision of delivery.

8. A "substation" will mean a station receiving energy from a subtransmission system and delivering it to a distribution system. The substations are a part of the delivery system.

9. "Distribution" will mean the plant and process involved in the transportation of energy from the distribution substations to the consumers within a load area. It is also a subdivision of delivery.

10. "Installed capacity" of a station or group of stations is the sum of the rated capacities of all units installed therein of the kind of equipment that performs the major function of the station or group.

11. "Spare capacity" is the rated capacity of equipment installed in anticipation of breakdown or other service interruption of units of equipment.

12. "Firm rating" is the maximum load that the station is designed to carry with the spare capacity out of commission.

13. "Firm-rating factor" is the ratio of firm rating to installed capacity.

Methods used to provide electric service in any particular load area depend on the size of the area, the character and density of the load, and the available sources of power. An area to be served from a nearby generating station might be treated quite differently from an area to be served from high voltage transmission lines with one or more receiving stations delivering power to the subtransmission system within the area. The presence of a nearby generating station may be a large factor in determining the voltage and arrangement of the subtransmission system, and may affect the choice of voltage and the number of receiving stations or main distributing centers; whereas, in a territory served from high voltage transmission lines, there may be greater freedom in the choice of the subtransmission voltage and the number and location of receiving stations.

The problem considered in this paper is that of a typical large urban load area served from a nearby generating station. It is the intent to show the effect of various factors in the determination of a proper balance between transmission, subtransmission, substations, distribution feeders, etc., that will result in minimum over-all cost consistent with satisfactory reliability, efficiency, flexibility, voltage regulation, etc.

The principal elements of the problem are the determination of the voltage and arrangement of the subtransmission system, the size, type, and system of connection of substations and the capacity, length, voltage, and arrangement of distribution feeders. The secondary mains and service laterals will not be considered in this paper. With this exception, the entire problem of "delivery" within the load area will be considered as a whole, assign-

ing to each element such place, magnitude, and function as to give the best over-all results in the light of fundamental principles, and fully recognizing the opportunities offered by recent advances in the art.

Fundamental Principles

Some of the fundamental principles affecting the design of any load area delivery system are as follows:

1. The choice of the voltage for transmitting electric power depends not only on the distance, but also on the amount of power to be transmitted.

2. A proper economic balance should be established between subtransmission lines, substations, distribution feeders, etc., for the best over-all results.

3. The "firm-rating factor," or the ratio of "firm rating" to total installed capacity, is one of the most important factors in the over-all cost of any load area delivery system.

In applying these fundamental principles advantage should be taken of recent advances in the art which have a decided effect on the problem of load area delivery system design. The most important of these recent developments are (1) automatic substation equipment, and (2) unit type of construction.

Choice of Voltage

Choice of the voltage for transmitting electric power depends not only on the distance, but also on the amount of power to be transmitted. The effect of the amount of power often is overlooked though, as a matter of fact, it really affects the choice of voltage to an even greater extent than the distance. For instance, the proper voltage for transmitting a large block of power a distance of 100 miles probably would be at least 100 kv though the proper voltage for smaller amounts of power probably would be considerably less. An extreme case of this is found in modern telephone systems where very small amounts of power are transmitted 100 miles or more at voltages of the order of 100 volts.

The problem of determining the proper voltage for transmission often is encountered when a generating station is located on the outskirts of a city, and a choice must be made between high voltage transmission lines around the city to one or more main distributing centers on the opposite side for supplying some of the substations as compared with underground transmission direct from the generating station to all of the distribution substations at the voltage of the generating station bus. In many cases the over-all cost of the system would be higher with high voltage lines around the city than with underground transmission direct from the generating station, unless the amount of power to be transmitted to the opposite side of the city is quite large. In any case the reliability of service would be greater with a comparatively large number of underground circuits than with a smaller number of overhead lines.

This particular problem was encountered in Buffalo, N. Y., in connection with the building of the new 60-cycle delivery system. Experience in the development of the older 25-cycle system had led to the adoption of 22 kv for underground subtransmission in Buffalo as long ago as about 1920. The principal source of power for the 25-cycle system was the 66-kv transmission lines from Niagara Falls. These lines served 2 main receiving stations on opposite sides of the city. The C. R. Huntley Steam Plant operated principally as a stand-by station and was connected into the system at one of the 2 main receiving stations.

In the 60-cycle system, however, it was evident that the principal source of power would be the new C. R. Huntley Steam Plant No. 2 which was to be located about 8 miles from the center of gravity of the load. It is about 4 miles from the generating station to the nearest substation and about 16 miles to the farthest substation. The shortest available route for a high voltage transmission line to a receiving station on the opposite side of the city is about 20 miles. The total load involved is a little more than 100,000 kw. Studies indicated that the over-all cost of the system would be less with 22-kv underground transmission direct from the generating station to all of the distribution substations than with part of the substations supplied from the generating station and the rest supplied from a receiving station on the opposite side of the city with the necessary high voltage transmission lines, step-up and step-down transformers, and switching equipment.

Any of 3 conditions may change this situation in the future so that a high voltage system probably would be justified if: (1) the amount of power that could be distributed from the opposite side of the city increased to an amount of the order of 100,000 kw or more; if (2) a major source of power should be made available from elsewhere at high voltage in the future, because then it would be necessary to provide step-down transformers somewhere and their location would not greatly affect the cost; or if (3) continued growth should result in congestion of ducts and cables or excessive concentration of capacity at and near the generating station. This problem would be quite different if the subtransmission voltage were lower, and it might be affected by other local conditions. Each case therefore should be considered on its merits before arriving at a decision.

Balance Between Subtransmission and Distribution

A proper economic balance should be established among subtransmission lines, substations, distribution feeders, etc., for the best over-all results in any load area delivery system. Obviously, the subtransmission circuits should reach as near to the load as practicable in order to take full advantage of the subtransmission voltage before stepping it down. However, it would be a fallacy to extend these circuits to such a point that their additional cost would exceed the saving in distribution circuits.

The determination of this balance between subtransmission and distribution circuits is influenced greatly by the size and spacing of substations as well as by the difference in voltage. It is one of the most important of the problems involved in delivery system design. The best over-all results in any delivery system will be obtained with a proper balance between subtransmission lines, substations, distribution feeders, etc.

Firm-Rating Factor

The firm-rating factor, or the ratio of firm rating to total installed capacity, is another highly important factor in the over-all cost of any distribution system. While the cost per unit of capacity of most electrical equipment varies inversely with the size of the unit, the use of small units nevertheless may result in a lower over-all cost on account of the higher firm-rating factor which may be obtained by the use of small units. As an illustration, a substation designed for 6,000 kva with one spare transformer unit may be designed with different numbers and sizes of units resulting in different firm-rating factors as shown in Table I.

Table I—Firm-Rating Factor as Affected by the Number and Size of Individual Units

No. of Units	Size of Units, Kva	Total Installed Capacity, Kva	Firm Rating, Kva (Without Overload)	Firm-Rating Factor, Without Overload	Firm-Rating Factor With 25% Overload
2	6,000	12,000	6,000	0.50	0.625
3	3,000	9,000	6,000	0.66	0.833
4	2,000	8,000	6,000	0.75	0.937
5	1,500	7,500	6,000	0.80	1.000

The over-all cost of such a substation with small units and a high firm-rating factor may be less than the cost with large units and a lower firm-rating factor. The firm-rating factor is equally important in the transmission system or in any part of the system where provision must be made for taking equipment out of service without interruption.

Design of Substations

The distribution substation is undoubtedly the most important element in the distribution system in any load area. Advances in the art have introduced opportunities for revolutionary changes in the design of substations which completely change the entire problem of delivery system design.

In the early days it was necessary to provide continuous manual supervision of all important substations, and the cost of this supervision made it necessary to limit the number of substations. This resulted in rather large substations serving large areas, and required long distribution feeders with considerable inequalities in the lengths of individual feeders. This made it necessary to provide individual voltage regulators on each feeder. The short-circuit current available in these large substations often reached values above the safe limits of the feeder regulators and made it necessary in many cases to provide feeder reactors to protect the regulators.

Probably the most important single development in load area engineering in the present generation was the introduction of automatic substation equipment. It entirely eliminated the need of continuous manual supervision, thus introducing the possibility of splitting up the substations almost without limit. This offered the opportunity of using a much larger number of substations, located much nearer their respective loads, and permitted extending the subtransmission circuits and shortening the distribution feeders. This made possible an entirely different balance between subtransmission and distribution circuits as compared with the balance when manual supervision was required. Naturally there was a considerable time lag before full advantage could be taken of these possibilities, and even now the influence of the old practice still may be recognized. Automatic equipment often has been used in large substations without taking advantage of the opportunity to split up the substations and obtain a more advantageous balance between subtransmission and distribution circuits.

One might naturally assume that the cost per unit of capacity of small substations would be higher than that of large substations, but this is not necessarily the case as the conditions controlling the design of substations change completely with their size and spacing. The use of smaller substations results in closer spacing and in shorter distribution feeders, and consequently less difference in the length of individual feeders. This eliminates the need of individual feeder regulators and permits the use of bus regulators using larger regulator units at a lower cost per unit of capacity. The total regulator capacity required for bus regulators is usually less than for individual feeder regulators on account of diversity between feeders, and this results in further savings. The short-circuit current can be kept low in small substations, and this permits further savings by omitting feeder reactors or by using smaller circuit breakers or both. There is much greater freedom in the choice of locations for small substations as they can be placed on small lots in almost any neighborhood; this may result in a lower total cost for land even though more parcels are required than for a system with large substations. These factors may combine to make the cost per unit of capacity for small substations no greater and in some cases considerably less than that for large substations.

Switching Equipment Vs. More Transformers or Circuits

While a certain amount of switching equipment always is necessary, and while additional switching equipment sometimes will increase the usefulness of transmission circuits, transformers, or other equipment, in many cases the cost of additional switching equipment would be higher than the cost of additional circuits or other equipment that would

accomplish even more than the additional switching equipment. For instance, the cost of a single 22-kv oil circuit breaker of reasonable interrupting capacity with the necessary structure and accessories may equal or exceed the cost of 10,000 kva of substation transformer capacity, or 2 miles of underground cable. The space occupied by switching equipment also may be an important factor in determining how much of this equipment should be used.

In the early days it was common practice to provide high voltage switching equipment for each incoming line and for each transformer bank. The first important change in this practice consisted of connecting each subtransmission circuit directly to one substation transformer of about the same capacity and omitting the high voltage bus and switching equipment. The next important change in this practice consisted of connecting each subtransmission circuit to several transformers in different locations. This practice has become quite common in low voltage a-c networks, but the same scheme can be used to good advantage in serving distribution substations and, so applied, permits taking advantage of the economy of large transmission circuits, small distribution substations, and small units in each substation, all at the same time. (See Fig. 1.)

Another important factor in the design of substations is the use of smaller units than commonly have been used in the past. The principal advantage of the use of small units is the opportunity to obtain a high firm-rating factor by using more units in each substation. Small units also present an opportunity to take maximum advantage of standardization and unit type of construction, and permit the installation of additional capacity in small increments when and where it is required.

Another very important factor affecting the cost of substations is the physical arrangement of the equipment in the substation. Appreciable savings can be made by so arranging the equipment that a minimum of aisle space is required. Switching structures can be designed to require an operating aisle on only one side, and this alone permits appreciable savings particularly if the other equipment in the substation is so placed as to take advantage of the same aisle. (See Fig. 3.)

There are 2 other important advances in the art which affect the problem of distribution substation design. The more general use of self-cooled transformers, resulting from improvements in transformer design and construction, offers greater freedom in the determination of the size and spacing of substations by the elimination of water cooling. The introduction of metal enclosed bus and switching structures greatly facilitates standardization and unit type of construction.

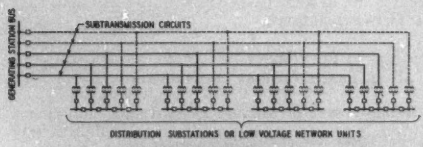


Fig. 1. Diagram of typical group of subtransmission circuits in Buffalo

Each subtransmission circuit serves several units in different locations permitting the use of large circuits even with small substations and small substation units

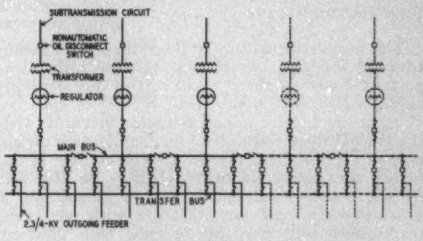


Fig. 2. Diagram of typical distribution substation in Buffalo

Units paralleled on the low voltage side only with no high voltage bus or automatic high voltage switching

The use of small automatic substations with small units and with a minimum amount of switching equipment probably offers greater opportunities for savings than any other element in the design of load area delivery systems.

Small Unit Type Substations at Niagara Falls

One of the first applications of small, unit type of substation construction to a general distribution system was made at Niagara Falls starting in 1925. This was not a complete revamping of the system, but involved only rather minor additions to the existing system to take care of the growth of the load. In this case the subtransmission voltage is 12 kv and each subtransmission circuit serves 2 2,000-kva units in 2 different substations. The initial installation consisted of 4 units, 2 of which were installed as single unit substations with reserve connections from the old 2.3-kv distribution system. Additional units have been installed as required by the growth of the load until at present there are 13 units installed at 5 different substations. Some of these substations still depend on the old 2.3-kv distribution system for reserve connections, but others are entirely independent of the old system. The old system is still in service and will continue in service to the limit of its capacity without any undesirable effect on the newer parts of the system.

New System in Buffalo

An outstanding example of what can be accomplished by the use of small substations with small standardized units is the new 60-cycle load area delivery system in Buffalo, a description of which

has been published. (See "100,000-Kw Distribution System as a Single Project," *Electrical World*, July 25, 1931.) In this system the subtransmission voltage is 22 kv and each subtransmission circuit serves 4 2,500-kva units in 4 different substations. The subtransmission circuits are all underground because of city ordinances. There is a total of 26

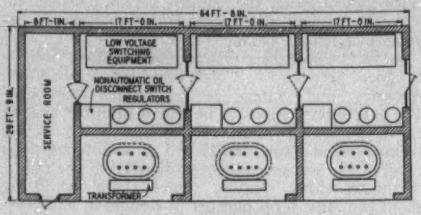


Fig. 3. Floor plan of typical distribution substation in Buffalo

Placing the equipment along a single aisle permits compact arrangement without sacrificing accessibility or safety

substantially identical substations each serving a territory of about one square mile (except in the outlying sections). The initial installation at each substation consists of 3 2,500-kva units served from 3 different subtransmission circuits, and paralleled on the low voltage side only. There is no high voltage bus or switching equipment except a nonautomatic oil disconnecting switch for each transformer. Provision is made for at least 5 units at each substation location. The transformers are located in compartments accessible from the outside of the building and may be enclosed readily in locations where noise is a factor. (See illustrations.)

The low voltage switching equipment consists of a main bus and a transfer bus with one oil circuit breaker for each transformer circuit and each feeder, and with bus section breakers in the main bus between units. Bus regulation is provided by a bank of induction regulators in the low voltage circuit of each transformer bank. A simple wattless compensator scheme insures stability between regulators and permits compensation for line drop even though the regulators are paralleled on the load side.

All switching is done in the 4-kv circuits. The transformer circuits are equipped with overcurrent and reverse power relays, thus providing full automatic protection to isolate faults in subtransmission circuits, substation transformers, or regulators, without any interruption to service. With this scheme, low voltage a-c network units may be and are supplied from the same transmission circuits as substation units. This permits spreading the supply to the low voltage a-c network over a large number of different subtransmission circuits and taking advantage of the diversity between substation and network loads in the subtransmission circuits.

Careful attention was given to the physical arrangement with the result that, while all of the equipment is readily accessible, these substations occupy an area of only about 0.25 sq ft per kva of installed capacity including the transformer compartments. This was accomplished by designing the low voltage switching structure in such a way that it requires an operating aisle on only one side, and by providing a single central aisle running the full length of the substation with the low voltage switching structures along one side and the regulators and high voltage oil disconnects along the other. By this arrangement a minimum of space is occupied without sacrificing accessibility or safety, for there are at least 2 ways out from any place in the substation where men have occasion to work (see Fig. 3).

Distribution feeders are comparatively small, and the only additional equipment required for additional feeders is the feeder breakers which are small because of the low short-circuit capacity of the small substations. The distribution feeders are so short that there is no need of carrying the main feeder to the load center and providing radial branches from there. Instead, the load is picked up along the main feeder without any duplication between the feeder main and branches. With the small short distribution feeders, each feeder has a limited exposure and the number of customers affected by an outage is comparatively small.

While this is probably the largest load area delivery system ever built at one time as a single project, the striking economies realized in this system were not the result of the unusual conditions incident to the construction of an entire system at one time, but were due almost entirely to the careful application of the fundamental principles expressed in this paper. The substations are small, simple, unit type substations providing a high degree of reliability of service with a minimum of switching equipment. The firm-rating factor is high for both substations and subtransmission circuits, and there is a proper balance between subtransmission and distribution circuits.

Comparison of Primary Network and Radial System Used in Buffalo

Before the new system in Buffalo was built, careful consideration was given to the choice of the type of system to be used. For the principal business district, the low voltage a-c network was adopted. For the rest of the territory, several different schemes were considered. Early studies clearly indicated the advantage of small automatic substations with short distribution feeders, and the choice soon narrowed down to 2 schemes: (1) the primary network, and (2) the radial system finally adopted which really was the outgrowth of the earlier application of these ideas at Niagara Falls. Further study of these 2 schemes indicated definitely that a radial system with small, unit type, automatic substations would be at least the equal of the primary network in reliability, efficiency, and operating characeristics, and would be more flexible and would cost considerably less than a primary network with equivalent firm rating.

Two particular difficulties in the primary network scheme were brought out in the studies. One is that the irregularities in the system caused by parks, waterways, railroads, etc., affect the firm-rating factor to a much greater extent in a primary network than in a system with separate substations. The other difficulty is that, even in a uniform network, the load will not divide uniformly among the transformers in service under all conditions of operation on account of the impedance in the network. The effect of this is 2-fold: It requires more transformer capacity than might be expected in a network, to avoid excessive load on any unit when some units are out of service; and it dictates the location where transformers must be installed, as load cannot be forced at will from one location to another in a network. This difficulty is encountered both in the initial installation and in providing for growth of the load, which means that units must be placed, or added, at or near the loads they are intended to carry.

In the Buffalo radial system the load on each substation always will divide uniformly among the transformers in service; the division of load between substations can be controlled definitely, and load may be shifted and forced from one substation to another from time to time at will, by simply cutting and rearranging the distribution feeders. Ordinarily this would consist of transferring sections of distribution feeders from one feeder to another in the areas where the feeders from one substation meet those from another substation. In such a system, where the substations are comparatively close together, the flexibility in this respect is almost unbelievable.

Recognition of these factors in the studies indicated that the total transformer capacity required for a primary network would be as great, or even greater than that required for the Buffalo radial system. The studies indicated that the total mileage of subtransmission circuits required for a primary network would be considerably greater than for the Buffalo radial system because of the scattered locations of substations and the need of interleaving in the network. Some additional subtransmission mileage might be justified if a saving could be made in distribution circuits, but these studies indicated practically no difference in the total mileage of distribution circuits in the 2 systems. This apparently is due to the fact that, while there would be about the same total number of feeders, each feeder in the Buffalo radial system runs from its substation to its load and stops; whereas, in the primary network each feeder must continue beyond its load to the adjacent substation, and these continuations often involve crossing areas where there is no other need for distribution circuits.

These studies indicate also that the total cost of substations would be considerably higher in the primary network because the primary network unit substations are so small that the cost per unit of capacity would be considerably higher than for the substations used in Buffalo. In addition to this, nearly twice as much switching equipment would be required in a primary network as in the Buffalo radial system because in a network there must be a circuit breaker at each end of each feeder, whereas, only one circuit breaker is required for each feeder in the Buffalo system with about the same total number of feeders.

The fact that the cost of subtransmission circuits and substations would be considerably higher for a primary network than for the Buffalo radial system, without a corresponding saving in distribution circuits, indicates that the primary network scheme involves extending the subtransmission circuits beyond the economic balance point.

As to the operating characteristics, there is little to choose between the 2 systems so far as reliability, efficiency, and voltage regulation are concerned. The only interruptions to be feared in either system are those caused by faults on the distribution circuits themselves, and such faults will cause interruptions to all of the service connected directly to the faulty circuit in either system. Since there would be about the same total number of feeders in both systems, there would be about the same amount of load on each feeder, and the number of customers affected by an outage on a distribution circuit would be about the same in either system. Loop feeders would offer some protection, but complete protection against such faults would require multiple supplies at service voltage from different distribution feeders in either system.

The Buffalo system has a decided advantage over a primary network in flexibility on account of the facts that the division of load can be controlled definitely, and that load can be shifted and forced from one location to another at will. This means that if load growth appears near a substation that is fully loaded and spare capacity is available in a nearby substation, the installation of additional capacity at the fully loaded substation often may be avoided by simply cutting and rearranging distribution feeders to shift load to the substation having spare capacity available. It also means that if

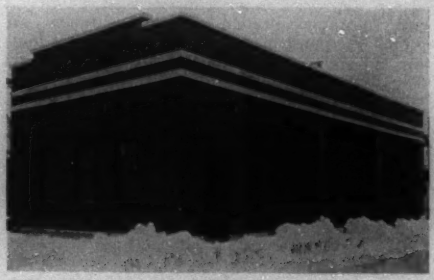


Fig. 4. Exterior of typical distribution substation in Buffalo

Small substations may be located on small lots in almost any neighborhood. Transformers are accessible from the outside and may be enclosed where noise is a factor

load growth appears along a group of fully loaded subtransmission circuits and spare capacity is available in a nearby group, the installation of additional subtransmission circuits often may be avoided by shifting load to the lightly loaded subtransmission circuits. In a primary network there would be practically no choice except to install additional capacity at or near the load, even though spare capacity might be available elsewhere in the network. The Buffalo radial system also would have the advantage should uniform growth of load appear over the entire area; in that case a minimum of additional subtransmission and substation capacity could be installed and made available to the entire area by shifting load to the new units, whereas, in a primary network it would be necessary to install additional capacity throughout the network. This advantage is particularly noticeable and significant in a large area.

The Buffalo radial system also has remarkable flexibility in serving industrial loads. The distribution feeders are so short that there is very little voltage drop in the feeders themselves, and the voltage regulation at the substation bus requires only a very slightly rising characteristic. This means that small industrial customers may be served from the same distribution feeders as lighting customers. Industrial customers of moderate capacity, even up to several thousand kilowatts, may be served from any of the substation busses by means of separate 4-kv feeders. Larger industrial customers may be served directly from the 22-kv subtransmission circuits in which case high voltage switching equipment could be installed in the customer's plant; or preferably, an installation similar to the power company's own distribution substations could be used for large industrial customers.

It is interesting to note that in the new system in Buffalo there is already one group of 3 22-kv subtransmission circuits that serves 2 substations in residential districts, 1 substation in the wholesale and warehouse district, 1 substation serving a large industrial customer, and several low voltage a-c network units in the principal business district. As the system develops, advantage will be taken of such opportunities to benefit by the diversity between the various types of load, to the maximum possible extent.

Actual layouts and comparative estimates have been made of a primary network equivalent to the Buffalo radial system as built and of both systems extended to double the firm rating. These estimates indicate that the comparative cost of the 2 systems would be about as shown in Table II.

These studies indicate the difficulty of making a satisfactory application of the primary network scheme under actual conditions, particularly in a large area. Several trials were required to accomplish a reasonable layout, and even after repeated attempts the initial installation of 130 units has 13 units with only 2 tie feeders and 45 units with only 3 tie feeders, leaving only 72 of the 130 units with 4 tie feeders. In the extension with 217 units there are 19 units with only 2 tie feeders and 84 units with only 3 tie feeders, leaving only 114 of the 217 units with the 4 tie feeders. Even these layouts include a number of "impossibilities" such as tie feeders crossing Delaware Park, substation units in the midst of the very finest residential sections, and several things that simply could not be done at all in an actual installation.

Conclusions

To review briefly, modern load area delivery systems must provide a high degree of reliability, efficiency, flexibility, voltage regulation, etc., with the maximum over-all economy. Reliability requires multiple subtransmission circuits to each substation, multiple units in each substation, and small short distribution feeders. Economy requires a proper economic balance between the various elements of the system. It requires also that maximum use be made of existing equipment before additions are made, and that when additional capacity is required it be installed in small increments.

The radial system, if designed in accordance with the principles outlined in this paper, meets these requirements very effectively. It takes advantage of the economy of large subtransmission circuits; at the same time, by serving several substation units from each subtransmission circuit, it permits the use of small, simple, multiple unit substations and short distribution feeders. It provides high grade service and takes maximum advantage of diversity between domestic, commercial, and industrial loads. The radial system permits shifting of load to allow maximum use of existing facilities before additions are made. It permits the installation of additional capacity in small increments when required and offers considerable freedom in the location of such additional capacity. It is an economical system either as a supplement to an existing radial system or as a complete system covering an entire area. In either case it may be installed in small increments as required by the growth of the load. In short, the radial system provides maximum flexibility and efficiency of use of equipment and is at least equal to any other system, except the low voltage a-c network, in reliability, efficiency, voltage regulation, and other operating characteristics.

Table II—Comparative Capital Costs of Buffalo Radial System and an Equivalent Primary Network

	Initial Installation			
	Buffalo Radial System		Equivalent Primary Network	
Subtransmission	243 miles	100%	346 miles	142%
Substations	26 7,500-kva substations	100%	130 1,500-kva units	171%
Distribution feeders		100%		100%
Total		100%		138%

	Double Initial Firm Rating			
	Buffalo Radial System		Equivalent Primary Network	
Subtransmission	407 miles	100%	570 miles	131%
Substations	26 12,500-kva substations	100%	217 1,500-kva units	183%
Distribution feeders		100%		100%
Total		100%		138%

The 3-Phase Electric Arc Furnace

The 3-phase electric arc furnace has established itself definitely as an important industrial unit in the production of ferrous materials. With the efficiency of the arc furnace being increased, and with the overall cost of installation and operation now being comparable with that of an equivalent open hearth, an even more extensive application is indicated for the future. This paper discusses in a general way the classification, rating, and methods of operation of 3-phase arc furnaces, outlines some of the modern developments in design, and points out the relative advantages of these units in specific applications.

By
SAMUEL ARNOLD, 3rd
NONMEMBER

Engr. & Sales Representative, Heroult Electric Furnaces, Pittsburgh, Pa.

A QUARTER OF A CENTURY of progress in steel making has firmly entrenched the 3-phase arc furnace as an industrial unit. In the entire field of ferrous metal production, the 3-phase arc furnace has been developed to the point where it would be difficult if not impossible to produce certain grades of material without its assistance, and many advances in the art of utilizing ferrous materials could not have been possible.

In the past few years in particular, large arc furnaces have been employed with excellent results. One of the problems of the use of large furnaces is the introduction of power into the furnace, and in particular the utilization of the energy without unnecessarily superheating the bath at certain points. The maximum rate at which energy can be introduced into a molten bath without detrimental effect as yet is undetermined, but it is known definitely that there are certain limits.

Efficiencies of arc furnaces, and in particular of large units, have been increased materially by the use of higher energy inputs; however, the problem of high power demand charge has made it necessary to consider efficiency increases along other lines, such as insulation. As yet little has been done with the insulation of arc furnaces, but the successful insulating of open-hearth units has indicated possibilities.

Advantages accruing from the application of arc furnaces are not to be considered from a cost standpoint only, but increased flexibility and metallurgical control obtainable with the use of the 3-phase arc furnace has been largely responsible for its continued application. In large units, the costs of installation and operation, all things considered, are now somewhat comparable to open-hearth costs; with this in mind, the possibilities of increased use for the 3-phase arc furnace are better than ever before.

Classification

For general classification, 3-phase arc furnaces can be divided into 3 types: furnaces used only as melting units, furnaces used for both melting and refining, and furnaces used for refining only. Under this general classification the arc furnace can be subdivided depending upon the quality and type of product desired, the material available for conversion, and the metallurgical results to be obtained. While in nearly all arc furnaces used for melting some refining is done incidental to the operation, the term "melting" unit is given to a furnace in which conversion of material primarily necessitates melting. The term "melting and refining" unit generally is given to an arc furnace in which it is necessary not only to melt the charge, but also to effect some metallurgical change and produce a material different in chemical and metallurgical qualities from the initial charge. By a "refining" furnace usually is meant one in which hot metal is charged either from an open hearth, bessemer vessel, or a cupola, and the hot metal changed chemically or metallurgically to produce a product different from the initial charge. Obviously, there is considerable overlapping in these classifications.

Arc furnaces are classified also with relation to the product, and here 2 general terms can be applied, namely: arc furnaces for the production of ingots, and arc furnaces for the production of castings. In general in the production of steel ingots, the furnace is supplied with a basic or magnesite bottom, and is termed a "basic" unit, while most of the furnaces used for the production of castings have bottoms of acid material or silica, and are called "acid" units. There are, of course, a few applications of acid furnaces for the production of ingots and, conversely, quite a number of basic furnaces used in the production of castings.

Of the ferrous materials produced in arc furnaces, the application is generally for carbon and alloy steel ingots, carbon and alloy steel castings, gray iron, and malleable castings. As a rule furnaces for producing castings are of the smaller sizes, varying from 500 lb to 10 tons in capacity. Ingot making furnaces are usually from 3 to 100 tons in capacity, although some relatively small ingot producing furnaces are used in the tool steel field.

Furnaces for producing metal for both ingots and castings can be operated as batch type units with cold charge, batch type units with hot charge, or semi-continuous melting units with either hot or cold

Full text of a paper recommended for publication by the A.I.E.E. committee on electrochemistry and electrometallurgy, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 13, 1933; released for publication Nov. 3, 1933. Reprinted for the author and for the American Bridge Company.

A 100-ton 20,000-kva 6-electrode Heroult electric melting furnace; batch charge with cold scrap for ingot production

charge. In batch type operation the charge is placed in the furnace, melted and/or refined, and then tapped by means of tilting the unit. In semicontinuous operation a full charge, either hot or cold, is placed in the furnace, melted and/or refined, and then a portion of the metal is tapped at intervals at which times charges of approximately the same tonnage are added. In semicontinuous work the furnace is drained at intervals, depending upon the cycle of operation, and usually the quantity of the charge is reduced so that at the proper time the last tap will completely drain the furnace. In the past, and particularly during the World War, some ingot producing furnaces were operated with charges of hot metal. However, in nearly every operation today where carbon or alloy ingots are produced in arc furnaces, the batch type of cold melt is employed; and there is at least one furnace in which the semicontinuous melting process is utilized, charging cold scrap. In casting work where carbon or alloy steel castings are produced, the usual practice is to batch-melt, while in the iron and malleable fields there is a tendency toward semicontinuous operation with either hot or cold charges.

Rating and Capacity

A great deal of confusion in the capacity rating of furnaces has been caused by nonuniform ratings. In the early development of 3-phase arc furnaces, a nominal tonnage rating was given the units which was based upon the holding capacity with a molten bath and a theoretical contour of bottom, allowing a certain volume for slag. In nearly every case it was found that by slightly changing the shape of the bottom, additional tonnage could be placed in the furnace, and with the introduction of higher power inputs the furnaces were overloaded. Later a tons-per-hour rating was given furnaces, which was explicit only when associated directly with the particular product to be made. Sometimes the size of the shell and the transformer capacity were given, but these did not tell the operator what tonnage might be expected. Nominal ratings still are given, usually arbitrary ratings based upon the size of the shell.

A description of the various methods of operating 3-phase arc furnaces may illustrate to better advantage what is involved in establishing capacity ratings. For batch type melting in the casting industry, assume a furnace rated at 3 tons nominal capacity. The furnace is lined with an acid bottom composed of gannister or silica sand and the side walls and roof are of silica brick. The transformer capacity is approximately 2,500 kva with taps of various voltages available at the will of the operator. A charge of approximately 6 net tons is placed in the furnace either through the door by means of hand charging or chute charging, or through the roof which can be removed for this purpose. The transformer switch is closed and some intermediate voltage applied that has been found most desirable for the type of charge utilized. The electrodes are started down and the load put on the furnace. This intermediate voltage usually is maintained from 10 to 20 min. until the electrodes have bored a hole through the scrap and the arc is more or less under cover. At this time the transformer taps are changed and full load is thrown on the furnace at a higher voltage until the charge is nearly melted. Usually at this period both the voltage and the load are reduced and after complete melt, the furnace operator takes samples of the steel for analysis. If ordinary steel castings are being produced, the melter by breaking a sample and reading the fracture can tell, approximately the carbon content of the bath, although present practice usually augments this by laboratory analysis. When reports have been received from the laboratory, the melter makes the necessary additions; and after the metal has reached the proper metallurgical condition and temperature, the tap is made. For ordinary steel castings this usually takes about 2 hours, so the furnace may be said to have a nominal rating of 3 tons per hour.

If alloy castings are being produced, and particularly alloys requiring basic treatment, the furnace, of course, is operated with a basic bottom. In most cases the first slag produced after melting is raked off, as this slag is usually of an oxidizing nature; and as it is slagged off, the impurities such as phosphorous contained in the slag are removed. A second slag then is made, and in rare cases 3 or 4 slags are necessary. In basic furnaces the time usually required for refining is much longer, as the metallurgical results desired are entirely different. For this reason furnaces with basic bottoms require a longer period of time for making the heat and usually are not rated on a tons-per-hour basis.

As an example of batch type refining or batch type superheating with hot metal, assume a 15-ton unit containing about 20 tons of hot iron. This unit would be acid lined, and the charge made from a ladle through the rear door. The metal would have a temperature of approximately 2700 deg F when received into the furnace and must be superheated to 2,950 deg F. This is accomplished by applying about 5,000 kw at a comparatively low voltage, the time required being from 15 to 20 min. While some slag is formed, if from no other source than from the drippings of the side walls of the unit, very little attention is given to metallurgical changes except in the results obtained by superheating; and as soon as the proper temperature is obtained, the furnace is tapped. In this case 3 taps will be made per hour or 60 tons removed from a 15-ton unit in an hour; the furnace thus would have a rating of 4 times its nominal capacity in tons per hour.

Again, assume a furnace rated at 25 tons and used for producing alloy steel ingots; this furnace, depending of course upon the size of the scrap, would be charged with some 30 to 35 gross tons by means of an open-hearth charging machine. The melt would be made in the usual way, and after melting down, the first slag would be removed as previously mentioned. Careful laboratory analysis would be made of samples taken from the furnace and additions made to produce the grade of steel desired. Careful working of the furnace slags would be in order; and after the melter was satisfied as to temperature and metallurgical conditions, the heat would be tapped. Usually from $4^1/_2$ to 5 heats would be produced in 24 hr, and so the tons-per-hour rating of a furnace of this sort would depend entirely upon the type of product.

The foregoing examples serve to show that the tonnage rating of a furnace depends entirely upon the final product and the type of charge used. Usually in the casting industry a ton is spoken of as 2,000 lb of metal, and in the ingot industry 2,240 lb of metal. Some furnaces are rated on a tons-per-hour basis, some on a nominal holding capacity basis, and some are rated as to size of shell and transformer capacity; for each size of shell and a given transformer capacity a tons-per-hour rating can be determined for the product desired. As to furnace ratings, therefore, the size of the shell, the transformer capacity, and the nominal holding capacity should be given, as well as the approximate tons-per-hour rating for a definite specified product.

Modern Developments

Great progress has been made during the past 25 years in the mechanical features of arc furnaces. Designs have been made coördinating workability with efficiency of operation; and such parts as water cooled door frames, arches and doors, electrode holders, electrode cooling glands or roof coolers, and other important parts have been much improved and simplified in design. In addition, methods of carrying heavy currents over the furnace by the use of water cooled copper tubing to minimize hysteresis and eddy current losses, the design of the mast structure to permit various changes of electrode circles for different operating characteristics, and such mechanical features as ball and roller bearings in the moving parts, all have tended to make for efficiency and improved operating characteristics. On the surface there is seemingly little chance for material improvement of design along mechanical lines, except perhaps in the methods of charging; but unquestionably improvements will be made as the use of electric furnaces increases and new problems arise.

Electrical equipment, of course, has kept pace with other developments. With improvements in regulators and transformer design, and a knowledge of the proper values of reactance for given conditions, the method of introducing energy into the furnace has been changed materially. In addition to this, modern furnaces usually are equipped with the so-called "multiple voltage control" which provides several voltages available at the will of the operator. On small furnaces, usually 3 voltage taps are provided; but on the larger units 5 or 6 and in one case as many as 12 different voltages are available at the immediate will of the operator, by means of a combination of transformer taps and delta-Y switching accomplished by motor operated tap changers with the control on the operator's panel. This gives the operator a choice of different lengths of arc and allows him to choose the voltage that is most desirable for the different steps of melting and refining.

In the past few years the tendency has been toward larger transformer capacities for quicker melting, hence shortening the radiating period during the melt with consequent higher efficiency. Of late, however, consideration has been given to transformer capacities primarily on account of the usual high power demand charge, and doubtless a great deal of thought is being given to improving the efficiency of arc furnaces by means other than simply forcing power into the furnace as rapidly as possible. There is a limit, of course, to the amount of energy that can be utilized with a certain size of furnace shell, as refractory and metallurgical problems arise when energy is introduced into the furnace at too rapid a rate.

In recent years open-hearth furnaces in some instances have been insulated successfully, and this naturally leads to the thought that 3-phase arc furnaces also can be insulated to increase their efficiencies; while some experiments are being carried out along this line, there have been as yet

no definite results. The major problem of insulating an arc furnace is in limiting the power input so that energy will not be introduced at a rate sufficient to increase the temperature difference between the refractories and the charge. Depending upon the temperature, energy can be dissipated in a ferrous bath at a certain rate; and if power be introduced too rapidly, it, of course, would raise the temperature of the furnace itself to the point where refractory failure would occur. There are other problems in connection with insulating arc furnaces, but they are of a minor nature and no doubt can be overcome.

A 15-ton 5,000-kva 3-electrode Heroult electric melting furnace; semicontinuous hot charge for gray iron castings

The insulation of arc furnaces and the consequent reduction in power input would accomplish 2 things: (1) the demand charge for a given size of unit would be lowered; and (2) the efficiency of the unit would be increased as a result of the reduction in radiation losses. Obviously, if a certain length of time is required to make a certain heat with a given power demand in a furnace that is not insulated, the same heat could be made in the same time with a lower power demand in an insulated furnace. This is because the rate of radiation is relatively high during the refining period as well as during the melting period; and regardless of transformer capacity and rapidity of melt, this loss during the steel making cycle is not changed, as it is a function of the rate of radiation and the time required to accomplish the metallurgical results.

If, therefore, arc furnaces can be insulated successfully, the operating costs can be improved by lowering the amount of energy consumed per ton of metal produced and also by reducing the power demand charge. The over-all cost of production then will depend upon whether the savings in demand charge and energy requirements will offset the apparently increased cost of refractories. The difficulty is in determining the maximum rate at which energy can be introduced into an insulated furnace, and at present the human element involved has made progress rather slow along this line. New refractories are being developed, however, and new insulating materials tried; and there are excellent possibilities of some good results being obtained.

Large Furnaces

Problems arise in connection with 3-phase arc furnaces of nominal ratings of 25 tons and more which, of course, do not occur with the smaller units. These problems deal with the introduction of large amounts of power. In general, the transformer capacity, or power input per hour per ton of rating, is much less than for furnaces of smaller size. As most of the power available is at 60 cycles, difficulties are experienced with the conduction of heavy currents in introducing the power into the furnace at a good power factor, and careful design is necessary. The tendency on first thought, when higher inputs are considered, is to increase the voltage; but in an arc furnace an increase of furnace voltage means a longer arc, and if the arc is too long the energy is not entirely introduced into the charge—rather, a large portion of it is radiated to the side walls and roof of the furnace with consequent high refractory costs. It is necessary, therefore, to keep within certain limits of furnace voltage and this in turn means higher currents with the increased power. Currents of from 30,000 to 40,000 amp per phase have been applied successfully to arc furnaces with reasonable power factors, but it is questionable if these values will be exceeded. It might be said, therefore, that from the electrical standpoint, there is no difficulty in introducing large amounts of energy through 3 electrodes, and at present as much as 12,000 kw have been applied to a 3-electrode 3-phase arc furnace.

In introducing large amounts of energy, however, the point is approached where the steel will not absorb energy rapidly enough from 3 concentrated areas. Some believe that the limit of power input per electrode is approximately 3,000 kw. With higher values the metal tends to become superheated directly under the electrodes, and when the charge is partially melted down, there is a great deal of agitation and "slopping" of the bath. The actual upper limit of power input per electrode as related to energy dissipation in the charge as yet is undetermined; it depends upon several factors, the primary one of which is the maximum rate at which heat can be disseminated through various ferrous materials.

It is for the reasons previously outlined, therefore, that in the larger 3-phase arc furnaces the rate of power input per ton of charge is lower than in smaller units, and this also is the reason for utilizing multiple electrode furnaces or furnaces with 6 or 9 electrodes which unquestionably will be developed to a greater extent in the future. At present the largest furnace that has been built using 3 electrodes is a unit having a shell 18 ft in diameter. This furnace has a holding capacity of from 60 to 75

gross tons and a transformer capacity permitting 10,000 kw input for the period of melt. There is also one furnace in operation at the present time that has an elliptical shell 29 ft by 20 ft. This furnace has 6 electrodes and is capable of introducing 10,000 kw on each set of electrodes, or 20,000 kw total; the furnace has been charged with as much as 135 gross tons.

Application

One does not use a tool unless there is some advantage in so doing. In a great many cases production could be made in other than electric furnaces at less cost, but the product would be inferior. In other cases the electric furnace shows the best cost. Whether the electric furnace should be utilized or not, depends upon a great many factors including power rates, cost of scrap, metallurgical considerations, and type of product. In general, in the small steel foundry, the electric furnace has proved itself to be a most excellent and economical tool. In the iron foundry where superheating is necessary or where a high grade product is demanded, the electric furnace is well adapted. In the ingot producing field for tool steels and for special alloy steels including stainless steels, the 3-phase arc furnace is unquestionably paramount. In the manufacture of ingots and ordinary grades of steel such as bar stock and steels that usually are made in the open hearth, the use of an electric furnace will depend on the cost of electric power as opposed to fuel costs, and the cost of scrap as opposed to the cost of the charge of the open hearth. In all cases, attention should be given to, and a careful analysis made of, relative costs; for while the electric furnace has the disadvantage of a high energy cost, this disadvantage can be overcome largely by the higher yield and higher efficiency of the electric furnace and the higher quality product that very often is obtained at no additional over-all cost.

During the past few depression years the flexibility of the electric furnace has been brought to the fore, and where this tool has been used it has been recognized unequivocally as having many desirable operating characteristics. As is often the case there have been applications of the arc furnace where such were not warranted, but the resultant failure of the arc furnace to measure up to expectations in these few instances has served only to emphasize the desirability of its use in other fields. The development of the arc furnace in the future undoubtedly will be along the line of large units, as the cost of operation of these units, with the exception of energy, is quite comparable to open hearths of like rating; and as power is produced and sold more cheaply, the large electric furnace will take its place as a close competitor of the open hearth. The use of alloy steels is on the increase, and the arc furnace so far has shown itself to be the most desirable tool for producing alloy steels. In the casting industry, the development of high test irons and the ease with which these irons may be superheated in a 3-phase arc furnace will result in an increased growth in the use of the arc furnace. In the steel casting industry, while at present the arc furnace is used almost exclusively as a smaller melting unit, unquestionably the use of larger arc furnaces will follow the inevitable adjustment between present fuel and power costs.

As an example of what now is being accomplished, it has been demonstrated definitely that with the exception of energy, a large arc furnace can show production costs equal or nearly equal to the production costs obtained in a similar open-hearth where scrap and cold pig are used. The electric furnace is more efficient as to melting loss and, therefore, has a higher yield, and the investment cost of a large electric furnace is not greater but usually less than the cost of a similar open-hearth installation. By similar furnaces is meant, of course, furnaces capable of producing the same number of tons per month. As to energy costs, however, the electric furnace is the more expensive unit to operate. Assuming $1 per ton for open-hearth fuel costs, on the same basis the electric furnace with energy at 6 mills per kwhr would show about $4.50 per ton for power and electrodes. This differential of about $3.50 per ton often can be more than offset by low investment in plant and auxiliaries, in increased metal yield, and in increased yield in the use of alloys. In addition to this, the resultant higher quality product is usually more salable and in most cases commands a higher price.

It is difficult, of course, to visualize the future of arc furnaces; but the rapid recognition of these units, and the part they have played in the development of ferrous materials in the past few years, would indicate an even more extensive application in the future. It seems entirely logical to predict that during the next inevitable cycle of prosperity, the arc furnace will play an increasingly important part in the ferrous industry.

A 50-ton 10,000-kva 3-electrode Heroult electric melting furnace; semicontinuous charge cold scrap for ingot production

Electrodes—Carbon and Graphite

Carbon and graphite electrodes play an important part in many industries; the number of uses of these electrodes is increasing year by year, and the field of application is widening. In spite of these facts, however, published information regarding them appears to be quite meager. In this paper the history of carbon and graphite electrodes is outlined briefly, and the methods of manufacture and industrial applications are described.

By
FRANK J. VOSBURGH
NONMEMBER

National Carbon Co., Inc., New York, N. Y.

THOUGH carbon and graphite electrodes play an exceedingly important part in several industries, notably in the production of abrasives, aluminum, iron, steel, alloys, and carbide in the electric furnace, as well as in the electrolytic production of chlorine, caustic soda, and other substances, the information regarding them is unusually meager. Undoubtedly, this is due primarily to the fact that such electrodes in general have a simple structure and a wholly uninteresting appearance, giving no indication of the difficulties encountered in bringing them to their present state of carefully manufactured articles.

Materials used for manufacturing carbon and graphite electrodes are chiefly anthracite coal, petroleum coke, and hard and soft pitch. The electrodes may be extruded through dies or molded under pressure, after which they are given special baking and cooling treatments. About 2 months are required for manufacturing carbon electrodes, and 3 months for graphite. They can be made in practically any shape and size up to a maximum of 40 in. in diameter for carbon, and 18 in. for graphite.

Graphite electrodes usually are preferred for electrolytic operations, while in electrothermic work both are used depending upon the nature of the process and the result desired. Where either type of electrode may be used, the choice naturally depends primarily upon the over-all cost. Although graphite electrodes cost more than carbon electrodes of the same physical size, the electrical resistivity of graphite electrodes is lower than that of carbon, and hence graphite electrodes are much smaller than equivalent carbon electrodes. The electrode consumption per ton of product varies widely, depending, of course, on the nature of the process and the relative size of the equipment, as well as on the ability of the operator.

Historical Facts

Historically, electrodes are dated as of 1800 when Sir Humphrey Davy produced the first electric arc using a voltaic pile as the source of current. Davy made the first electrodes by a process not so dissimilar from that now in effect. He took powdered wood charcoal as the carbon and syrup of tar as the binder, mixed them, and compressed the mass to form electrodes for his experiment. Today the process is the same except that coal and coke replace the charcoal, and tar and pitch replace the syrup of tar; molding under pressure still is used, though most electrodes now are extruded under pressure. The final product of today is baked, while Davy does not seem to have carried out that operation.

Little advance was made in the manufacture of electrodes until after the invention of the dynamo in 1867 when larger sources of power became available and better and larger electrodes were necessary. The names of early experimenters in the electric field are also a part of electrode history, and those connected with arc lighting are especially prominent. The real necessity of larger electrodes came with the development of the electric furnace. Heroult, Braun, Zellner, and Hardmuth are names inseparably linked with the development of electrodes in Europe, while in America, Charles F. Brush and Washington H. Lawrence did most to make the production of electrodes a real business. Lawrence first used petroleum coke, then a nearly worthless by-product of one of the oil refineries.

After 1900 the production of suitable electrodes a few inches in diameter was no novelty, but Heroult's requirements of electrodes for his furnaces, which had capacities as large as 15 tons, changed the picture; and thereafter development for some years was rapid as the need for electrodes increased immeasurably.

Manufacturing Process

The process of manufacturing electrodes has not changed radically since early dates in the art; still a brief description of the methods of making carbon and graphite electrodes may be of interest. The chief raw materials are high-grade anthracite coal selected primarily for strength of particle, petroleum coke of low ash content, and hard and soft pitch. All of these materials are used in making carbon electrodes, the latter ones in making "coke" electrodes which are to be graphitized and for the carbon electrodes used in the aluminum industry. Both the anthracite coal and petroleum coke are treated at very high temperature to drive off volatile matter and induce shrinkage, but primarily to reduce the electrical resistivity to a low value. After

Full text of a paper recommended for publication by the A.I.E.E. committee on electrochemistry and electrometallurgy, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1933. Manuscript submitted Sept. 14, 1933; released for publication Oct. 31, 1933. *Not published in pamphlet form.*

calcination, both materials are ground to predetermined sizes, depending upon the size of electrode to be made, and mixed with exact quantities of pitch in heated mixers.

The green mix may be extruded through dies under high pressure or molded under pressure to form the green electrodes in any one of the many sizes now required by a varied trade. The green electrodes must be made to an exact size with proper allowances for the shrinkage that occurs in the baking and graphitizing processes. The dies are machined most accurately—in fact, usually hand finished to templates—as the flow of materials through them must be controlled exactly to give a suitable finished product.

The green electrodes are packed in furnaces surrounded by fine coke, which supports them during the preliminary softening period as the heat is applied, and are baked to a final temperature of 1,000 deg C, the temperature being raised gradually to the maximum. Baking and after-cooling requires up to 5 weeks' time. After baking, the electrodes are cleaned by hand to remove the packing coke, and are inspected carefully for every one of a possible dozen or more faults. The coal carbon electrodes are sent to storage or to the threading and finishing department. The coke electrodes are ready to be graphitized.

The graphitizing process invented by E. G. Acheson is generally familiar. In this process the carbon material of electrodes is wholly changed into graphitic carbon through raising it to a temperature of at least 2,200 deg C by the heat generated by passing current through the material, which acts as a resistance body. The material is packed closely in large open furnaces and covered with coke. The current is supplied through huge contacts at the furnace ends; by manipulation of the current control the temperature is regulated and gradually brought to the desired maximum.

The complete cycle, packing, graphitizing, cooling, and unpacking, requires from a week to 10 days. After slow cooling the electrodes are cleaned and stored, or machined, as required for the various purposes for which they are to be used.

Electrode Specifications

There are certain definite requirements that all electrodes, carbon or graphite, should meet. First, they should be formed properly within the limits of the art, the usual specifications being ± 2 per cent of the dimensions for diameter or side; they should be straight, meeting a specification that the distance from a chord to the arc of the electrode should not be more than 0.5 per cent of the length. The electrodes should be of high density, and the usual manufacturing specification is that the apparent density shall not be less than 1.50 for carbon electrodes, and 1.51 for graphite electrodes. They should not show signs of coring or laminations. The surfaces should be clean and free from pits or blow holes, as well as relatively free from "alligator" markings. It is not customary in the trade to impose resistance specifications, though manufacturers inspect their own electrodes on that basis. The operator rarely is interested in the exact resistivity, his criticism being based upon performance in his own operation, which of course is influenced by whether or not the electrodes have suitably low resistivity.

Both carbon and graphite electrodes are made in a wide variety of shapes and sizes for innumerable uses. Round electrodes vary from $^1/_{16}$ in. in diameter and 12 in. long to 18 in. in diameter and 72 in. long for graphite, and up to 40 in. in diameter and

Extruding a carbon electrode 40 in. in diameter

110 in. long for carbon. It takes 500 of the $^1/_{16}$-in. size to make a pound, while the largest size mentioned weighs, 7,500 lb with its connecting pin. Rectangular electrodes have been made weighing up to 8,500 lb each.

Carbon and graphite manufacturers have a wide range of dies for manufacturing electrodes of various sizes, and any shape within wide limits that can be extruded or molded can be made. However, if time is an important element, any one contemplating the use of formed carbon or graphite will do well to consult the manufacturer to determine what sizes are in stock as 2 months are required to make carbon electrodes and 3 months to make graphite electrodes, even when the dies are available.

Applications of the 2 Types of Electrodes

For practically all electrolytic operations, graphite electrodes are preferable to carbon because of the much more rapid oxidation of carbon in the electrolyte as compared with graphite. In most electrolytic work carbon electrodes are wholly unsatisfactory.

For electrothermic work the division of the kinds of electrodes among the several types of operations is not so clear cut. All aluminum furnaces or pots use carbon electrodes, and this industry is by far the largest user of electrodes since about $^3/_4$ of a pound of electrode is used to produce every pound of aluminum. In fact, the aluminum industry consumes more electrodes alone than all other types of operations. The use is so large that these industries in the United States and Canada manufacture for themselves practically all of the electrodes they need. The carbide industry is another large user of electrodes, and practically without exception all carbide furnaces operate on carbon electrodes. Likewise, the ferro-alloy industry uses carbon electrodes almost without exception, though for some of the higher grade alloys, particularly those that must contain minimum amounts of carbon, graphite electrodes are used.

The nonferrous industry uses graphite electrodes exclusively because the electric furnace most generally used for the production of nonferrous metals is equipped to use graphite electrodes only.

When the iron and steel industry is considered the matter becomes complicated. More than half of the tonnage of steel ingots produced by electricity comes from furnaces equipped with graphite electrodes, though more than half of the furnaces use carbon electrodes. This is because several of the larger furnaces use graphite. In the steel casting field the division is more even; but in the gray iron industry most of the furnaces use graphite electrodes, partly, at least, because one type of furnace uses graphite electrodes only.

There are reasons for the distribution of electrodes in the various industries mentioned, and of course, the primary one is cost, that is, the cost of electrodes per pound or per ton of product. In the production of aluminum, carbide, and ferro-alloys the electrodes last for days, and in some cases several weeks. The electrodes must carry power into the furnaces at the lowest cost, and must have a relatively large area of working surface; and since the electrodes are consumed mostly by oxidation, the electrode having lowest cost is most satisfactory. New electrodes are added so infrequently that the fact that carbon electrodes are necessarily much larger and therefore more difficult to handle than graphite electrodes that might serve, does not have any particular weight. The same comments apply in general to the ferro-alloy industry, but there are exceptions as mentioned previously in the case of special alloys where the higher cost of graphite is more than offset by other advantages.

In iron and steel furnaces new electrodes are added often, sometimes several times a day, so the fact that a graphite electrode need be only a little over half as large as a corresponding carbon electrode to carry the same power is of importance from the operator's point of view. Graphite electrodes are joined together more easily, and because of their lesser weight the furnace superstructure need not be designed as substantially. Graphite electrodes cost approximately twice as much as carbon electrodes per pound, and this would seem to give carbon electrodes a great advantage; however, in operations such as those in the steel and iron industry, approximately half as much graphite is used per ton of product as carbon, therefore the higher cost is offset by the lower consumption. Other factors enter in as well, and before the operator determines whether he will use carbon or graphite electrodes, a number of points should be considered.

Carbon electrodes having a larger end area melt down a larger proportion of the charge under them and there is less tendency to bore down through the charge. However, the large area may prove to be a disadvantage because the arc is brought nearer the side walls of the furnace and the refractory cost may be higher as a result. Still, the larger end area, since it better protects the arc, may prevent so much heat from being reflected against the roof and reduce that cost.

Table I—Electric Furnaces in the United States

Year	Ferrous	Nonferrous*
1910	10	
1915	41	
1920	323	60
1925	479	310
1930	560	325
1933	580	560

* Does not include induction furnaces.

Table II—Tons of Steel Produced by Electricity in the United States

Year	Ingots	Castings	Total
1910	51,000	1,300	52,300
1915	46,000	23,000	69,000
1920	346,000	155,000	501,000
1925	335,000	280,000	615,000
1930	307,000	305,000	612,000
1932	141,000	100,000	241,000

American Iron & Steel Institute Tables.

Since the diameters of graphite electrodes are much smaller than those of equivalent carbon electrodes, the graphite ones may be broken more easily by scrap caving in on them or by being struck by furnace bars when the charge is worked. This situation is offset by the fact that graphite electrodes are machined easily, and pieces recovered from the furnace can be rethreaded in any machine shop and used again. Carbon electrodes are very difficult to machine, and it is rare that any operator recovers broken pieces except by sending them back to the manufacturer. The fact that no joint compound is used in making up graphite joints, while that material is a necessity for carbon electrodes, may be a deciding factor in determining which type of electrode is used if the desire of the operator is considered.

The lesser weight of the graphite electrode may make the control apparatus more effective because there is less inertia to overcome when the electrodes move up and down. Larger carbon electrodes may prove just as active, however, as there is a greater area to make contact with the slag or metal. Graphite having a lower resistance, the loss of power in graphite electrodes would be less if the same sizes of graphite and carbon were compared; but since much smaller graphite electrodes are used, the power losses in the 2 types of electrodes will not be greatly different. The reverse of this statement applies to heat conductivity, for graphite has much higher heat conductivity than carbon; but a smaller size keeps the 2 losses about the same.

Carbon and graphite electrodes do not act quite the same in the furnace, and this is more noticeable in connection with high-grade steel than steel castings. As a result, whether one kind or the other is used may become a matter of the melter's preference. One operator will claim that slags are made and maintained more easily under carbon electrodes than under graphite, while an equally good man will claim the reverse. One melter will state definitely that there is more chance of carbon pick-up if carbon electrodes are used in making special steels having a low carbon requirement, while another man making the same steel will *prefer* carbon electrodes. Such questions clearly demonstrate that while both types of electrodes have their proponents, still the adoption of one or the other is not necessarily based upon facts alone.

Another point that frequently enters into consideration is the matter of freight. For reasonably short hauls the fact that only half as much graphite is required as carbon to do the same work is not particularly important, for the difference in freight charges constitutes a small percentage of the total electrode cost; but for long hauls where the freight rate exceeds $1 per 100 lb, the differential may become quite a deciding factor.

As melting furnaces have become larger and the transformers back of them increased to a point where capacities of 10,000 to 12,000 kw are being used, furnace designers have been more inclined to use graphite electrodes since the carbon size required would be very large, 30 to 35 in. in diameter, and weights up to 4,000 or 5,000 lb per electrode. Such electrodes require very heavy superstructures which are expensive to build, and the electrode ports being very large the roof structure of the furnace may be weakened seriously or at least become difficult to maintain.

In the abrasive industry both carbon and graphite electrodes are used, the bulk of the material being produced by furnaces using carbon electrodes. For certain types of abrasives, such as those very light or even white in color, only graphite electrodes will serve.

It should be evident that no one can say offhand what type of electrode should be used for any of the industries except those producing aluminum and carbide. Many factors enter into the problem and each one must be given consideration before any conclusion is reached. Electrode manufacturers appreciate this situation and will be found willing to coöperate with any present user of electrodes to determine if he is operating under the best conditions, and to help a new operator determine which type of electrode is best suited to his problem. In many cases, furnace operators appreciating the situation have run tests on both types of electrodes and have tried more than one size to find out which combination gives the best operating results as well as the lowest cost. Lowest cost does not necessarily mean lowest electrode cost only, but rather the lowest combined cost of electrodes, power, refractories, and labor, because the kind and size of electrodes may influence all of the other factors.

Table III—Electrode Consumption in Pounds Per Ton of Product

Product	Carbon	Graphite
Nonferrous castings (net ton)		2.5–10
Iron castings, cold scrap (net ton)		5–10
Iron castings, duplex (net ton)		3–14
Steel castings (net ton)	9–20	5–12
Steel ingots (net ton)	17–30	10–20
15% Ferrosilicon (gross ton)	25–50	
50% Ferrosilicon (gross ton)	50–75	
80% Ferrosilicon (gross ton)	80–120	
High-silicon Ferrosilicon (gross ton)	150–300	
Calcium carbide (net ton)	30–200	
Aluminum (net ton)	1500–2000	

Electrode Consumption in Various Fields

The question of electrode consumption in the various industries is one that frequently brings forth arguments, and it is no wonder since so many factors enter into the problem. It would not be fair to compare a carbide furnace using 1,000 kw with one using 20,000 kw any more than it would be equitable to compare the electrode consumption of a furnace producing ordinary steel castings with one turning out the highest quality alloy steel. Every factor must be taken into consideration, the type of product, size of the furnace, as well as the ability of the operators. Indefinite figures on electrode consumption have little value, but in some cases they may be interesting.

As indicated before, consumption of electrodes in the aluminum industry ranges from 1,500 to 2,000 lb per ton. Electrode consumption for calcium carbide may be as low as 30 lb of carbon electrodes

per ton in large furnaces under advantageous conditions and as high as 150 to 200 lb of carbon electrodes in small and poorly designed furnaces. The consumption of electrodes in the ferro-alloy industry varies widely depending, of course, upon the material produced; it may be as low as 25 lb of carbon electrodes per ton for 15 per cent ferrosilicon, 50 lb per ton for 50 per cent ferrosilicon, 65 lb for 80 per cent ferromanganese, and 150 to 300 lb per ton for silicon alloys containing the higher percentages of silicon when these materials are produced under good operating conditions, but 2 or 3 times these figures for the same alloys produced under less advantageous conditions.

In the nonferrous industry, figures as low as $2^1/_2$ to 3 lb of graphite electrodes per ton are reported, but the average is undoubtedly nearer double that quantity and figures much higher often are reported.

In making high-grade steel, alloy steel, tool steel, stainless steel, etc., electrode consumptions as low as 17 lb of carbon electrodes per ton have been reported, but figures in that neighborhood are rather unusual and the average is probably nearer 25 lb. The figures for graphite are not as low as the expected $^1/_2$ of the figures for carbon because of the long finishing time required for these metals. During that period the electrodes are consumed largely by oxidation; and although this is less with the graphite electrode because of its smaller size, still the proportion is not maintained and graphite consumption of less than 12 lb per ton is unusual. In the steel casting field, the consumption of graphite electrodes is very nearly half that of carbon ones, with graphite consumptions reported as low as $4^1/_2$ to 5 lb comparing with carbon at 9 to 10 lb, and as high as 10 lb per ton, comparing with 20 lb for carbon. Such figures are influenced greatly by the rate of operation, that is, the number of heats per day and the amount of power put into the furnace per hour; and if the oxidation loss is proportionately great, as in the production of high-grade steel, the figures for graphite do not appear to as good advantage as they do when the bulk of the electrode consumption is accounted for by the transmission of power to the charge. Electrode consumption for iron may be as low as 3 lb per ton of graphite electrodes for furnaces charged with hot iron from the cupola, or may run as high as that for steel castings. Relatively few carbon electrodes are used in the gray iron industry, either duplexing or straight.

Conclusion

The number of users of carbon and graphite electrodes is increasing year by year, and the field of application is constantly widening. The future growth of the industry depends largely upon the use of the right electrode in the right place to secure the desired result, whether that be a new product or an old product made in a new way at a lower cost.

Electrode manufacturers have made clear their desire to coöperate at all times with electrode users, and particularly in the later years operators have shown more inclination to benefit by the assistance the manufacturers were willing to give.

Induction Motors as Selsyn Drives

The power Selsyn unit, an adaptation of the wound rotor induction motor, provides accurate remote control of angular motion, using only an electrical connection. The characteristics of these units are described briefly in this paper, and methods of calculating their performance are offered. Typical applications of Selsyn drives also are given.

By
L. M. NOWACKI
ASSOCIATE A.I.E.E.

General Elec. Co., Schenectady, N. Y.

THE SELSYN device is used for repeating or reproducing by remote electrical control angular motion, both as to speed and total angle. The word "Selsyn" is an abbreviation of the expression "self-synchronous" and indicates the normal use of the apparatus. The function of the Selsyn system is to transmit motion by electrical means between 2 points which cannot conveniently be interconnected mechanically.

The power Selsyn unit is an adaptation of the conventional wound rotor induction motor. The principle of operation is a familiar one. For simplicity, 2 identical 3-phase wound rotor induction motors will be considered. The stator windings are excited from a common power source, and the rotors electrically interconnected. One Selsyn unit is located at the point where the motion is generated and the other unit is located at the point where the motion is duplicated. Under these conditions, for each pair of poles, there is only one relative position of the rotors where the secondary voltages will be exactly opposed so that no current will circulate in the secondary windings. For other positions, a current will circulate in the rotor windings and torques will result tending to turn the rotors to that position where the voltages are again equal and opposite. If, therefore, one rotor is turned, the other rotor will tend to assume exactly the same position.

Selsyn units are synchronized at standstill by applying single-phase excitation. This introduces several problems which bear directly on the choice of control and winding connections. A study of

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 17, 1933; released for publication Nov. 3, 1933. *Not published in pamphlet form.*

the several synchronizing characteristics is important to the thorough understanding of the Selsyn drive. Both operating and synchronizing torques are expressed in terms of induction motor operating characteristics, thus enabling the direct translation of induction motor characteristics into synchronizing and operating data.

General

Selsyn devices were first built over 20 years ago. They were originally designed as instruments for transmitting and receiving an indication by an angular movement. In these applications the Selsyn receiver carried on its shaft only a very light dial pointer or possibly a cam. The characteristics of the Selsyn device, however, soon made it desirable that the receiver be capable of exerting enough torque to perform such work as operating relay contacts or turning a valve. Simultaneously with this development came also requests for Selsyn control systems where the units were required to rotate continuously at high speeds in addition to carrying mechanical loads. In the last 5 years, considerable progress has been made in extending the Selsyn principle to industrial machine drives.

The study of Selsyn behavior has not been given much attention in technical literature. Several papers were published in trade journals bearing, in the main, on application problems. The increasing popularity of the Selsyn drive made urgent a thorough understanding not only of the underlying principle of the Selsyn system, but, also, of the operating and synchronizing characteristics. It is the purpose of this paper, therefore, to describe briefly the behavior of the Selsyn units, to offer a convenient method for determining their characteristics, and to suggest the possible arrangements of the Selsyn tie.

Three-Phase Operating Characteristics

The 2 Selsyn units are connected as shown in Fig. 1. One unit, the transmitter, is driven. The second unit, the receiver, rotates in synchronism with the transmitter. The angle of deflection between the 2 rotors is given in electrical degrees and is designated by α. For any angle α and slip s, the transmitter and receiver torques, for rotation against the revolving field, are:

$$T_t = \frac{6.09\ V(I - I_m)}{\text{rpm}} \sin\theta \sin\alpha + T_0 \sin^2\frac{\alpha}{2} \quad \text{lb-ft} \tag{1}$$

$$T_r = \frac{6.09\ V(I - I_m)}{\text{rpm}} \sin\theta \sin\alpha - T_0 \sin^2\frac{\alpha}{2} \quad \text{lb-ft} \tag{2}$$

where

V is the line voltage
I is the induction motor current for slip s
$\cos\theta$ is the induction motor power factor for slip s
T_0 is the induction motor torque for slip s
I_m is the induction motor magnetizing current
rpm is the induction motor synchronous speed

The above factors, as designated, are determined for an induction motor operating at the given slip. Thus the induction motor characteristics may be translated directly into Selsyn drive performance.

Similarly, the currents:

$$I_t = \left(I_m \cos\frac{\alpha}{2} + jI \sin\frac{\alpha}{2}\right) \angle -\frac{\alpha}{2} \tag{3}$$

$$I_r = \left(I_m \cos\frac{\alpha}{2} - jI \sin\frac{\alpha}{2}\right) \angle +\frac{\alpha}{2} \tag{4}$$

The line current:

$$I_l = 2\left(I_m \cos^2\frac{\alpha}{2} + I \sin^2\frac{\alpha}{2}\right) \tag{5}$$

The rotor current:

$$I_R = jI_l \sin\frac{\alpha}{2} \tag{6}$$

All the currents are expressed vectorially. I_R is the rotor induction motor current for slip s.

Torque characteristics are shown in Figs. 2 and 3.

The torque expressions of eq 1 and 2 consist of 2 components, the first a synchronizing component due to the rotor displacement, acting in the direction to decrease the angle, and a rotor loss torque, acting in the direction of the rotating field. On this account, the receiver torque is higher for rotation with the field and the transmitter torque for rotation against the field. The synchronizing torque is highest and the induction motor torque is lowest for slips greater than unity. Therefore, to obtain the highest synchronizing torque efficiency, Selsyn units are recommended for operation against field rotation. Similarly, to obtain the highest motor torque efficiency, the units are recommended for operation in the direction of field rotation. Rotation in the direction of the revolving field is much limited by the loss of synchronizing torque in the neighborhood of synchronous speed. Here, if there should be a sudden change in speed, particularly if the inertia of the system is appreciable, the transmitter and receiver may momentarily interchange their functions and possibly fall out of step. Operating in each direction with respect to the revolving field has its definite applications, all factors considered.

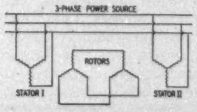


Fig. 1 (left). Connection diagram of 2 Selsyn units

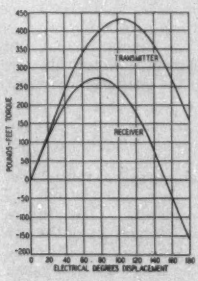


Fig. 2 (left below). Three-phase torque-angle characteristics at standstill, illustrated for 2 25-hp 8-pole 60-cycle 3-phase wound-rotor induction motors

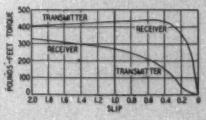


Fig. 3 (below). Three-phase maximum torque characteristics, illustrated for same motor as Fig. 2

Synchronizing of Selsyn Units

Selsyn units are synchronized at standstill. Single-phase power is applied first, and, after a momentary time delay, 3-phase excitation is applied. Although the units may be synchronized 3-phase, synchronizing single-phase is more practical and eliminates certain difficulties.

If 3-phase power is applied to the 2 units and if the initial angle of displacement is large, then, if the 2 units are unrestrained, they may tend to come up in speed in the direction of the revolving field. One machine will serve as a short circuit for the rotor of the other. The machines will not assume any definite speed but will fluctuate. If one unit is restrained, the other may come up to speed as an induction motor. With single-phase excitation, this occurrence is avoided, for the only torque existing is the synchronizing torque and continuous traction is not possible. Once the units are synchronized, 3-phase power is applied and the Selsyn tie is operative.

Single-phase excitation may be applied in one of 3 ways as shown in Figs. 4, 5, and 6, respectively. In all cases, the rotors are interconnected 3-phase. Each connection has its particular torque-angle characteristic.

The connection of Fig. 6 is suitable for synchronizing. The maximum torque is high and occurs in the neighborhood of 150 electrical degrees, the region where the synchronizing torque is least for the other connections. A possible objection to this connection, for some applications, is the rapid decrease in torque for angles less than 90 deg. A convenient arrangement, from an operating point of view, is the sequence of connections of Fig. 6 and Fig. 4. The connection of Fig. 4 prepares for the next step, the simultaneous application of the 3-phase excitation to all units.

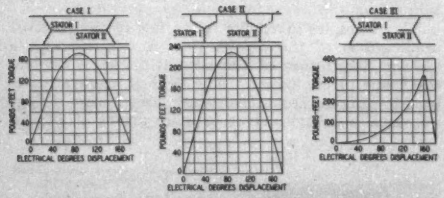


Fig. 4. Case I. Fig. 5. Case II. Fig. 6. Case II

Figs. 4, 5, and 6. Single-phase torque-angle characteristics at standstill for 3 different connections of same motors as illustrated in Fig. 2

The connection of Fig. 5 has the advantage that the magnetic flux is increased in the ratio of $2/\sqrt{3}$. The torque, like that of the connection shown in Fig. 4, varies as the sine of the displacement angle. For a given flux, the 2 connections have identical torque-angle characteristics at standstill. The connection of Fig. 5 has particular value when single-phase excitation is employed under running condition. This arrangement is poorest for induction motor action, but, on the same account, it is best for single-phase Selsyn operation.

Case I:

$$T = \frac{3.05\ V(I - I_m)}{\text{rpm}} \sin\theta \sin\alpha \text{ lb-ft} \tag{7}$$

$$I_l = \frac{\sqrt{3}}{2}\left(I_m \cos^2\frac{\alpha}{2} + I \sin^2\frac{\alpha}{2}\right) \tag{8}$$

Case II:

$$T = \frac{3.50\ V(I - I_m)}{\text{rpm}} \sin\theta \sin\alpha \text{ lb-ft} \tag{9}$$

$$I_l = \frac{2}{\sqrt{3}}\left(I_m \cos^2\frac{\alpha}{2} + I \sin^2\frac{\alpha}{2}\right) \tag{10}$$

The nomenclature is the same as for the 3-phase characteristics. The 3-phase induction motor values are determined for the slip of one and translated directly into single-phase synchronizing data.

The connection of Fig. 6 is a very special case and does not yield a simple solution. An analysis of this case is given in detail in Appendix II. For one thing, the magnetic flux varies with the displacement angle, increasing in the ratio of $\sqrt{2}$ for 90 deg displacement. The increased flux results in saturation and in an appreciable change in the several circuit constants. For this reason, the problem becomes involved and a rigorous solution difficult. It is to be noted that a definite second harmonic is present in the torque characteristic, which, in part, accounts for the decreased torque for the low values of displacement angle, and for the increased torque for the high values of displacement angle.

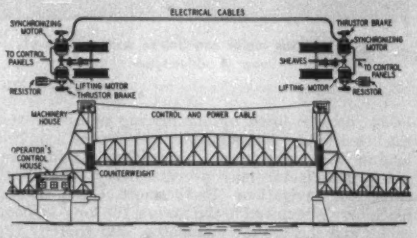


Fig. 7. Lift bridge operated by power Selsyn drive

Application of Selsyn Drives

A common and a simple application of Selsyn units is the tie of 2 parallel drives. An interesting arrangement is the synchronized drive for the long lift bridge, as shown in Fig. 7. The 2 ends of the bridge are lifted by separate motors. A power Selsyn unit is direct connected to each main motor and the 2 Selsyn rotors are electrically interconnected. The main motors, as well as the 2 Selsyn units, are energized from the same power source. The Selsyn units are first synchronized, and, after a short time delay, 3-phase power is applied to the 4 machines. By this tie, the 2 main motors are held

in step during acceleration and running, and the 2 ends of the bridge are lifted and lowered in synchronism. In addition to this feature, the synchronized drive embodies several other points of interest. By using 4 duplicate units, 2 for the main drives and 2 for the synchronous tie, the entire

Fig. 8. Lifting motor and Selsyn unit on top of tower of bridge span

bridge may be lifted by one driving motor in case the other fails. Although this will impose a double load on the acting motor, nevertheless, in an emergency, this factor may prevent delay to railway traffic and navigation. Furthermore, the operating machinery is removed to the towers, the long-haulage cables and sheaves are eliminated, and thereby the weight of the total span is substantially reduced. A lifting motor and Selsyn unit of this type are shown in Fig. 8.

The Selsyn tie is applied to synchronize a group of unit motor drives, as shown in Fig. 9, for the straight-line high-speed newspaper press. The Selsyn unit is built integral with each driving motor, as shown in Fig. 10. The entire group of Selsyn elements is energized from a common power source and all the rotor windings are electrically interconnected. The Selsyn units are first locked in step and when driven by their respective motors, start simultaneously and rotate in synchronism. Any unbalance in power between the several driving motors is equalized through the Selsyn units. The movement of any individual rotor in this combination is accompanied by a simultaneous and equivalent movement of each of the other rotors. The inherent function, therefore, of such a group of Selsyn units is to hold in step and resist any external force to pull them apart. In the event of failure of any driving motor, continuity of operation is assured. The Selsyn unit, deriving its energy from the other Selsyn units, will carry the total load of the individual drive. Such loading of the Selsyn unit is not generally recommended for long periods, but in an emergency, this feature is desirable. The application of the Selsyn tie to the segregated drive for newspaper presses made for greater flexibility and convenience. It made possible the complete elimination of all forms of interconnecting drive shafts, gears, and bearings commonly associated with the usual form of press drives, with possible savings in cost of labor and maintenance.

Selsyn units are used to synchronize auxiliaries with the main drive in many industrial equipments. A Selsyn generator is direct connected to the main motor and the several auxiliary units are driven by separate Selsyn motors. This form of a Selsyn tie is shown in Fig. 11, for the poidometer drive. In mill operations, it is often necessary to vary the kiln speed, and it is desirable to vary the feed in like manner. The tube mills, for instance, are fed with 2 materials and it is necessary to have close regulation of the proportions of the materials in order to insure uniformity of product. Also, to obtain a maximum satisfactory output of the mill, it is important to have control of the quantity of material carried on the conveyors. By adapting the Selsyn tie to the poidometer drive, the kiln may be operated at any desired rate with a corresponding change in

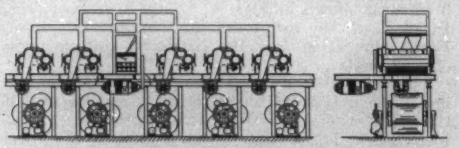


Fig. 9. Arrangement of motor drive with Selsyn tie-in, for straight line high-speed newspaper press

the conveyor speeds. In this manner, the proportions of the raw materials are fixed irrespective of the kiln speed.

The examples given are but a few of the possible applications of the Selsyn tie. A detailed and a specific description of the several drives is beyond the scope of the paper. The field of application is broad, ranging from fractional horsepower ratings for small auxiliary drives to main drives of 75 and

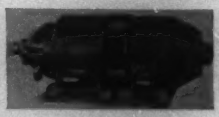


Fig. 10. Selsyn unit printing press drive

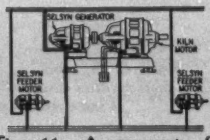


Fig. 11. Arrangement of Selsyn tie for poidometer drive

100 hp. The practicability of the Selsyn tie is fully recognized and its usefulness is more and more realized by the industrial engineer. The flexibility of the drive, the simplicity of operation, and the resulting economy will, no doubt, lead to the further adoption of the Selsyn principle to the synchronized motor drive.

Appendix I—Calculation of 3-Phase Characteristics

The equivalent circuit of 2 identical Selsyn units is the combined induction motor circuit for the 2 rotors in series. The electrical angle of displacement between the 2 rotors is equivalent to the same displacement between the Selsyn terminal voltages. The circuit constants are per phase star and are referred to the stator.

The equivalent circuit of Fig. 12 is resolved into the 2 component circuits of Fig. 13 and Fig. 14, respectively. The currents and voltages are determined for each component circuit, and, by superposition, are combined to give the currents and voltages of the original circuit.

The power transferred across the air gap is $E_g I_2 \cos \theta_2$, where E_g is the air gap voltage, I_2 is the rotor current, and θ_2 is the angle between them. In terms of the 2 component circuits, the power transferred is

$$P = P' + P'' \tag{11}$$

This is permissible, for the secondary current is common to the air gap voltages of the 2 component circuits.

$$P = E_g' I_2'' \cos \phi' + E_g'' I_2'' \cos \phi'' \tag{12}$$

where:

E_g' is air gap voltage of 1st component circuit
E_g'' is air gap voltage of 2nd component circuit
I_2'' is secondary current of 2nd component circuit
ϕ' is angle between E_g' and I_2''
ϕ'' is angle between E_g'' and I_2''

$$E_g' = \frac{jx_m E}{r_1 + j(x_1 + x_m)} \cos \frac{\alpha}{2}$$

$$= \frac{x_m E}{Z'} \cos \frac{\alpha}{2} \angle -\theta_1' + \frac{\pi}{2}$$

$$I_2'' = I_2 \sin \frac{\alpha}{2} \angle -\theta_2'' + \frac{\pi}{2}$$

$$\phi' = \theta_1' - \theta_2''$$

where:

$Z' \angle \theta_1'$ is the impedance of 1st component circuit
$I_2 \angle -\theta_2''$ is the induction motor rotor current for slip s
x_m is the induction motor magnetizing reactance

$$P' = \frac{x_m}{Z'} E I_2 \sin \frac{\alpha}{2} \cos \frac{\alpha}{2} \cos (\theta_1' - \theta_2'')$$

$$= \frac{x_m}{2Z'} E I_2 \sin \alpha \left[\sin \theta_1' \sin \theta_2'' + \cos \theta_1' \cos \theta_2''\right]$$

$$= \frac{E I_2 \sin \alpha}{2} \left[\frac{x_m(x_1 + x_m)}{(Z')^2} \sin \theta_2'' + \frac{r_1 x_m}{(Z')^2} \cos \theta_2''\right] \tag{13}$$

Equation 13 is rigorous, but, for convenience, it may be simplified by making the following assumptions:

$$\frac{x_m (x_1 + x_m)}{(Z')^2} = 1 - ab$$

$\frac{r_1 x_m}{(Z')^2}$ is negligible

$$I_2 \sin \theta_2'' = I \sin \theta_1'' - I_m$$

$$P' = \left[\frac{I^2 x_0}{2} - \frac{I_m^2 x_m}{2}\right] (1 - ab) \sin \alpha \tag{14}$$

where:

I is the induction motor current for slip s
I_m is the induction motor magnetizing current
x_0 is total induction motor leakage reactance
x_m is induction motor magnetizing reactance

$$ab = \frac{I_m x_0}{E}$$

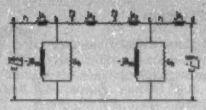


Fig. 12. The equivalent circuit of 2 identical Selsyn units

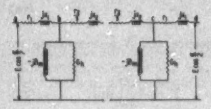


Fig. 13. The first component circuit

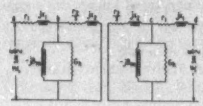


Fig. 14. The second component circuit

$$P'' = \frac{I_2^2 r_2}{s} \sin^2 \frac{\alpha}{2}$$

$$= \frac{I^2 r_2}{s} (1 - ab) \sin^2 \frac{\alpha}{2} \tag{15}$$

Combining eq 14 and 15, the Selsyn transmitter torque, for rotation opposite to the magnetic field, is:

$$T_t = \frac{21.1}{\text{rpm}} I^2 (1 - ab) \left[\left(\frac{x_0}{2} - \frac{a^2 x_m}{2}\right) \sin \alpha + \frac{r_2}{s} \sin^2 \frac{\alpha}{2}\right] \text{lb-ft} \tag{16}$$

Similarly, the receiver torque:

$$T_r = \frac{21.1}{\text{rpm}} I^2 (1 - ab) \left[\left(\frac{x_0}{2} - \frac{a^2 x_m}{2}\right) \sin \alpha - \frac{r_2}{s} \sin^2 \frac{\alpha}{2}\right] \text{lb-ft} \tag{17}$$

where:

rpm is the induction motor synchronous speed
r_2 is the induction motor secondary resistance
s is the induction motor slip
α is the displacement angle between rotors in electrical degrees

$$a = \frac{I_m}{I}$$

The transmitter current:

$$I_t = \left(I_m \cos \frac{\alpha}{2} + jI \sin \frac{\alpha}{2}\right) \angle -\frac{\alpha}{2} \tag{18}$$

The receiver current:

$$I_r = \left(I_m \cos \frac{\alpha}{2} - jI \sin \frac{\alpha}{2}\right) \angle \frac{\alpha}{2} \tag{19}$$

The line current:

$$I_l = 2 \left(I_m \cos^2 \frac{\alpha}{2} + I \sin^2 \frac{\alpha}{2}\right) \tag{20}$$

The rotor current:

$$I_R = jI_2 \sin \frac{\alpha}{2} \tag{21}$$

But for a small error, eq 16 and 17 may be written in the following form, as presented in the text:

$$T_t = \frac{6.09\, V}{\text{rpm}} (I - I_m) \sin \theta \sin \alpha + T_s \sin^2 \frac{\alpha}{2} \text{ lb-ft} \tag{22}$$

$$T_r = \frac{6.09\, V}{\text{rpm}} (I - I_m) \sin \theta \sin \alpha - T_s \sin^2 \frac{\alpha}{2} \text{ lb-ft} \tag{23}$$

THE SINGLE-PHASE SYNCHRONIZING TORQUES

The method employed for the 3-phase calculations may be extended for the first 2 cases of the single-phase excited units. The direct-phase and reverse-phase-sequence voltages are determined and the corresponding currents and torques calculated. For case I, the component voltages at standstill are:

$$E_D = E_R = \frac{E}{2} \tag{24}$$

Where D denotes direct-phase sequence and R reverse-phase sequence.

$$T_D = \frac{1}{4}\left[\frac{6.09V}{\text{rpm}}(I - I_m)\sin\theta\sin\alpha - T_0\sin^2\frac{\alpha}{2}\right] \text{ lb-ft} \tag{25}$$

$$T_R = \frac{1}{4}\left[\frac{6.09V}{\text{rpm}}(I - I_m)\sin\theta\sin\alpha + T_0\sin^2\frac{\alpha}{2}\right] \text{ lb-ft} \tag{26}$$

$$T = T_D + T_R = \frac{3.05V}{\text{rpm}}(I - I_m)\sin\theta\sin\alpha \text{ lb-ft} \tag{27}$$

Similarly for case II:

$$E_D = E_R = \frac{E}{\sqrt{3}} \tag{28}$$

And

$$T = T_D + T_R = \frac{3.50\,V(I - I_m)}{\text{rpm}}\sin\theta\sin\alpha \text{ lb-ft} \tag{29}$$

The nomenclature is the same as for the 3-phase case. All the actors are determined for locked-rotor 3-phase induction motor.

Appendix II—Single-Phase Characteristics of Case III

The stators and rotors are connected as shown in Fig. 6. Deflecting one rotor from the other is equivalent to displacing the 2 stator fields by the same angle. If the angle of deflection between the 2 rotors is α, the stators may be represented diagrammatically as shown in Fig. 15.

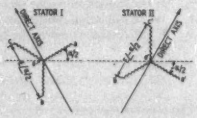


Fig. 15. Schematic diagram of the 2 single-phase fields

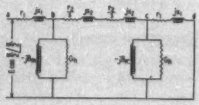


Fig. 16. Three-phase impedance offered to the in-phase voltage component

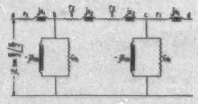


Fig. 17. Three-phase impedance offered to the quadrature voltage component

Let voltage $E\angle - \alpha/2 = 0$. Refer $E\angle\alpha/2$ to the direct axis of stator II, namely $(E\angle\alpha/2)(\cos\alpha - j\sin\alpha)$. $E\cos\alpha\angle\alpha/2$ induces no voltage in phase $0'a'$. For this component, the short circuit may be considered 3 phase. The impedance offered to $E\cos\alpha\angle\alpha/2$ is a balanced 3-phase secondary impedance as represented by the circuit of Fig. 16.

$-jE\sin\alpha\angle\alpha/2$ induces no voltage in phases $0'b'$ and $0'c'$. For this component, the 2 phases may be considered open circuited. The impedance offered to $-jE\sin\alpha\angle\alpha/2$ is a balanced 3-phase secondary impedance represented by the circuit of Fig. 17.

Similarly let $E\angle\alpha/2 = 0$. Refer voltage $E\angle - \alpha/2$ to the direct axis of stator I, namely $(E\angle - \alpha/2)(\cos\alpha + j\sin\alpha)$. The impedance of Fig. 16 and Fig. 17 is now offered to $E\cos\alpha\angle - \alpha/2$ and $jE\sin\alpha\angle - \alpha/2$, respectively.

The several voltages are further resolved into the in-phase and quadrature components:

Voltages at a	Voltages at d
$E\cos\alpha\cos\alpha/2$	$E\cos\alpha\cos\alpha/2$
$jE\cos\alpha\sin\alpha/2$	$-jE\cos\alpha\sin\alpha/2$
$-jE\sin\alpha\cos\alpha/2$	$jE\sin\alpha\cos\alpha/2$
$E\sin\alpha\sin\alpha/2$	$E\sin\alpha\sin\alpha/2$
$jKE\sin\alpha\cos\alpha/2$	$-jKE\sin\alpha\cos\alpha/2$
$KE\sin\alpha\sin\alpha/2$	$KE\sin\alpha\sin\alpha/2$

Inspecting the 6 sets of component voltages, it may be noted that 3 pairs are in phase addition and 3 in phase opposition. One set of 3 operates on the open-circuit impedance of Fig. 13 and the other on the short-circuit impedance of Fig. 14. The 2 voltages are designated by E' and E''.

$$E' = E(\cos\alpha\cos\alpha/2 + (1 + K)\sin\alpha\sin\alpha/2) \tag{30}$$

$$E'' = jE(\cos\alpha\sin\alpha/2 - (1 - K)\sin\alpha\cos\alpha/2) \tag{31}$$

E' and E'' are single-phase voltages producing pulsating fields. The 2 pulsating fields are each resolved into the 2 rotating fields of direct and reverse-phase sequence which, at standstill, are $E'/2$ and $E''/2$.

As for case I and case II:

$$T = T_D + T_R = \frac{21.1}{2\,\text{rpm}}Eg'I_s''\cos\phi' \quad \text{lb-ft} \tag{32}$$

where:

Eg' is the air gap voltage of the open circuit
I_s'' is the secondary current of the short circuit
ϕ' is the angle between Eg' and I_s''
rpm is the synchronous speed

The factor K is an impedance ratio. It is determined from the circuit of Fig. 17.

$$K = \frac{E_d}{E_a} \tag{33}$$

where E_a and E_d are the voltages at a and d, respectively.

References

1. SYNCHRONIZED DRIVES WITHOUT MECHANICAL CONNECTIONS, H. W. Reding. *Elec. Jl.*, v. 30, 1933, p. 277–80.

2. THE APPLICATION OF THE SYNCHRONOUS TIE TO MODERN CONTROL PROBLEMS, R. H. Wright. *Iron and Steel Engr.*, v. 10, 1933, p. 123–30.

3. SYNCHRONIZED MECHANICAL MOTION WITHOUT MECHANICAL CONNECTION, C. W. Drake. *Maintenance Engg.*, v. 90, 1932, p. 441–3.

4. SELSYN CONTROL FOR PAPER MACHINES, F. M. Roberts. *Paper Trade Jl.*, v. 95, 1932, p. 18–20.

5. SAFEGUARDING AND CONTROLLING SEQUENCE OPERATIONS, R. H. Rogers. *Elec. World*, v. 99, 1932, p. 372–5.

6. SYNCHRONIZING CONVEYORS BY PHOTOCELLS AND SELSYNS, W. B. Snyder. *Elec. World*, v. 99, 1932, p. 327.

7. SELSYN DEVICES AND THEIR APPLICATIONS, L. W. Bailey. *Combustion*, v. 3, 1931, p. 21–5, 39, 46.

8. VERSATILITY OF APPLICATION OF SELSYN EQUIPMENT, R. A. Corley. *Gen. Elec. Rev.*, v. 33, 1930, p. 706–11.

9. APPLICATION OF SELSYN REMOTE CONTROL IN THE OIL REFINING INDUSTRY, L. De Florez. *Gen. Elec. Rev.*, v. 33, 1930, pp. 378–83.

10. PRINCIPLES OF SELSYN EQUIPMENTS AND THEIR OPERATION, L. F. Holder. *Gen. Elec. Rev.*, v. 33, 1930, p. 500–4.

11. METER READINGS AND SIGNALS TRANSMITTED BY SELSYN MOTORS, A. B. Bailey. *Power*, v. 68, 1928, p. 434–5.

Corona Losses From Conductors of 1.4-Inch Diameter

A sequel to an earlier paper by Carroll and Cozzens concerning corona loss measurements for the design of transmission lines, this paper presents data resulting from comparative tests on 6 different designs of 1.4-in. conductor, the size selected for a 275-kv transmission line from Boulder Dam to Los Angeles. Data covers 3-phase, single-phase, and rain tests, and adds materially to the corona loss data previously reported.

By
JOSEPH S. CARROLL
ASSOCIATE A.I.E.E.
Director, Ryan Laboratory, Stanford University, Calif.

BRADLEY COZZENS
ASSOCIATE A.I.E.E.

THEO. M. BLAKESLEE
ASSOCIATE A.I.E.E.
Research Engineers, Dept. of Water and Power, City of Los Angeles, Calif.

FROM CORONA LOSS tests sponsored by the Los Angeles Department of Water and Power at the Harris J. Ryan high voltage laboratory at Stanford University[1] and other previous tests,[2] a corona loss formula was developed from which an economic diameter of 1.4 in. was determined for the department's 275-kv transmission line from Boulder Dam to Los Angeles. In response to the specifications for the 1.4-in. conductor, the 6 different designs shown in Fig. 1 were submitted by various manufacturers.

During 1933 the Department of Water and Power conducted further tests at the Ryan laboratory, using factory samples of each of the 6 designs, as a result of which the following conclusions were reached:

1. The importance of the die grease as affecting corona loss was further emphasized by the 1933 tests.

2. Complete grease removal either by thoroughly washing, or by washing in connection with a period of aging, is necessary to obtain consistent corona loss data.

3. Both gasoline and soap and water washings are necessary to accomplish complete cleaning of the cables.

4. Rain greatly increases the corona loss from conductors, but there appears to be little correlation between loss and rainfall rate.

5. While the differences in the corona loss for separate types of 1.4-in. stranded conductors are slight, the tests indicate that the size of the outside strands and the neatness of the stranding are factors affecting corona.

6. Smooth, properly formed segment conductors have a lower corona loss than stranded conductors of the same diameter.

7. The smoothness of the segments is of prime importance in eliminating loss from a segment type of conductor.

Details of procedure and results are given in the following text and illustrations.

Test Arrangement and Procedure

Samples were furnished for a 3-phase test line 700 ft long and were erected in 2 equal spans of horizontal configuration, 30-ft spacing, 30-ft ground clearance and 16-ft sag. With slight modifications, the test arrangement was the same as that used in the 1931 tests, and the measurements were made with the same equipment and in the same manner as previously described.[1]

In each insulator string supporting the test line, 20 units of 10-in. diameter were used. The line end of each string was shielded with a torus of 3-ft outside diameter made up of 6-in. stove pipe elbows and the ground end of each string was shielded with the 2-ft aluminum radio shield previously described.[2] Suspension clamps were shielded further by smooth housings 6-in. in diameter. Fig. 2 shows the dead-end assembly and the suspension shield fittings. Insulators thus shielded showed no visible corona at line voltages up to 600 kv under dry weather conditions.

Although the set-up was free from insulator loss for the dry conditions, previous experience[2] indicated that the loss over the insulators when damp could not be ignored. One duplicate dead end and one duplicate suspension string were erected in the open near the line and power loss over these strings was measured simultaneously with the line loss. When for a line voltage of 395 kv the loss over the two strings was greater than 10 watts, the values as read were multiplied by the proper value and subtracted from the total power to give the correct corona loss.

In the two cases where loss measurements were obtained during rain, a burette tube equipped with a large mouthed multiplier was placed in proximity to the line and, from readings taken on this tube at definite intervals, curves were drawn from which the rainfall rate could be determined.

Past experience[1,2,4,7] has shown that die grease or other lubricants used in the manufacture of cable greatly affect the corona loss. In most of the tests here described the loss measurements were obtained on the conductor as received from the factory. As

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 9, 1933. Reprinted for Stanford University.

1. For all numbered references, see list at end of paper.

Fig. 1. Sections of the various designs submitted for the large sized conductors required for the 275-kv line to carry Boulder Dam power to the City of Los Angeles

Type A. A copper conductor made up of a 7-wire strand surrounded by 6 twisted I-beams with a single layer of round wires over all. The outer layer is composed of 30 wires each 0.125 in. in diameter having an 11-in. right hand lay.

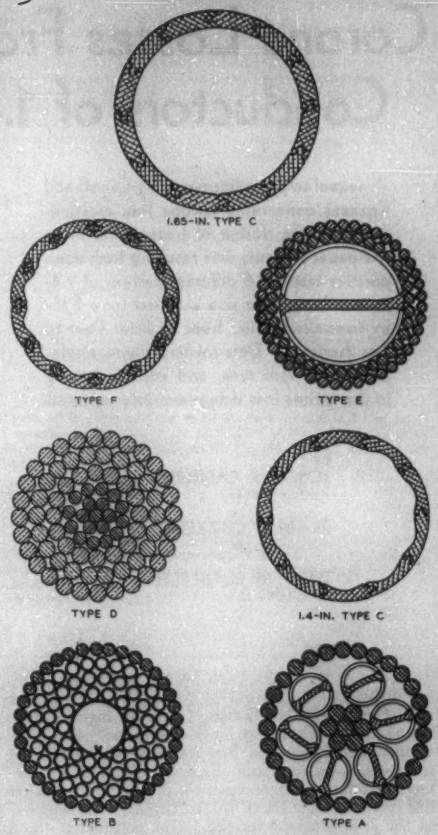
Type B. A copper conductor with an inner structure composed of a central tube surrounded by layers of smaller tubes with a single outside layer of 37 solid round wires each 0.104 in. in diameter and with a 14-in. left hand lay.

Type C. A hollow copper conductor made up of 10 segments with a 28-in. right hand lay. The segments are interlocked, forming a self supporting structure presenting a smooth outer surface. The 1.65-in. type C cable was of similar construction, but made up of 12 segments having a 34-in. right hand lay.

Type D. An aluminum conductor steel reinforced, having 28 outside strands each 0.1355 in. in diameter with a 14.5-in. left hand lay.

Type E. A copper conductor of the regular twisted I-beam construction having 2 layers of round wires, the outside layer made up of 37 wires each 0.1077 in. in diameter with a 10.9-in. right hand lay.

Type F. A hollow copper conductor made up of 12 segments with a 19-in. right hand lay. The segments are grooved to fit an oval wire which holds them together. The surface of each segment has a shorter radius of curvature than that of the conductor, a feature which tends to "submerge" the seams between strands.



in previous tests, the cables then were lowered and washed with gasoline followed by a scrubbing with soap and water and a thorough rinse with clear water. A loss measurement followed this treatment. After weathering for some time, the cables were given an additional cleaning with fiber brushes and clear water and again tested. This procedure was modified for some particular cables and situations; for example, to determine if it was necessary to follow the gasoline washing with the soap washing and water rinsing, the type *B* cable was tested after the gasoline washing and again after the soap-and-water treatment.

The first sample tested in the 1933 series was the 1.65-in. type *C* conductor. Special tests on this cable included measurements taken hourly over a 19-hr period; also during rain, and before and after the application of a dust layer (half clay and half feldspar) to the cable. Four days later grease was

Fig. 2. Dead end insulator assembly and detail of suspension string shield used in tests

Fig. 3. Interior grease spreading over exterior surface of 1.65-in. type C (tubular segment) cable

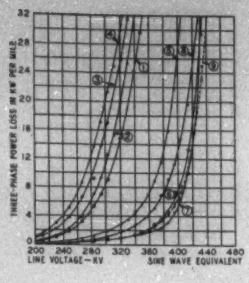


Fig. 4 (left). Three-phase corona loss curves for type A cable

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	3-21-33	As Received (paper wrapped)	29.91	32	62.0	73.0
2	3-22-33	1 day later	29.86	52	53.0	60.0
3	3-24-33	3 days later	30.14	62	55.0	59.5
4	3-30-33	9 days later	30.02	58	60.0	70.0
5	4- 3-33	After gasoline, soap and water washing	29.78	53	71.5	82.0
6	4-12-33	After clear water washing	29.99	31	73.0	86.0
7	4-14-33	2 days later	29.79	27	77.5	83.0
8	4-18-33	6 days later	29.85	45	57.0	66.0
9	5- 9-33	After 2d clear water washing	29.85	50	53.0	58.0

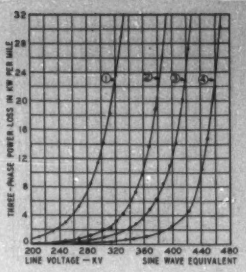


Fig. 5. Three-phase corona loss curves for type B cable

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	5-11-33	As received	29.96	60	56.0	61.0
2	5-12-33	After gasoline washing	29.97	61	58.0	64.0
3	5-16-33	After soap and water washing	29.95	62	59.5	62.0
4	5-31-33	After clear water washing	29.83	40	65.5	70.0

Curve 4 based on single phase measurements on lines 1 and 2.

observed spreading over the surface of the cable from the segment interstices. Fig. 3 shows how plainly this spreading grease was indicated by the dust layer.

The construction of the type *C* and type *F* conductors permitted the circulation of gasoline through their interiors. Profiting by the experience with the 1.65-in. type *C* conductor, the 1.4-in. types *C* and *F* conductors were flushed prior to the regular exterior cleaning by circulating gasoline through each sample for from $1^1/_2$ to 2 hours, followed by air circulation for an equal period. The effect of this cleaning on the corona loss was so marked that the 1.65-in. type *C* cable was retested with gratifying results after similar treatment.

Single phase measurements obtained on single conductors with the other 2 conductors grounded helped to emphasize the importance of surface condition, especially grease, as it affects corona loss.

Tests on Type *A* Conductor

Three-Phase Tests. The range of power losses revealed by a series of 3-phase tests on type *A* cable is shown by the curves of Fig. 4. The cable was brushed with fiber brushes at the factory and upon receipt at the laboratory the three lengths were taped with heavy wrapping paper to preserve the surface as received. Loss measurements obtained on this cable 1, 2, 4, and 10 days after it was erected are reflected in curves 1 to 4 which show the progressive shift of the loss curves toward the low voltage abscissa due to the grease spreading over the surface from within the cable.

Curve 5 gives the loss on this same cable immediately after a gasoline, soap and water washing, and reveals that a shift of 60 kv was accomplished by the cleaning. Loss measurements taken 1, 5, and 8 days after the same washing gave less than 5 kv shift from curve 5 and are not plotted.

Nine days after the same washing the cable was washed in clear water and again tested. The results as given by curve 6 show a shift of from 40 to 50 kv from curve 5. Curve 7 shows the loss on this same cable 2 days after the clear water wash as being slightly less at the bend portion of the curve. A brisk wind during the time curve 7 was obtained was the only thing to make it different from curve 6. Six days after the clear water wash the loss had increased to a value as shown by curve 8, and within another 2 days it was practically identical with the values of curve 5. Some of this increase in loss could have been caused by light rain during the interim[2] although more probably it was caused by grease working to the surface of the cable. After 12 days of generally cool and cloudy weather the loss curve moved back to lower loss values approximating those of curve 7.

Approximately a month after the clear water washing the cable was given a second clear water wash and immediately tested again. These results, as shown in curve 9, closely approximate those of curves 6 and 7, and well represent the corona loss from a clean cable of the type *A* construction.

Single-Phase Tests. Single-phase corona losses from the individual conductors of the test line were obtained for 3 conditions: (1) as received, (2) after gasoline, soap and water washing, and (3) after first clear water washing. As received, the loss on line 3 (the conductors of the test span were designated lines 1, 2, and 3 with line 2 the center conductor) was appreciably greater than the loss on lines 1 and 2. After the gasoline, soap, and water wash the difference in loss between individual conductors was less, and was decreased further after the clear water wash. Part of these variations may be due to difference in the cable surface, but, from tests on this and other types of conductor, it is apparent that the principal difference is in the amount of grease on the cable surface.

Tests During Rain. Inasmuch as previous measurements[2] have indicated a large increase in corona loss during rain, a few single phase measurements on the greasy type *A* cable as received from the factory were made during rain periods with concomitant measurement of rainfall. The measurements were

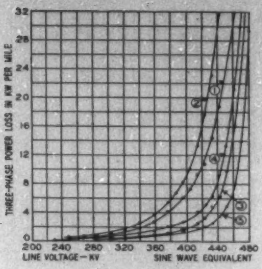


Fig. 6. Three-phase corona loss curves for 1.4-in. type C conductor

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	6- 2-33	As received (paper wrapped)	29.88	44	61.0	66.0
2	6- 5-33	4 days later (paper wrapped)	29.81	56	65.0	68.0
3	6- 8-33	After gasoline, soap and water washing	29.91	25	76.0	88.0
4	6-22-33	14 days later	29.84	42	72.0	76.0
5	6-23-33	After clear water washing	29.86	36	70.0	78.0

made at 185 kv to ground on line 1, simultaneously taking readings of total line loss, of insulator loss, and on the rain gage. The loss did not show the expected variation with rainfall rate because, although this value varied from as much as 0.12 in. per hour to less than 0.005 in. per hour, the corona loss varied only from 40 kw per mile to 32 kw per mile. The corresponding single phase, dry weather loss on the same conductor was approximately 2 kw per mile. The foregoing wet weather values were corrected for insulator loss as previously described.

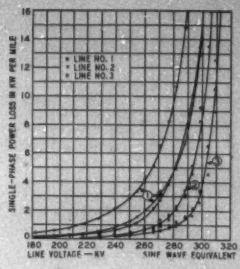
Tests on Type *B* Conductor

Three-Phase Tests. Power losses for the type *B* cable, as revealed by 3-phase tests are shown by the curves of Fig. 5. This cable received no cleaning at the factory and hence, though well stranded, was very greasy. Erected without the protective paper covering, and as received from the factory, this cable had a corona loss as shown in curve 1. Washed in gasoline only the day after erection, the cable showed (curve 2) a shift of about 70 kw from the "as received" condition. Four days later the cable was given the soap and water cleaning, which caused a further shift of 35 kv (curve 3). A loss curve taken two days later showed a shift of less than 5 kv and is omitted. The fact that each treatment gave a decided shift in the loss curves indicates that both the gasoline and the soap and water cleaning are necessary. It being necessary to accelerate the tests, two lengths of type *B* cable were left in position as lines 1 and 2 and a single length of type *E* cable was substituted for line 3, requiring the remaining measurements on type *B* cable to be made single phase.

Three-phase power loss may be approximated

Fig. 7 (right). Single-phase corona loss curves for 1.4-in. type C cable

Curve Set	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	6- 2-33	As received	29.91	37	63.0	74.0
2	6- 8-33	After gasoline, soap and water washing	29.91	34	75.0	86.0
3	6-23-33	After clear water washing	29.86	46	68.0	76.0



from the single phase measurements, the conversion involving the premise that corona loss is dependent upon the voltage gradient surrounding the conductor. Since, for the same conductor under different conditions equal charging currents indicate equal gradients, it should be true that equal charging currents would be accompanied by equal corona losses. From a straight line relation of charging currents with respect to voltage for single phase and 3-phase conditions, the equivalent single phase and 3-phase voltages corresponding to any particular value of charging current and, by premise, to any particular value of corona loss may be obtained. Because of less definite factors than gradient (space charge[6]), three-phase loss curves obtained by this method are generally lower than curves from actual 3-phase tests, but the accuracy is sufficient to allow conversion when 3-phase data are lacking. Curve 4 of Fig. 5 gives the 3-phase results obtained by the above conversion method on the type *B* cable after the clear water rinse. This additional rinse shifted the loss approximately an additional 55 kv.

Single-Phase Tests. Single-phase measurements made on the individual conductors as received, showed lines 2 and 3 to have similar loss values with line 1 having a lower loss value equivalent to a shift of from 25 to 30 kv. After the gasoline washing, the curves for all 3 lines showed less than a 10-kv separation. A further test after the soap and water wash showed lines 1 and 3 to have practically identical loss, with line 2 having the greater loss by a voltage shift of about 10 kv.

Tests on 1.4-In. Type *C* Cable

Three-Phase Tests. Results of 3-phase tests on 1.4-in. type *C* cable are shown in the curves of Fig. 6. This cable was washed exteriorly at the factory, and at the laboratory was taped with wrapping paper to protect the surface, but prior to erection the paper became discolored by grease working to the surface from within the conductor. Loss measurements taken on the cable in this condition are given by curve 1. Four days after erection a second loss measurement gave considerable higher loss values (curve 2) as a result of the grease spreading over the cable surface. Inasmuch as the exterior cleaning obviously would not have been sufficient for a satisfactory test, the cable was given an interior flushing as already described.

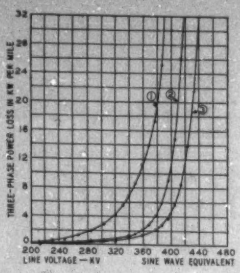


Fig. 8 (left). Three-phase corona loss curves for type D cable

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Air	Temp. Deg F Cable
1	7- 6-33	As received	29.68	45	77.0	90.0
2	7-11-33	After gasoline, soap and water washing	29.75	26	93.0	102.0
3	7-27-33	After clear water washing	29.63	31	86.0	100.0

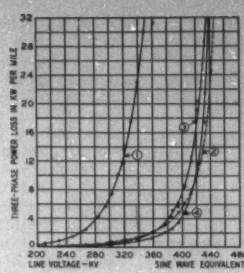


Fig. 9. Three-phase corona loss curves for type E cable

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Air	Temp. Deg F Cable
1	8- 2-33	As received	29.90	50	74.0	84.0
2	8- 3-33	After gasoline, soap and water washing	29.92	52	71.0	.....
3	8-11-33	8 days later	29.71	36	81.0	94.0
3	8-16-33	13 days later	29.88	51	81.0	95.0
4	8-16-33	After clear water washing	29.77	36	90.0	100.0

Curve 3 gives the corona loss after the interior flushing and the exterior gasoline, soap and water wash. It will be observed that the shift at the bend portion of the curve is greater than at the higher voltage values, showing that the grease is primarily effective in *starting* corona. Loss curves were obtained 5 and 14 days after this cleaning and the latter curve is presented as curve 4.

As with the other types of cable, a clear water rinse shifted the loss to still lower values (curve 5). A test made 7 days later gave a loss curve identical with curve 3, whereas a further test made 12 days later and under adverse weather conditions showed the loss to have increased until the curve was practically identical with curve 4. This latter shift can be explained by the results of study by graduate students at Stanford University[6] which showed that the amount by which corona loss varies with increased humidity is dependent upon the foreign matter on the surface of the conductor. Thus the 12-day accumulation of dust and other foreign matter on the 1.4-in. type *C* cable gave a higher loss with the high humidity than would be encountered under dry weather conditions.

Single-Phase Tests. The 3 sets of curves in Fig. 7 show the corona loss of individual conductors (1) as received, (2) after a gasoline, soap and water wash, and (3) after further clear water rinse. While the curves for the cable as received show a difference in excess of 15 kv, it may be seen that after each washing treatment the separation between individual samples is very slight.

Tests on Type *D* Cable

Three-Phase Tests. Results of 3-phase tests on type *D* cable are shown in the curves of Fig. 8. Although this cable was given the regular factory cleaning normally applied to this type of conductor, it still carried considerable grease. To prevent accretion of dust and dirt, the cable was prevented from coming in contact with the ground during erection. Curve 1 gives the loss as erected, and tests made 4 days later gave practically the same values.

In an attempt to clean this cable thoroughly, practically twice the gasoline used on other cables was used and the cable was rinsed in gasoline prior to the soap and water washing. Curve 2 gives the corona loss after this washing and, as with the type *C* cable, shows the shift to be greatest at the bend portion of the curve. Tests 9 and 15 days after washing showed little shift from curve 2. Even with this thorough initial cleaning, a subsequent washing with clear water shifted the loss curve still farther, as shown by curve 3. Single-phase loss measurements taken 5 days after the clear water washing showed little difference from those taken immediately after that washing.

Single-Phase Tests. This cable was no different in action under single-phase measurements than any others. Differences between individual conductors when initially tested became less after the gasoline, soap and water wash and still less after the clear water rinse.

Tests on Type *E* Cable

Three-Phase Tests. Curves of Fig. 9 show the results of 3-phase tests on type *E* cable. This cable was cleaned at the factory with rotating brushes, and was erected without protective covering. Curve 1 shows the corona loss on this cable as received. To accomplish a thorough cleaning of this cable, 2 gasoline rinses followed the regular brushing with gasoline. Tests made after the gasoline, soap and water washing showed a shift of more than 100 kv, as indicated in curve 2. Measurements made 8 and 13 days later gave values as shown by curve 3, with little difference between the 2 measurements. That the initial cleaning was thorough is shown by the slight shift (curve 4) following the final washing with clear water.

Single-Phase Tests. Contrary to the condition with the other cables, the loss on the individual conductors for the type *E* cables as received was practically identical. After gasoline, soap and water

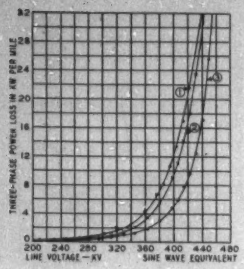


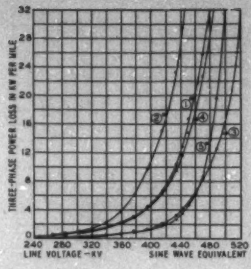
Fig. 10. Three-phase corona loss curves for type F cable

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	8-18-33	After gasoline, soap and water washing	29.73	57	73.0	84.0
2	8-29-33	10 days later	29.81	44	70.0	75.0
3	8-29-33	After clear water washing	29.81	48	73.0	82.0

Curves 2 and 3 based on single-phase measurements on lines 2 and 3

Fig. 11 (right). Three-phase corona loss curves for 1.65-in. type C cable

Curve No.	Date	Condition	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	9-1-33	2 days after gasoline, soap and water washing	30.13	60	45.5	58.0
2	9-21-33	22 days after gasoline, soap and water washing	29.99	45	62.0	73.0
3	9-24-33	After clear water wash	30.13	25	60.5	67.0
4	3-18-33	22 days after clear water wash	30.22	51	59.0	69.0
5	9-7-33	After second gasoline, soap and water wash	29.57	20	82.0	94.0



washing there was a slight difference that did not change appreciably with the clear water rinsing.

Tests on Type *F* Conductor

Three-Phase Tests. Results of 3-phase tests on type *E* cable, of tubular construction, are reflected in the curves of Fig. 10. This cable received no cleaning at the factory, but was flushed with gasoline before erection. Because grease continued to ooze from the cable a second flushing was required, after which the regular exterior gasoline, soap and water treatment was given. The resulting loss is given by curve 1. An accident prevented further 3-phase tests being made, so the remainder were made single phase and converted as previously described.

Single-Phase Tests. The single-phase tests showed the characteristic difference in loss from individual conductors. After the clear water washing, some difference still existed between conductors 2 and 3, though they were free from grease. Single phase loss measurements taken 10 days after the soap and water cleaning, and converted to 3-phase values, are given by curve 2. The results after the clear water wash as obtained by the same method are given by curve 3.

Tests on 1.65-In. Type *C* Conductor

Three-Phase Tests. Curves of Fig. 11 reflect the results of tests on the 1.65-in. type *C* tubular conductor. This was the first conductor tested during 1933. At the close of the tests on the 1.4-in. cables, the larger cable was flushed with gasoline and given a second gasoline, soap, and water washing. The cable was initially erected in wet weather so was given the normal exterior gasoline, soap and water wash before testing. The first loss measurement (curve 1) was made 2 days after the initial washing, a slight rain occurring in the interim. Measurements obtained a day later showed a slightly lower loss, whereas those obtained 22 days after the initial washing gave appreciably higher losses (curve 2). This increased loss was found to result, first, from the spreading of grease over the cable surface from between the segments and, second, from the accumulation of bird dung on the cable. Consequently, the cable was washed with clear water and tested again (curve 3).

Tests made to determine the effect of dust on the cable surface showed that as long as the cable was dry the change in loss was negligible. Another test on the same cable made 22 days later however, yielded the results shown in curve 4, revealing that grease and more bird dung had accumulated. After this the cable was stored for 6 months and then flushed and rewashed with gasoline, soap and water, whereupon another test yielded the data shown in curve 5.

Tests made with loss measurements taken hourly over a 19 hour period were made immediately after the dust, grease, and bird dung were removed. Though previous experience had shown the loss to vary appreciably after nightfall and with increasing humidity, these tests showed a maximum shift in the loss curves of less than 20 kv, undoubtedly due to the absence of foreign matter on the cable as previously mentioned.[8]

Rain tests and single phase measurements on this cable exhibited nothing different from that mentioned with respect to other cables.

Recapitulation

After Gasoline, Soap and Water Washing. The corona loss curves for all cables tested in 1933 together with the 1.49-in. and 2-in. cables tested in 1931[1] are presented in Fig. 12. Type *A* (curve 1) shows the highest loss, possibly due to incomplete grease removal, difficulty in obtaining smooth stranding with the multiple I-beam construction, and larger diameter of strands in the outer layer. The type *B* cable (curve 2) appears to be slightly high for this type of cable, possibly due to incomplete cleaning. The type *D* cable (curve 3) having large strands and possibly being not completely clean, also is high. Curve 4 for the type *E* cable probably is the best that can be expected from a clean, well made cable of this diameter having small wire strands. The

type *E* cable shows a lower loss than the 1.49-in. stranded cable (curve 5) tested in 1931, possibly due partly to a less complete washing of the latter cable and partly to the fact that the type *E* cable was stranded better and was brush-cleaned at the factory. Curve 6 for the 1.4-in. type *C* conductor in a thoroughly clean condition shows the advantage of this type of conductor, from a corona loss standpoint, over conventional stranded cable of the same diameter. The segment type of conductor (type *F*, curve 7) shows loss values very close to those for stranded cables of the same diameter. Curve 8 shows the corona loss for the 1.65-in. type *C* conductor after being cleaned inside and out with gasoline and with the exterior soap and water washing. The loss for the 2-in. cable from previous tests, after the standard gasoline, soap and water wash, is given by curve 9.

After Clear Water Wash. Fig. 13 gives the corona loss curves for all the 1.4-in. conductors tested. These curves give a better laboratory comparison of corona loss performance than the conditions given in Fig. 12, although the latter curves probably represent more nearly the conditions that might be encountered in practice. The type *A* cable (curve 1) still shows the highest loss, probably due to larger strands and to difficulty in obtaining a smooth contour with this type of construction. The types *D* and *E* cables (curves 2 and 3) show almost identical loss although type *D* has appreciably larger strands. The type *B* cable (curve 4) was obtained from single phase measurements, which gives lower loss values; however, all the shift cannot be accounted for by this fact and may be attributed to the exceptionally smooth stranding and small wires in the outer layer. The type *F* conductor (curve 5) although showing a relatively low loss in the higher voltage range has a high loss in the low voltage or operating range. This probably is due to roughness of the individual segments and to the arched segment construction used. As was the case with the previously described condition, the type *C* conductor (curve 6) showed the lowest loss of any of the 1.4-in. conductors. No tests were available on the 1.65-in. type *C* conductor. Referring to curve 8 of Fig. 11 for the 1.65-in. type *C* conductor, it may be seen that it has practically the same loss as the 1.4-in. type *C* conductor after the latter had a second clear water rinse. The 1.4-in. conductor was manufactured in the United States and was a smoother job than the 1.65-in. conductor which was of foreign make.

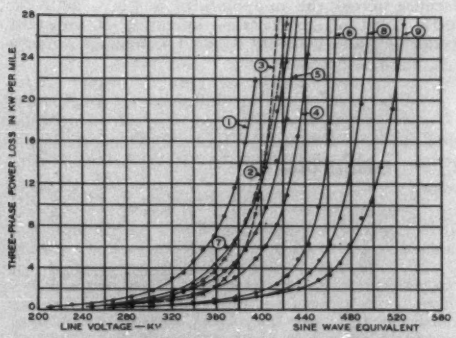


Fig. 12. Corona loss curves for all cables after gasoline, soap and water washing

Curve No.	Date	Cable	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	4- 3-33	Type A	29.78	53	71.5	82.0
2	5-16-33	Type B	29.95	62	59.5	62.0
3	7-11-33	Type D	29.75	26	93.0	102.0
4	8- 3-33	Type E	29.92	52	71.0	
5	10-27-31	1.49-in. stranded copper	30.05	27	71.0	80.0
6	6- 8-33	1.4-in. type C	29.91	25	76.0	88.0
7	8-18-33	Type F	29.73	57	73.0	84.0
8	9- 7-33	1.65-in. type C	29.57	20	82.0	94.0
9	11-12-31	2-in. stranded aluminum	30.05	21	66.0	80.0

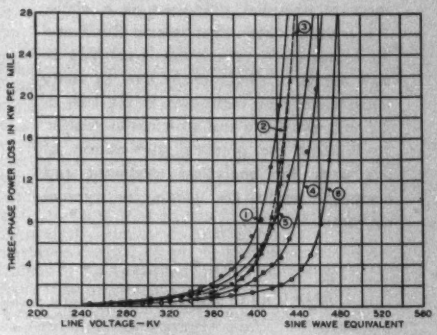


Fig. 13. Corona loss curves for all cables after clear water washing

Curve No.	Date	Cable	Barom. In. Hg	% Rel. Humid.	Temp. Deg F Air	Temp. Deg F Cable
1	4-12-33	Type A	29.99	31	73.0	86.0
2	7-27-33	Type D	29.63	31	86.0	100.0
3	9-16-33	Type E	29.77	36	90.0	100.0
4	5-31-33	Type B	29.83	40	65.5	70.0
5	8-29-33	Type F	29.81	48	73.0	82.0
6	6-23-33	1.4-in. type C	29.86	36	70.0	78.0

References

1. Corona Loss Measurements for the Design of Transmission Lines to Operate at Voltages Between 220 Kv and 330 Kv, J. S. Carroll and Bradley Cozzens. A.I.E.E. Trans., v. 52, 1933, p. 55.

2. Corona Loss Measurements on a 220-Kv, 60-Cycle, 3-Phase Experimental Line, J. S. Carroll, L. H. Brown, and D. P. Dinapoli. A.I.E.E. Trans., v. 50, 1931, p. 36.

3. Development of a Corona Loss Formula. Discussion W. S. Peterson. A.I.E.E. Trans., v. 52, 1933, p. 62.

4. Corona Energy Loss—Influence of Surface Conditions as Affecting Corona Energy Loss, W. D. Weidlein. A.I.E.E. Trans., v. 51, 1932, p. 154.

5. The Space Charge That Surrounds a Conductor in Corona, J. S. Carroll and J. T. Lusignan. A.I.E.E. Trans., v. 47, 1928, p. 50.

6. Variation in Corona Loss With Controlled Atmospheric Conditions, Louis Hegy and G. W. Dunlap, Thesis, June 1933, Stanford University.

7. Koronaverluste an Kupfer—und Aluminiumseilen, K. Pottho ff. *Sonderdruck aus der "Elektrizitätswirtschaft,"* Sept. 1931.

Cross Potential of a 4-Arm Network

This paper treats the loci of potential difference across the midpoints of a 4-arm network with constant coefficients and constant applied voltage. When the network is operated at constant frequency and any one of its arms varies along one of its components or at constant phase angle, the locus of potential difference is a circle. When the network arms remain fixed and the frequency is varied, the locus may or may not be a single circle and in many instances may be expressed as the sum of 2 circles or a circle and a bicircular quartic. To illustrate the practical application of this work, the analytical treatment and numerical results are given for typical networks.

By
ANATOLI C. SELETZKY
ASSOCIATE A.I.E.E.
Case School of Applied Science, Cleveland, Ohio

INCREASING USE of bridge circuits, consisting chiefly of 4-arm networks, not only for measurements of electrical quantities, but also for control and recording purposes, calls for a more critical consideration of the performance of such circuits. In measurements of electrical quantities, where one or more of the bridge arms are varied until null voltage exists across the midpoints of the bridge, a frequent question that arises is the choice of the most appropriate type of circuit which will yield the greatest accuracy and sensitivity. When the choice of a bridge circuit has been narrowed to a single network, as determined by voltage requirements, current carrying capacity, available ranges of precision apparatus, type of null detector, and convenience and speed of manipulation, another problem still remains. This is the proportioning of the impedances of the network arms to obtain maximum sensitivity and accuracy. It is no longer sufficient merely to evaluate the conditions of the variable arm which produce null potential difference across the detector, but it is necessary to compute the currents flowing through the detector, or the potential difference across it if it draws no current, as the variable arm ranges through both sides of the balance point.

Computations of midpoint potential difference and detector currents have been avoided as much as possible because they invariably involve point-by-point calculation of several complex quantities comprising the analytical expression, in a none too convenient form. Obviously, when demands upon accuracy and sensitivity are not important the consideration of the unbalanced conditions may be omitted. However, when bridge networks are used for control and recording purposes, they may or may not be operated with null potential difference across the midpoints. Here, of course, the calculation of midpoint potential differences cannot be dispensed with.

This paper treats the variation of potential difference across the midpoints of a 4-arm network at both constant and variable frequencies. The results are obtained by considering the midpoint potential difference as one or more linear fractional transformations. The work necessary to determine the loci of the transformations, in general, entails less computation than the determination of 1 or 2 points in the usual point-by-point calculation. The treatment throughout is perfectly general and may be applied directly to the performance of any 4-arm network, the coefficients of which do not vary with frequency. To illustrate the practical application of this work, the analytical treatment and the numerical results are given for typical networks when either the frequency or one of the arms is varied.

The results show that the locus of potential difference across the midpoints of a 4-arm network, with constant coefficients, operated at constant frequency and constant applied voltage is a single circle when (1) any one of the arms varies in magnitude at a constant phase angle; or (2) any one of the arms varies along one of its components. When the frequency is varied, the locus may or may not be a single circle. When the locus is not a single circle and no higher powers of frequency than the second occur in the expression for the potential, that expression may be broken down by partial fractions into the sum of 3 terms. In the most complicated case of this sort, these terms are a constant, a circle, and the square of a circle. The determination of loci by use of the Schenkel form of linear fractional transformation has been found to afford an accurate

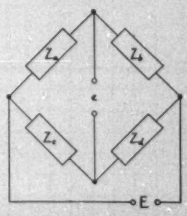


Fig. 1. General 4-arm network

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Sept. 22, 1933; released for publication Nov. 10, 1933. Reprinted for the author.

and rapid method of ascertaining the complete path of cross potential difference as a function of any variable desired.

General 4-Arm Network

In its most general form, the 4-arm network may be considered to be composed of 4 elements, having impedances, Z_a, Z_b, Z_c, and Z_d as shown in Fig. 1. If the applied voltage across the network be E, the cross potential difference, e existing across the midpoints, is

$$e = E\,\frac{Z_cZ_d - Z_bZ_a}{(Z_c + Z_b)\,(Z_a + Z_d)} \tag{1}$$

For most purposes it is more convenient to express the potential difference across the midpoints of the network in terms of volts per volt of applied voltage e',

$$e' = \frac{e}{E} = \frac{Z_cZ_d - Z_bZ_a}{(Z_c + Z_b)\,(Z_a + Z_d)} \tag{2}$$

Since this paper deals exclusively with the potential difference e' in terms of volts per volt of applied voltage, the author will take the liberty to refer to it as "cross potential," "midpoint potential," or merely, "potential."

To treat the loci of the cross potential under various conditions, the equation of a circle will be used as originally applied to a-c circuits by Schenkel (*Elektrotechnische Zeitschrift*, v. 22, Dec. 19, 1901, p. 1043–4). For present purposes the canonical form of the circle will be

$$S = \frac{\alpha + \beta\rho}{\gamma + \delta\rho} \tag{3}$$

in which ρ is a scalar variable that may range from minus to plus infinity, and α, β, γ and δ are constants. Thus S is a variable vector emanating from the origin, whose extremity describes a circle as ρ ranges from minus to plus infinity. The form of eq 3, containing the variable ρ in the first degree only, is known as a linear fractional transformation and yields a circle when the variable is a scalar.

Networks at Constant Frequency

A number of conditions that, at constant frequency of applied voltage, give rise to circular loci for the cross potential now will be studied.

When the impedance of one of the arms, for example, Z_d, varies at constant phase angle, then Z_d may be written as $Z_d = Z_d'\rho$ where Z'_d is a unit vector having the same phase angle as Z_d, and ρ as before is the scalar variable. Then eq 2 may be expressed as

$$e' = \frac{-Z_bZ_a + Z_cZ_d'\rho}{(Z_c + Z_b)Z_a + (Z_c + Z_b)Z'_d\rho} \tag{4}$$

$$\left.\begin{aligned} \alpha &= -Z_bZ_a & \gamma &= (Z_c + Z_b)Z_a \\ \beta &= Z_cZ'_d & \delta &= (Z_c + Z_b)Z'_d \end{aligned}\right\} \tag{5}$$

Equation 4 is seen to be a circle in the form of a linear fractional transformation as given by eq 3; the corresponding constants are given in eqs 5.

When the resistive component of any one of the arms, as Z_d, varies, $R_d + jX_d = Z_d$ is substituted into eq 2, which gives

$$e' = \frac{-Z_bZ_a + jZ_cX_d + Z_cR_d}{(Z_c + Z_b)\,(Z_a + jX_d) + (Z_c + Z_b)R_d} \tag{6}$$

$$\left.\begin{aligned} \alpha &= -Z_bZ_a + jZ_cX_d \\ \beta &= Z_c \\ \gamma &= (Z_c + Z_b)\,(Z_a + jX_d) \\ \delta &= Z_c + Z_b \\ \rho &= R_d \end{aligned}\right\} \tag{7}$$

Similarly, when the quadrature component of any one of the arms, as Z_b, varies,

$$e' = \frac{-Z_bZ_a + Z_cR_d + jZ_cX_d}{(Z_c + Z_b)\,(Z_a + R_d) + j(Z_c + Z_b)X_d} \tag{8}$$

$$\left.\begin{aligned} \alpha &= -Z_bZ_a + Z_cR_d & \delta &= j(Z_c + Z_b) \\ \beta &= jZ_c & \rho &= X_d \\ \gamma &= (Z_c + Z_b)\,(Z_a + R_d) \end{aligned}\right\} \tag{9}$$

Both eqs 6 and 8 have circles for their loci since R_d and X_d are the respective scalar variables, the constants in each case being given by eqs 7 and 9.

Equations 4, 6, and 8 show that at constant frequency the cross potential of a 4-arm network follows a circular locus for either of the following conditions: (1) variation of impedance of any one of the arms at constant phase angle; (2) variation of either resistive or quadrature components in any one of the arms. The variable under either condition may vary over any part or all of the range from minus to plus infinity. The importance of eqs 4, 6, and 8 is that in lieu of a separate computation involving complex quantities for each value of the variable desired, a circle that includes all possible values of the variable may be determined very simply from the network constants. Another feature of equal significance is that a "scale line," that is, a straight line correlating directly the linear scale of

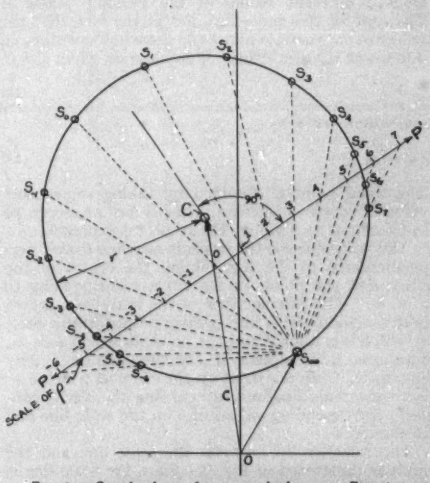
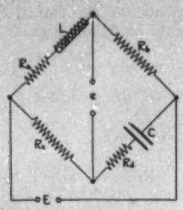


Fig. 2. Circular locus for network shown in Fig. 1, note relationship between the scale line and circle

Fig. 3. A typical 4-arm network



the variable arm with corresponding points on the circle, may be obtained readily by utilizing an invariant point of the transformation.

Of the various methods available for determining the radius and the center of the circle, 2 will be described. (See W. O. Schumann, "Zur Theorie der Kreisdiagramme," *Arch. f. Elektrot.*, v. 11, July 28, 1922, p. 140–6.) The first method, analytical in character, follows directly from the equations necessary to demonstrate that the form of eq 3 is circular. From these equations it has been shown that the radius r and the center vector c (the vector joining the center of the circle with the origin) are:

$$r = \left|\frac{\alpha\delta - \beta\gamma}{\delta\gamma_c - \gamma\delta_c}\right| \tag{10}$$

$$c = \frac{\alpha\delta_c - \beta\gamma_c}{\gamma\delta_c - \delta\gamma_c} \tag{11}$$

in which the subscript c indicates the conjugate of the vector to which it is attached. Thus the determination of the position of the center and the radius of the circle involves merely straightforward substitution in the foregoing formulas.

The second method of locating the circle is the determination of the center point and the radius from 3 different values of the variable scalar ρ. The ease of this procedure lies in the fact that the values of the variable may be so chosen as to reduce eq 3 to much simpler forms. For instance, when $\rho = 0$

$$S_0 = \frac{\alpha}{\gamma} \tag{12}$$

and when $\rho = \infty$

$$S_\infty = \frac{\beta}{\delta} \tag{13}$$

The third point is obtained by taking some other value of ρ, which likewise in many instances can be so chosen as to simplify the resultant expression.

The scale line for the circle is any line drawn perpendicularly to the line joining the center of the circle and the point on the circle corresponding to $\rho = \infty$. The intersections of the scale line, drawn in this manner, with lines joining points on the circle at which ρ is known and the point at which $\rho = \infty$, determine a linear scale of ρ on the scale line. Any line drawn from the point on the circle at which $\rho = \infty$ to the scale line and intersecting the circle, connects corresponding values of ρ on the scale line and on the circle.

The relationship between the scale line and the circle is illustrated in Fig. 2. Here the scale line is represented by PP', drawn perpendicularly to the line CS_∞. Lines drawn from S_∞ to any points on the circle, such as S_0 and S_1, fix the scale on the scale line. The scale then is extended linearly along PP'. Then any vector, such as OS_5, represents the value of S in magnitude and phase for $\rho = 5$, since the line joining S_∞ and S_5 cuts the scale line at $\rho = 5$.

These methods of drawing circular loci will now be applied to a resistance, inductance, and capacitance network, as shown in Fig. 3. The cross potential will be evaluated as a function of the capacitance C. The constants of this network are

$$Z_a = R_a + j\omega L \qquad Z_c = R_c$$
$$Z_b = R_b \qquad Z_d = R_d - \frac{j}{\omega c}$$

Inserting these constants into eq 2, the midpotential becomes

$$e' = \frac{(R_a + j\omega L)\left(R_d - \frac{j}{\omega c}\right) - R_bR_c}{(R_a + R_b + j\omega L)\left(R_c + R_d - \frac{j}{\omega c}\right)} \tag{14}$$

Since C is now the scalar variable representing ρ in eq 3, the expression for potential in eq 14 must be reduced to an appropriate circular form with C as a factor of a single term in the numerator and the denominator. Rearranging the terms in eq 14 accordingly gives

$$e' = \frac{R_a + j\omega L}{R_a + R_b + j\omega L} \times \frac{-j + C\omega\left(Rd - \frac{R_bR_c}{R_c + j\omega L}\right)}{-j + C\omega\,(R_c + R_d)} \tag{15}$$

Equation 15 is now a circle S in canonical form, multiplied by a factor that has been taken out to simplify the component terms of the circle which are:

$$\left.\begin{aligned} \alpha &= -j & \gamma &= -j \\ \beta &= \omega\left(R_d - \frac{R_bR_c}{R_a + j\omega L}\right) & \delta &= \omega(R_c + R_d) \\ & & \rho &= C \end{aligned}\right\} \tag{16}$$

Then the cross potential is

$$e' = \frac{R_a + j\omega L}{R_a + R_b + j\omega L} \times S \tag{17}$$

Thus the locus of e' is obtained by multiplying the scale of S by the absolute value of $\frac{R_a + j\omega L}{R_a + R_b + j\omega L}$ and rotating the axes through an angle equal and opposite to the phase angle of the same factor.

Substituting the various terms of eq 16 in eqs 10 and 11, the radius of S becomes

$$r = \left|\frac{-R_c}{2(R_c + R_d)}\left[1 + \frac{R_b}{R_a + j\omega L}\right]\right| \tag{18}$$

and the center vector

$$c = \frac{1}{2(R_c + R_d)}\left[R_c + 2\,R_d - \frac{R_bR_c}{R_a + j\omega L}\right] \tag{19}$$

The evaluation of r and c allows the circle to be drawn in its correct position. To locate the scale line S must be evaluated for 2 points. Likewise S could be calculated for a third point to give 3 points for the determination of the circle without recourse to eqs 18 and 19 for the radius and the center vector. Thus when $C = 0$, $S_0 = 1$, and when $C = \infty$

$$S_\infty = \frac{1}{R_c + R_d}\left[R_d - \frac{R_bR_c}{R_a + j\omega L}\right]$$

It will become apparent from the numerical example

that follows, that the value of C for the third point may be so chosen as to render the calculation of S for that point quite simple. In fact, if R_d has an appropriate value, so that the locus of e' passes through the origin, then that value of C for which S is zero may be used conveniently.

These results now will be applied to a numerical example. Suppose that it is desired to operate the network at 1,000 cycles per second and to have null potential across the midpoints for a particular value of the capacitance arm. The conditions for null cross potential for this network are

$$\left.\begin{aligned} R_d &= \frac{R_a R_b R_c}{R_a^2 + \omega^2 L^2} \\ C &= \frac{R_a^2 + \omega^2 L^2}{R_b R_c \omega^2 L} \end{aligned}\right\} \qquad (20)$$

The following constants will be employed:

$L = 0.2870$ h
$R_a = 1{,}130$ ohms
$R_b = R_c = 2{,}000$ ohms
$R_d = 1{,}000$ ohms

The locus of e' now will be determined as C varies from zero to infinity. From eqs 20 the potential across the midpoints will be zero when $R_d = 1{,}000$ ohms and $C = 10^{-7}$ farad. Using these constants,

When $C = 0$, $S_0 = 1$
When $C = 10^{-7}$, $S = 0$
When $C = \infty$,

$$S = \frac{1{,}000 - \dfrac{2{,}000 \times 2{,}000}{1{,}130 + j2\pi \times 1{,}000 \times 0.2870}}{2{,}000 + 1{,}000} = j\,0.5305$$

These 3 values of S now may be used to determine the circle. The position of the center and the radius also may be checked by eqs 18 and 19 which give:

$$r = \left|\frac{-2{,}000}{2(2{,}000 + 1{,}000)}\left[1 + \frac{2{,}000}{1{,}130 + j2\pi \times 1{,}000 \times 0.2870}\right]\right| = 0.5658$$

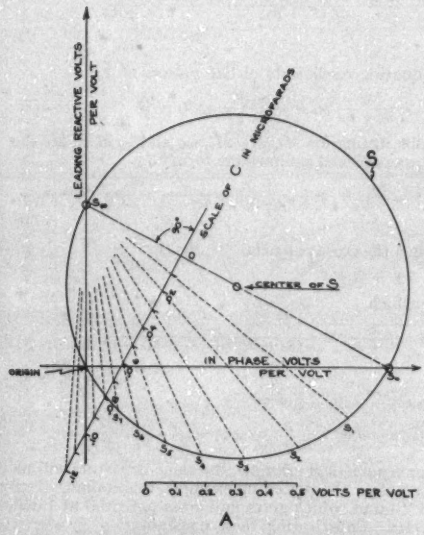
$$c = \frac{2{,}000 + 2{,}000 - \dfrac{2{,}000 \times 2{,}000}{1{,}130 + j2\pi \times 1{,}000 \times 0.2870}}{2(2{,}000 + 1{,}000)} = 0.5003 + j\,0.2654$$

The resultant locus for S is shown in Fig. 4A. To obtain the locus for e', S must be multiplied by $\dfrac{R_a + j\omega L}{R_a + R_b + j\omega L} = 0.5891\underline{/29.94°}$ as shown in Fig. 4B. The scale line then is drawn as previously described, using the points on S for $C = 10^{-7}$ and $C = 0$. The value of cross potential for any value of C now may be read directly on Fig. 4B. Variation of the magnitude and phase of the cross potential with capacitance is shown in Fig. 5.

Any type of 4-arm network with constant coefficients, in which one arm varies at constant phase angle or along one of its components, may be treated exactly as in the foregoing example.

Networks at Variable Frequency

The expression for the cross potential of a 4-arm network when all the arms remain fixed and the frequency is varied, in many cases does not yield a single circular locus. It is necessary in each in-



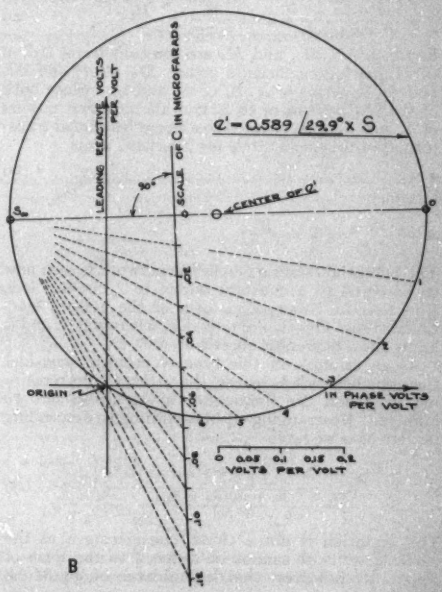


Fig. 4. Circular loci for circuit shown in Fig. 3 showing variation of e′ with C, at constant frequency

stance to set up the equation for e' in terms of the particular impedances at hand and then to rearrange the terms with respect to ω with a view of reducing the expression to the canonical form of the circle in eq 3. When only first powers of ω occur, the entire process is exactly similar to the problem first studied, namely, the determination of e' as a function of one of the network arms, with the exception that the frequency is treated as the scalar variable. However, when second or possibly higher powers of ω occur in the equation for e', it is possible to resolve e' into a sum of linear fractional transformations having circles for their loci. This particular method was developed by Hauffe (G. Hauffe, "Zur Theorie der Allgemeinen Ortskurven," *Elektrot. u. Masch.-Bau*, v. 48, Jan. 19, 1930, p. 57–8) for the determination of loci of the simple series circuit, but, as will be shown here, the same treatment is readily applicable to the 4-arm network.

Let it be assumed that the constants of the network are such that no powers higher than the second enter into the equation for the cross potential. Then the expression for e' may be written as

$$e' = \frac{A\omega^2 + B\omega + C}{\omega^2 + D\omega + E} \tag{21}$$

in which A, B, C, D, and E are constants. Let the denominator be solved as a quadratic in ω, giving, say, 2 different roots ω_1 and ω_2, which may be real or complex. The case involving equal roots will be treated later.

Unequal Roots. Using partial fractions the cross potential is put into the form

$$e' = \frac{A\omega^2 + B\omega + C}{\omega^2 + D\omega + E} = M_1 + \frac{M_2}{\omega - \omega_1} + \frac{M_3}{\omega - \omega_2} \tag{22}$$

in which M_1, M_2, and M_3 are constant terms free of ω. Equating coefficients gives: $M_1 = A$, and M_2 and M_3 in terms of A, B, C, ω_1, and ω_2. Since both of the last 2 terms of eq 22 contain only first powers of ω, each may be reduced to a linear fractional transformation having a circle for a locus. Thus

$$e' = A + S_2 + S_3 \tag{23}$$

in which

$$S_2 = \frac{M_2}{\omega - \omega_1} \text{ and } S_3 = \frac{M_3}{\omega - \omega_2}$$

The potential existing across the network is seen now to be equal to a constant added to 2 circular loci. Equation 21 is a special form of the general fractional transformation of degree n, where n is 2, and is known as a bicircular quartic.

As an example of this type of problem, consider the same network as before, the various arms remaining fixed and the frequency varying from zero to infinity. Rearranging eq 14 according to descending powers of ω we have

$$e' = \frac{\dfrac{1}{R_c + R_d}\left\{\omega^2 R_d - \dfrac{j\omega}{CL}\left[L + C(R_a R_d - R_b R_c)\right] - \dfrac{R_c}{CL}\right\}}{\omega^2 - \dfrac{j\omega[L + C(R_a + R_b)(R_c + R_d)]}{CL(R_c + R_d)} - \dfrac{R_a + R_b}{CL(R_c + R_d)}} \tag{24}$$

This equation is not a circle, considering ω as the variable, since it cannot be reduced to the form of eq 3. If, however, the denominator of eq 24 be

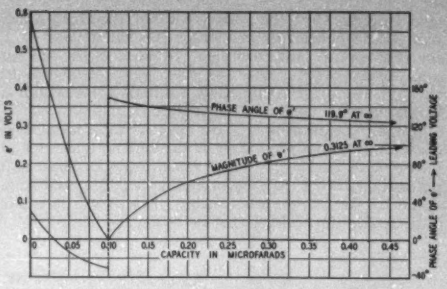


Fig. 5. Variation of cross potential with capacitance for a circuit as shown in Fig. 3 having the following constants:

L = 0.2870 h $\quad R_b = R_c$ = 2,000 ohms
R_a = 1,130 ohms $\quad R_d$ = 1,000 ohms

solved as a quadratic in ω, the entire expression will break down into the sum of a constant term and 2 circular loci as described. If the 2 roots of the denominator are not equal, they are

$$\omega_1 = \frac{j}{C(R_c + R_d)} \text{ and } \omega_2 = j\frac{(R_a + R_b)}{L}$$

The cross potential then may be expressed as

$$\frac{\dfrac{1}{R_c + R_d}\left\{\omega^2 R_d - \dfrac{j\omega[L + C(R_a R_d - R_b R_c)]}{CL} - \dfrac{R_c}{CL}\right\}}{\omega^2 - \dfrac{j\omega[L + C(R_a + R_b)(R_c + R_d)]}{CL(R_c + R_d)} - \dfrac{R_a + R_b}{CL(R_c + R_d)}} = M_1 + \frac{M_2}{\omega - \omega_1} + \frac{M_3}{\omega - \omega_2} \tag{25}$$

Equating coefficients of like powers of ω,

$$M_1 = \frac{R_d}{R_c + R_d};\ M_2 = \frac{-jR_c}{C(R_c + R_d)^2};\ M_3 = \frac{jR_b}{L}$$

Substituting for M_1, M_2, M_3, ω_1, and ω_2 in eq 25, the cross potential assumes the form

$$e' = \frac{R_d}{R_c + R_d} - \frac{jR_c}{(R_c + R_d)[\omega C(R_c + R_d) - j]} + \frac{jR_b}{\omega L - j(R_a + R_b)} \tag{26}$$

Thus the cross potential

$$e' = S_1 + S_2 + S_3$$

in which

$$S_1 = \frac{R_d}{R_c + R_d};\ S_2 = \frac{-jR_c}{(R_c + R_d)[\omega C(R_c + R_d) - j]};$$

$$S_3 = \frac{jR_b}{\omega L - j(R_a + R_b)}$$

When $\omega = \infty$, $S_2 = S_3 = 0$

When $\omega = 0$, $S_2 = \dfrac{R_c}{R_c + R_d}$ and $S_3 = \dfrac{-Rb}{R_a + R_b}$

For a numerical example, the same constants will be used as in the preceding example, maintaining C at 10^{-7} farad, which gives null cross potential at 1,000 cycles. Substituting these constants

$$S_1 = \frac{1{,}000}{2{,}000 + 1{,}000} = 0.3333$$

For zero frequency

$$S_2 = \frac{2{,}000}{2{,}000 + 1{,}000} = 0.6667 \text{ and } S_3 = \frac{-2{,}000}{1{,}130 + 2{,}000} = -0.6389$$

At infinite frequency both S_2 and S_3 are zero. For the third point necessary to determine the circle take, for example, 1,000 cycles. Then

$$S_2 = \frac{-j\,2{,}000}{(2{,}000 + 1{,}000)\,[2\pi \times 1{,}000 \times 10^{-7}\,(2{,}000 + 1{,}000) - j]} = 0.3124\ \underline{/-62.05^\circ}$$

$$S_3 = \frac{j\,2{,}000}{2\pi \times 1{,}000 \times 0.2870 - j\,(1{,}130 + 2{,}000)} = 0.5536\ \underline{/150.06^\circ}$$

Using these values, the 2 loci S_2 and S_3 and the constant S_1 are plotted in Fig. 6. Scale lines are drawn for each of the circles and corresponding points on each circle are added together with the constant, giving the resultant cross potential across the network.

Double Root. When the roots of the denominator are equal, the general quadratic form is written as the sum of several fractions, as before.

$$e' = \frac{A\omega^2 + B\omega + C}{\omega^2 + D\omega + E} = M_1 + \frac{M_2}{\omega - \omega_0} + \frac{M_3}{(\omega - \omega_0)^2} \tag{27}$$

Here the root is ω_0. The first term on the right is a constant, equal to A, and the second term is a circle, as in the preceding example. If the third term be considered as the square of its square root, it then can be treated as the square of a circular locus, because the square root of the third term is a circle. Thus

$$e' = S_1 + S_2 + S_3^2 \tag{28}$$

in which

$$S_1 = A;\ S_2 = \frac{M_2}{\omega - \omega_0};\ S_3 = \frac{\sqrt{M_3}}{\omega - \omega_0}$$

When the locus of S_3 has been determined, a number of points on it are squared, giving the bicircular quartic, S_3^2. The locus of S_3^2 then is added to $(S_1 + S_2)$ thereby giving the desired locus of e'.

If the conditions for a double root be applied to the preceding problem, the coefficient M_3 will be found to be zero. Thus in this particular case the locus of the cross potential is a constant added to a single circle, the point S_2 for zero frequency being coincident with the point S_2 for infinite frequency. To illustrate the problem involving a double root, the network in Fig. 7 will be employed. It should be observed that with an inductance in the (a) arm, a capacitance in the (b) arm and resistances only in the remaining arms, the locus of the cross potential will not pass through the origin at any frequency.

Referring to eq 2 the cross potential for this network becomes

$$e' = \frac{(R_c + j\omega L)\,R_d + j\,\dfrac{R_c}{\omega C}}{\left[R_a + j\left(\omega L - \dfrac{1}{\omega C}\right)\right]\left[R_c + R_d\right]} \tag{29}$$

If all the resistances in the various arms are made alike and the equation rearranged according to descending powers of ω,

$$e' = \frac{1}{2} \times \frac{\omega^2 - j\dfrac{R}{L}\,\omega + \dfrac{1}{LC}}{\omega^2 - j\dfrac{R}{L}\,\omega - \dfrac{1}{LC}} \tag{30}$$

Considering the denominator as a quadratic in ω, the roots will be equal when $L = \dfrac{CR^2}{4}$, and the double root, ω_0 is $j\,\dfrac{2}{CR}$. The cross potential then may be written as

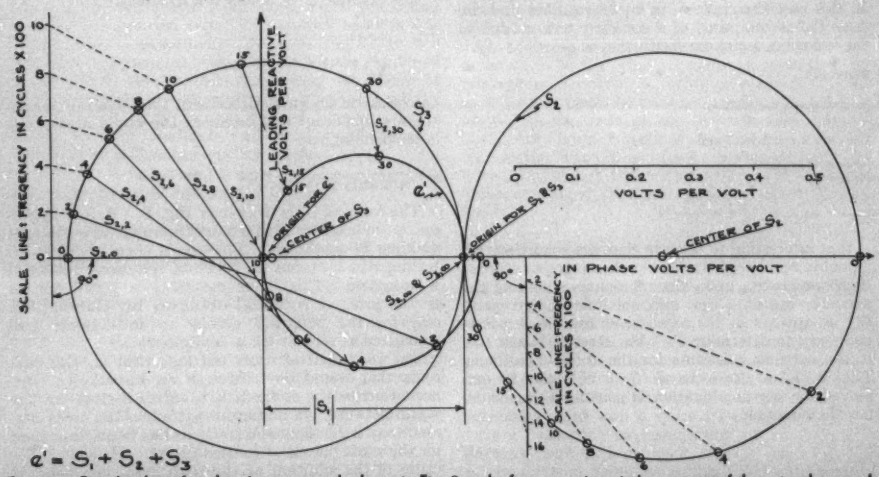


Fig. 6. Circular loci for the 4-arm network shown in Fig. 3 as the frequency is varied; constants of the network are such that the equation for cross potential contains no powers of ω higher than the second and the denominator has unequal roots

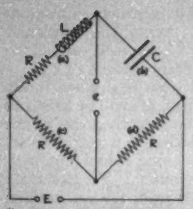


Fig. 7. A typical 4-arm network used to illustrate problem of variable frequency in which denominator of equation for cross potential has equal roots

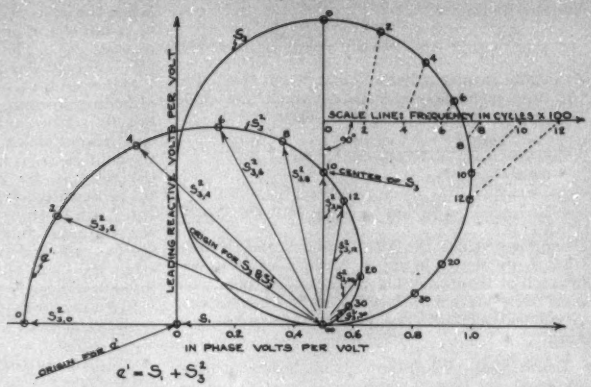


Fig. 8 (right). Loci for circuit shown in Fig. 7

$$\frac{1}{2} \times \frac{\omega^2 - j\frac{R}{L}\omega + \frac{1}{LC}}{\omega^2 - j\frac{R}{L}\omega - \frac{1}{LC}} = M_1 + \frac{M_2}{\omega - \omega_0} + \frac{M_3}{(\omega - \omega_0)^2} \tag{31}$$

Equating coefficients

$$M_1 = \frac{1}{2};\ M_2 = 0;\ M_3 = \frac{4}{C^2R^2} = \omega_r^2$$

Here, $\omega_r = \frac{1}{\sqrt{LC}}$, the angular velocity at which the reactances of the inductance and the capacitance are equal. Substituting these coefficients in eq 31 and noting that $\omega_0 = j\omega_r$ the cross potential becomes

$$e' = \frac{1}{2} + \left[\frac{\omega_r}{\omega - j\omega_r}\right]^2 \tag{32}$$

In this case the circle S_2 in eq 28 vanishes and the potential is composed of a constant term added to the square of a circular locus, that is $e' = S_1 + S_3^2$ in which

$$S_1 = \frac{1}{2} \text{ and } S_3 = \frac{\omega_r}{\omega - j\omega_r}$$

The critical points for S are:

for $\omega = \infty$, $S_3 = 0$
for $\omega = 0$, $S_3 = j$

$$\text{for } \omega = \omega_r,\ S_3 = \frac{1+j}{2} = \frac{\sqrt{2}}{2}\angle 45^\circ$$

It is interesting to observe that the conditions for a double root coupled with equal resistances exercise such constraints upon the relationships among the network constants, that only one independent quantity ω_r appears in the expressions for the 3 points necessary to determine S_3. The term S_1 is also free of the network constants for the above conditions. Thus a plot of the locus of $(S_1 + S_3^2)$ may be employed for any combination of constants that satisfies the equation

$$R^2 = \frac{4L}{C} \tag{33}$$

Referring to eq 11 for the center vector, the center vector of S_3 is

$$c = \frac{\omega_r}{-j\omega_r - j\omega_r} = \frac{j}{2}$$

Since the point for infinite frequency is at the origin and the point for zero frequency is at j and the center is at $j/2$, the circle is disposed symmetrically about the vertical axis. Furthermore from the value at $\omega = \omega_r$ of $S_3 = \frac{\sqrt{2}}{2}\angle 45^\circ$ it may be seen that a line drawn at an angle of 45° in the first quadrant will intersect the circle at a point corresponding to a frequency at which $\omega = 1/\sqrt{LC}$. Hence a circle drawn through these points will be valid for any set of constants satisfying eq 33. It only remains to subdivide the scale line from $\omega = 0$ to $\omega = \omega_r$ into suitable divisions.

For example if for a network in which

$C = 10^{-6}$ farad
$L = 0.02533$ h
$R = 2\sqrt{\frac{L}{C}} = 318.4$ ohms

the circle be drawn as described, then the 45° line in the first quadrant will intersect the circle at a point corresponding to

$$\omega = \frac{1}{\sqrt{0.02533 \times 10^{-6}}} = 6{,}283 \text{ or } 1{,}000 \text{ cycles}$$

The locus of S_3 is drawn in Fig. 8. A few points on S_3, sufficient to give a smooth curve, are squared yielding S_3^2 as shown. The origin then is displaced by the vector S_1 and the locus of the cross potential is complete. This locus describes a path similar to the locus of potential obtained by Hauffe (*loc. cit.*) for the potential across an inductance coil connected in series with a condenser.

The treatment of cross current, that is, the currents that would flow through an impedance connected across the midpoints, involves a study of the 5-arm network. In numerous instances the cross current may be evaluated exactly as has been described for the cross potential in this paper. However, because of the addition of the fifth arm, the general case is more complicated. The author hopes to treat the 5-arm network in a future paper.

Switching at the Hudson Avenue Station

By
C. M. GILT
MEMBER A.I.E.E.

Brooklyn Edison Co.,
Brooklyn, N. Y.

Part of a symposium on switching at modern large generating plants, this paper includes a description of the switching facilities at the Hudson Avenue station of the Brooklyn (N. Y.) Edison Company. Operating experience obtained with the connections and equipment used also is given.

SWITCHING facilities at the Hudson Avenue generating station of the Brooklyn (N. Y.) Edison Company had to be adapted to meet the particular requirements of a large generating station serving a metropolitan area having a load center close to the generating station. The exacting requirements of maximum reliability of service and the high cost of land available had a strong influence on the selection of the equipment and schemes to be used.

The load conditions which affected the design of the Hudson Avenue station are described in this paper, and the fundamental scheme of connections which was adopted is described. The physical design of the switching facilities and the actual equipment adopted is outlined, and those features which distinguish this plant from other large generating stations are pointed out. The control and relaying scheme used is described. The operating experience actually obtained at this station also is described in the paper, this experience covering the scheme of connections used, the equipment adopted, and the control and relay schemes used. Improvements which are now available and which might be used in future installations also are indicated.

Load Conditions Affecting Design

The Brooklyn Edison Company serves the borough of Brooklyn, N. Y., having a total area of approximately 80 sq miles, a net area served of 51 sq miles, a population of approximately 2,600,000, and a total coincident load of 323,000 kw. The load is largely residential, commercial, and small power, with no manufacturers using large, concentrated blocks of power such as are found in many heavy industrial areas. The load is fairly well diversified throughout most parts of the city, with the heaviest loads in the manufacturing and shipping areas along the waterfront and in the downtown Fulton Street area. All transmission above 5,000 volts must be underground. Such conditions, and the fact that the generating station is located in the city and close to the load centers, placed upon the station switching many of the requirements of a substation and precluded bulk power transmission. The life hazard and other hazards resulting from an extensive outage of power in a community containing such extreme concentration of population of heterogeneous characteristics put maximum continuity of service uppermost in the minds of the station designers. The high cost of land and foundations made a concentrated design essential.

In 1922, when the Hudson Avenue Station was planned, the total load amounted to 140,000 kw, of which approximately one third was at 60 cycles, the remainder being either direct current or at 25 cycles. The rapidity with which load was growing, about 14 per cent a year, and the inadequacy of the existing equipment made possible a combined new design of generating station and distribution system and the conversion of the old 2-phase substations and lines to the new 3-phase system.

There was a 60-cycle station of 63,000-kw capacity and a 25-cycle station of 125,000-kw capacity. Ties were provided between Hudson Avenue and this old 60-cycle station, and a 35,000-kw frequency converter provided an interconnection to the 25-cycle station. While it was believed that the general development of power supply in the metropolitan area would lead to interconnections with other stations, the new Hudson Avenue Station was designed to be the principal source of supply for the borough of Brooklyn, carrying as much of the 25-cycle load as could be done economically and safely, as well as the bulk of the 60-cycle load, without significant interconnections to other companies. The station was planned for 8 50,000-kw units and auto transformers, with all switching at 27,600 volts. When completed, the 8 units installed totaled 770,000 kw.

One-Line Diagram

The switching arrangement (see Fig. 1) is so closely related to the distribution system plan that the latter must be outlined briefy. The 60-cycle system was designed to be supplied from substations, each provided with 3 or more 10,000-kva transformers supplied by similarly rated cables from Hudson Avenue, without high voltage switching at the substation, and with a spare transformer energized from a cable ring interconnecting the various substations, switched at each station and supplied at one or more points by cables to Hudson Avenue. The 4,000-volt substation busses were sectionalized by circuit breakers and reactors, and the 27,000-volt

Full text of a paper recommended for publication by the A.I.E.E. committee on power generation, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 20, 1933; released for publication Nov. 8, 1933. *Not published in pamphlet form.*

feeders were carried over different routes and supplied from separated busses at the generating station so that the simultaneous outage of 2 supplies to a substation could be practically relegated to the rare coincident but unrelated outages of 2 feeders. Such second contingency conditions could be met if necessary by temporary 4,000-volt feeder reconnections. Later, direct supply to a low-voltage a-c network was developed and the same principle of diversified feeds was carried out.

In view of the fact that each substation was always provided with sufficient feeders and transformers to carry its load at any time with one feeder out, and that cable repairs or changes take so long that ordinary circuit breaker maintenance can be done while the feeder is out for other purposes, it was believed that one feeder breaker per feeder at the generating station was all that would be required and the costs, complications, and hazards of the second breaker could be eliminated. As a means of providing a back-up protection in case of feeder breaker failure and as a means of selecting between at least 2 sources of power, 4 feeder breakers were connected to a small group bus which could be tied to either of 2 generators through 1 of 2 automatic selector breakers. As originally planned, 2 groups of 4 feeders each, totaling 80,000 kva in feeder capacity, were allocated to each 62,500-kva generator. As the size of the units grew, the increased outlet capacity was obtained by increasing the cable size from 350,000 to 500,000 cir mils and by connecting 2 feeders to

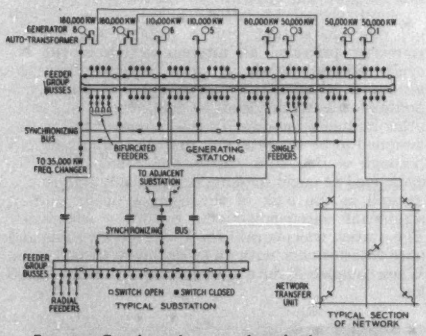


Fig. 1. One-line diagram of 27-kv bus connections at Hudson Avenue station, and typical system connections for supply to substations and to network

Note diversity of supply to typical substation and section of the network. Ties to Hell Gate station are distributed among the feeder busses. The diagram shows the bus connections for all units operating

1 feeder switch through non-automatic oil-immersed disconnecting switches.

While the object was sought of keeping bus sections small with thorough segregation to minimize the effect of station failures, yet some tie capacity between sections was considered important, first to avoid the necessity of tying busses together and operating in few large sections when the number of units was small; second, to provide for load transfer within the station so that units might be operated

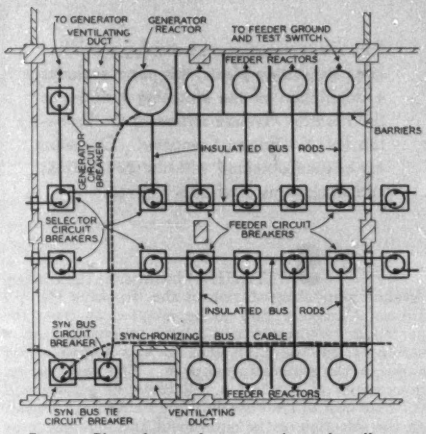


Fig. 2. Plan of typical section of switch gallery

Each section of 8 feeder reactors, circuit breakers, and associated bus and generator breakers is in a separate, fireproof room

for best economy without excessive unbalance of load and voltage on feeders; and, third, to provide a back-up supply of energy to all feeders so that the loss of a unit would have the minimum effect on any load. This was accomplished by connecting the generator busses through 10 per cent reactors and circuit breakers to a tie bus or "synchronizing bus" as it has been called. The synchronizing bus was built in the form of a ring and was provided with automatic sectionalizing breakers between each connection from a generator, so as to minimize the effect of a failure. The complete bus scheme is of the star design rather than the completely isolated or ring bus design. There are various advantages and disadvantages of the star bus as compared with the ring bus design, but probably the controlling factors in the selection of the star bus were the somewhat greater facility of maintaining small bus sections regardless of the number of units running, perhaps a little simpler relaying, and the fact that inherently there are at least 2 breakers between every feeder bus section so that the failure of any breaker will not affect more than one feeder bus section.

Some changes in connections were made necessary due to the fact that the station was planned for 8 50,000-kw turbines, but when completed there were installed 3 50,000-kw, 1 80,000-kw, 2 110,000-kw, and 2 160,000-kw units. These changes consisted essentially in reconnecting the 4 smallest machines

into 2 groups of 2 units each, making use of the double-winding principle in the autotransformers of the 2 largest units and connecting one half of each of these units in the positions originally assigned to them and the other half in the positions released by

Fig. 3. Photograph of 27-kv feeder circuit breaker installation

All 27-kv automatic breakers are of the disconnecting type supported on steel frames. Busses are insulated and barriers surround the disconnecting devices of the breakers. Doors between fireproof rooms were opened for taking of photograph

the transfer of connections of the second and fourth units. As compared to single winding units connected as originally planned this arrangement reduced the maximum short-circuit currents, made the generating capacity on each bus section more nearly uniform, and so distributed the connections of the 2 most economical machines among the busses that switching arrangements could be made under various conditions of load to permit their carrying their proper load with a minimum transfer through the synchronizing bus and reactors. The number of synchronizing bus sections was reduced to provide the additional generator breaker positions. In Fig. 1 is indicated the bus arrangements and typical connections to a substation, and a small section of the network. Obviously, some bus, breaker, and reactor current-carrying capacities had to be increased.

Physical Design and Equipment

In the endeavor to reduce the likelihood of accidental contact and failure, and to limit the extent of the failure should one occur, exposed live parts were eliminated as far as practicable. This seemed particularly desirable in view of the fact that the operating voltage is 27,600 volts, each generator feeding directly into a bank of Y-Y connected autotransformers with neutrals solidly grounded without any intervening switching. The synchronizing bus consists of lead covered cable, looped from one circuit breaker to the next, terminating at each end in a pothead forming part of the stationary contact of the circuit breaker. The busses connecting the generator switches, selectors, feeder switches, and reactors consist of short sections of factory insulated copper rod or tubing with taped joints supported on 37,000-volt insulators. The insulation is of the "herkolite" or "micarta" type. The same material is used to form shields which surround the bushings and disconnecting contacts of the elevating-type circuit breakers. The early feeder and "generator" reactors were of the bare copper concrete type but the later ones have all been provided with turn insulation. These are completely separated from the rest of the circuit breaker room by asbestos board barriers, except for small, screened ventilating openings, and asbestos board partitions are between the reactors.

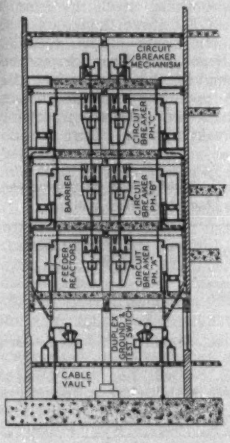


Fig. 4. Cross section of 27-kv switch gallery

The switch gallery is built on the vertical isolated phase principle. Cables are lead covered in ducts imbedded in concrete. Phase isolation is maintained from generator to ground and test switches

Autotransformers, reactors, breakers, and insulators were designed for an 81-kv test voltage. The factory insulated bus copper was given a 58-kv test and, in addition, is supported on insulators. The smaller cables have the same insulation used in the distribution system and are designed for at least 29-kv operation. The 1,500,000 and 2,000,000 cir-mil cables have a minimum of 375 mills paper insulation instead of a minimum of 328 mills as used in the 350,000 and 500,000 cir-mil sizes. As in the street work, insulation thickness has been somewhat decreased as improved cable became available.

The switch house is built on the vertical isolated phase principle with each generator switch and its associated selectors, breakers, synchronizing bus breakers, 2 groups of feeder breakers and reactors in a separate room with swinging, fireproof doors between rooms. In Fig. 2 is indicated the physical arrangement of one of these rooms, and a view inside these rooms is reproduced in Fig. 3. A cross section of the 27-kv switch gallery is shown in Fig. 4, and the feeder reactor installation is illustrated in Fig. 5. Ventilation is secured by ducts rising from the

ground floor, discharging under the reactors, picking up again above the reactors and discharging above the roof. There is a separate air duct for each phase of each group of reactors. Small screened openings top and bottom in the reactor barriers permit some air to by-pass through the open portion of the room.

The circuit breakers are of the General Electric *K*-130 elevating type, of 600, 1,200, 2,000, and 3,000-amp capacities. The 600-amp feeder breakers have an interrupting rating of 500,000 kva and are of the plain break construction, while all others are rated 1,500,000 kva and are equipped with explosion chambers. In Table I are shown the breaker ratings and the duties that may be imposed on them in actual operation. The breakers are supported on steel frames hung from the building steel, the frames for all breakers being of the same dimensions, so that breakers of all ratings are interchangeable. Screw shafts operated from the mechanisms on the floor above the top breakers raise and lower the breakers between the operating and disconnect positions and also still further lower the tanks for maintaining oil and breaker parts. There are no

Table I—Oil Circuit Breaker Current Carrying and Interrupting Ratings and Duties, Hudson Avenue Station

Circuit Breaker	Amperes: Current Rating	Amperes: Current Duty: Original Plan	Amperes: Current Duty: Present	Thousands of Kva: Interrupting Rating 2-OCO Cycle	Thousands of Kva: Interrupting Duty[4]: Original Plan[6]	Thousands of Kva: Interrupting Duty[4]: Present[7] Equipment
Feeder	600[1]	300	600	500	250	430[3]
Feeder	1,200		825	1,500		1,600[3]
Selector	1,200	1,200	1,200	1,500	850	1,500
Selector	2,000		2,000	1,500		1,700
Generator	2,000	1,310	1,310	1,500	500	1,050
Generator	3,000		2,880	1,500		975
Syn. Bus	3,000	2,400[5]	3,000	1,500	1,600	1,600
Syn. Bus Tie	3,000	2,400	3,000	1,500	1,600	1,600

1. Contacts rated 600-amp were the smallest advisable for 500,000-kva breakers
2. The increased duty on feeder breakers is due largely to larger feeder reactors having less impedance than original 300-amp reactors
3. Due to short time settings for certain tie feeders permitting feeder breakers to interrupt faults in feeder reactors
4. Two feeder groups of 1,200 amp each
5. Basis of calculation: All generators running at full rated load; all ties with other stations connected; decrement of fault current taken into account
6. As if for 8 50,000-kw generators, with all synchronizing bus switches closed
7. Maximum duties for station as actually completed, with generators totaling 770,000 kw, and with the synchronizing bus operated in 2 sections. Substantial reduction of these duties can be accomplished by further sectionalizing the synchronizing bus, and reduction also does accompany the normal operating condition with less than full rated load on the station

barriers between breakers within a building section as it was believed that the proximity of ample grounded steel would confine an arc to a short local path, and the practical elimination of exposed live parts would prevent the flashover of other circuits due to ionized gases. The whole construction preceded the introduction of metal-clad switch gear into this country, but is quite similar to some of the later designs except that the grounded metal coverings of the barriers around the disconnecting contacts and some of the busses are omitted.

Each feeder is provided with a permanent oil-immersed metal-clad ground and test switch by which the feeder may be connected to either ground or the test bus. An installation of these switches is shown in Fig. 6. The test bus may be grounded through an oil circuit breaker of proper closing characteristics to ground a feeder successfully even though alive from backfeed. The ground and test switches for the bifurcated feeders also have disconnecting switches built into them so that either branch may be disconnected and grounded or tested while the other is in operation. As these disconnecting switches are not suitable for opening under load, the feeder breaker is always opened and the circuit grounded before a branch of the feeder is disconnected or connected, and the feeder then restored to service.

Control and Relaying

Switching and generator control is effected at unit-type steel control cubicles, one for each generator and one for each associated section of feeder breakers and selector breakers. (See Fig. 7.) This arrangement was an endeavor to reduce the likelihood of operating error by making the control units distinct and has proved to be very satisfactory. It is also believed that a control wiring fire would not spread beyond the one unit. Lead-covered multiconductor control cables are installed in ducts throughout, except as flameproof single-conductor wires are required within control cubicles or switch mechanisms.

Voltage and frequency are hand controlled. A bell alarm and indicating lights immediately call the operator's attention to the automatic tripping of a breaker, and balanced current relays on the 2

Fig. 5. Feeder reactor installation with aisle barriers removed

Asbestos board barriers are between reactors and completely separate reactors from the aisle. These latter barriers, which have been removed for the photograph, cannot be opened unless the feeder breaker is open and the circuit grounded

branches of the bifurcated feeders indicate on which of the 2 branches the fault occurred.

A schematic diagram of relay protection on a typical section of 27-kv bus is given in Fig. 8. Feeder breakers are protected by induction type

overcurrent relays energized from bushing current transformers in the circuit breakers, and such feeders as are not tied directly to another high voltage grounded circuit are also protected by ground relays. The selector breakers are equipped with induction overcurrent relays having characteristics and settings such that they will back up the feeder breaker and trip if the latter fails to trip a feeder short circuit, but will trip ahead of the feeder breaker in case of feeder reactor failure. Each section of the synchronizing bus is relayed differentially and is backed up by overcurrent protection on the breakers between the synchronizing bus and the generator or so-called *H* bus. The generators and autotransformers are relayed differentially as a unit and in addition, all units except the last 2, which have double winding autotransformer operation, are equipped with current balance relays on the parallel windings.

Operating Experience With the Scheme of Connections

While Hudson Avenue Station was originally designed for feeding substations and without any

Fig. 6. Double ground and test switch installation

Each feeder may be connected to a metal-clad test bus or grounded by a permanent ground and test switch. The switches for the bifurcated feeders also include disconnecting features for each branch of the feeder

major ties to other 60-cycle stations, it has fitted in with the changed methods of distribution in a very satisfactory manner. The direct supply to the low-voltage a-c network has become the major method of distribution, and ties with the Hell Gate station of The United Electric Light and Power Company were a significant item in the selection of the later large-sized units and will become increasingly important as the loads in the territory develop.

The supply to the network has been secured following the same general principles used in feeding the substations; that is, feeders closely adjacent in a network area are connected to separated busses at the generating station, except that 2 feeders supplying a single street and subject to the same exposure by reason of being in a common duct bank may originate from a common bus. The supply to the network has introduced new problems, such as the necessity for closer voltage control and for maintaining minimum phase angles between bus sections. The direct supply to the network through feeders from the generating station without feeder regulators has placed the burden of voltage regulation on the station. This has been met by installing larger and more accurate generator voltmeters and varying the station voltage with load according to a voltage schedule. It has been possible to maintain a better average and a narrower range of delivered voltage than is received from the radial system with individual 4,000-volt feeder regulators.

The low-voltage network forms a low voltage tie between generating station bus sections which limits short circuits on it to such comparatively small magnitudes that they have little or no effect upon generating station operation. It might appear, therefore, that the network would furnish the tie between station units necessary for synchronizing and load transfer purposes and complete isolation between units within the station might be obtained. However, the network has certain characteristics which make load transfer facilities at the generating station even more desirable than when the latter feeds only distribution substations. The impedance between units feeding the network is not uniform, varying from a minimum where 2 or more network units are connected to a customer's bus, to a maximum where units are several blocks apart. As the transformer units are small compared to the feeder capacity, the circulating currents through some units, due to small differences in bus phase angle or voltage, may be out of all proportion to those in the feeders as a whole. As a result, advancing the phase angle of a bus section may load up a few network units, even with all feeders in service, before the total load transfer through the network becomes appreciable. The large number of small transformers closely related to local loads, connected to each feeder, requires that the feeders be out of service frequently for maintenance and construction purposes, with the result that scarcely a day goes by when one or more feeders from a station supplying 75 or 100 are not out of service. As the loadings on a few transformers adjacent to feeder that is out may be the limiting feature in load transfer through the network, the spare capacity installed in transformers and feeders for these so-called contingency conditions rarely can be used for load transfer purposes. It is desirable, therefore, to keep phase-angle differences between busses small, generally within about one degree. The transfer capacity of the synchronizing bus and the ability to connect each feeder group to either of 2 generators have made it possible to adjust the number of operating machines and their loadings for best economy consistent with proper running reserve and still keep the phase differences between busses within 0.5 deg most of the time.

When the connected station capacity is approximately 400,000 kw or more, the synchronizing bus is operated in 2 sections so as to keep possible short-circuit currents within the break ratings. The synchronizing bus is sectionalized in such a way that one or both of the 2 large units are connected to both

Fig. 7. Control room

Segregated steel control panels are installed for each generator and each section of feeders

sections, thus tying them together through the impedance of the double-winding autotransformers.

The double-winding principle and the spreading of the connections of the 2 160,000-kw units through the bus have been very helpful in maintaining proper voltages and phase angles in spite of the relatively large proportion of load carried by these units. Some further improvement might have been made by interchanging the connections of No. 6 unit with the nearest connection of No. 7 unit, thereby making it possible to connect all bus groups directly to one or the other of the 2 largest units (see Fig. 1), but it was believed that the gain would not be sufficient to warrant the added expense and complication. Somewhat closer regulation of voltage and phase angles might be obtained by making the connections to the synchronizing bus through autotransformers, or windings in the generator autotransformers, equipped with load-ratio control. Experience to date indicates that this is not necessary where there is some flexibility in connecting feeders to machines.

Some thought has been given to the possibility of eliminating the synchronizing bus entirely and thereby securing even greater segregation and reduction of short-circuit currents. This could be accomplished by providing adequate transfer facilities so that feeders could be switched among machines to secure the desired loadings on each unit. Such a scheme might involve extensive switching equipment and operations where the station is designed with many small bus sections, with the associated increased costs and hazards, and would lose the advantages of a back-up supply for all feeders in case of loss of a generator. The loss of a heavily loaded generator to which many feeders were connected, and the transfer of load to a lightly loaded generator to which few feeders were connected, might set up serious load and voltage disturbances in the distribution system until feeders could be transferred to the new source in the station.

The synchronizing bus or tie bus also furnishes an excellent point for connection of any large station-to-station ties in that it can deliver power from or receive power into the station with a minimum unbalancing of the loadings or phase angles of individual feeder bus sections. At the Hudson Avenue Station, the frequency changer tie to the 25-cycle system is made on the synchronizing bus, but the various ties to the 60-cycle Hell Gate Station and system of The United Electric Light and Power Company are at present distributed among the various feeder sections. These ties are in a state of transition and at present consist of 2 40,000-kva 27-kv ties with load-ratio control for ordinary load transfer purposes. These are operated to keep the busses of the 2 stations in phase with each other regardless of the load transferred across these ties. In addition, there are 10 27-kv so-called "tapped ties" without load-ratio control between Hudson Avenue and Hell Gate, and 2 27-kv feeders from Hudson Avenue that are tied to 13-kv feeders from Hell Gate by means of autotransformers in substations of the New York and Queens Electric Light and Power Company. These "tapped ties" average about 15,000-kva capacity each and are used to feed network and substation load in Brooklyn and Queens.

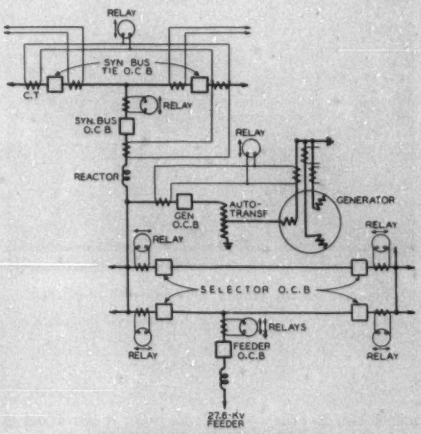


Fig. 8. Schematic diagram of relay protection on a typical section of 27-kv bus

In general, back-up protection has been provided, so that if one breaker or relay fails, the next in series will trip

They are not used normally for load transfer purposes because they feed into networks also supplied by radial feeders from the generating stations, and forcing load from one station toward the other would produce bad load distribution between transformers

fed from the "tapped ties" and those from closely associated radial feeders.

There are 12 27-kv 15,000-kva feeders which energize 13-kv feeders in lower Manhattan through autotransformers. These feeders supply substation and network load which also is fed by cables from the Hell Gate station. Here again there is no attempt to shift the load from one station to the other through the network because of the bad loading conditions that would result. However, the "tapped ties" through Queens and the "secondary intermesh" in lower Manhattan, as the installations are called, furnish added synchronizing power and stability between the stations and could be used for power transfer purposes during an emergency. These advantages were secured at little cost under present load conditions, but as the loads increase, and additional power transfer is needed or becomes economical under normal conditions, there will undoubtedly be some changes from the present connections.

The small bus sections have worked out splendidly. Such bus faults as have occurred have been cleared quickly and affected but a few feeders and have not affected any customer beyond the momentary dip during the failure. The single breaker per feeder and the 4 feeder breakers per 2 selectors have met all requirements. It has been possible to do practically all feeder breaker maintenance when the feeder was necessarily out for some other purpose. This is a little more difficult to accomplish when there are 2 feeders bifurcated on one switch, but it is usually possible to so schedule the outages of the 2 branches that an additional outage for circuit breaker maintenance is not necessary. The small sections of busses make it possible to clean them at times of light load when the outage of the 4 or 8 feeders, as the case may be, to separated sections of the load is not objectionable.

Operating Experience With the Equipment

The general principle of eliminating air as insulation in the 27-kv equipment has been most successful and it would appear desirable to carry the principle as much further as can be done without introducing more objectionable features, or too great a cost. With the exception of 1 or 2 porcelain bushing failures (not a part of the main bus or breaker equipment) the few failures which have occurred have been due to foreign material causing a flashover in air insulation. These have been a few feeder reactor failures at times of feeder short circuits due to foreign material in the windings, one being due to a rat finding a small opening and trying to climb a reactor insulator. In none of these cases was there any spread of the trouble. A serious reactor failure took place in the early days before the barrier installation was completed when one of the large reactors in a generator connection to the synchronizing bus was flashed over, probably due to being touched with a wooden scale, and badly burned. This spread to one adjacent feeder reactor and blistered and scorched some of the bus insulation and breaker disconnecting contact barriers but caused no other damage.

The most serious failure took place recently when apparently an over ambitious workman got some foreign material through the opening in the disconnecting contact barrier while a generator circuit breaker was down for maintenance. The flashover of the live bus insulator set fire to the protecting barrier and bus insulation and to an oil filter press standing below, and most serious of all, resulted in the only electrical operating fatality of the station. Enough soot from the burning insulation and oil deposited on other insulators, even through the small openings where the breaker bushings project into the barriers, so that one feeder breaker's stationary bushing arced over about 15 min later, but did not result in any fire. The readiness with which the insulation material burned and the fact that so much soot found its way into the breaker disconnecting contact bushings within the room, was somewhat disappointing.

The results of the failures as contrasted with failures involving live parts in older cell-type breaker and bus construction, even at 6,600 volts, has demonstrated the superiority of the later construction. Metal-clad switch gear which was not available when the station was built goes a step further, but also has its own disadvantages. It is doubtful whether metal-clad switch gear would have prevented this failure, and it is quite possible that the failure of the stationary disconnecting bushing would have released and ignited oil resulting in a more serious fire. The closer fit around the disconnecting bushings might have prevented the dangerous deposit of soot on the bushings of the other breakers. On the other hand it would be more difficult to cut clear damaged equipment to restore service and the larger amounts of inflammable oil or compound which might be released by a failure would introduce some additional fire hazard. However, it is believed that the complete surrounding of high voltage parts by grounded metal is a step in the right direction in reducing risks of failures and preventing the spread, should a failure occur. It is to be hoped that advances in designs and materials will bring equipment that can be cut clear more readily if trouble occurs in any part and will reduce the fire hazard of inflammable materials. Metal-clad reactors were studied for the latter part of the station, but cost, losses, space, and oil fire hazard brought the decision to continue the station with the open concrete core reactors having turn insulation instead of the earlier bare conductor type.

The breakers themselves were put into operation and have been maintained with comparatively little difficulty. The screw elevating and disconnecting features, such as have now become common on some metal-clad designs, have been highly satisfactory. The clamping and interlocking can undoubtedly be simplified and cheapened in cost, but the operation has been entirely satisfactory. As compared with a group of 7 33-kv metal-clad switch gear units in a substation of the company, for which there is one movable elevating platform, the built-in elevating features of the Hudson Avenue breakers is much safer and the speed with which a breaker may be lowered for disconnecting purposes, or raised and

restored to service, is particularly valuable where feeders must be disconnected fairly frequently. There have been a few cases of internal flashover of breakers in substations having the same design as the feeder breakers except for truck mounting. Tests indicate that this possibility can be removed by slightly internal barrier changes and additions. This will probably be undertaken although there have been no generating station breaker troubles. Some studies have been made looking toward the increase in interrupting rating of the bus breakers by installing oil blast features in place of the explosion chambers. This is not necessary now but may be undertaken later to increase the margin between breaker rating and possible short circuits when load conditions require more machine capacity on the bus and greater interstation tie capacity. (See Table I.)

The ground and test facilities have been decidedly valuable in making it possible to ground or test a feeder promptly and safely. The separate grounding breaker, designed to be able to close onto a short circuit, has been used to ground a feeder and force out a network switch which failed to trip on cable charging current, or transformer exciting current. Somewhat faster and more satisfactory operation would be secured if the double ground and test switches used on the bifurcated feeders, were capable of opening or closing load current at full voltage so that it would not be necessary to deënergize and ground both branches before one branch can be connected or disconnected. However, the need for placing the double ground and test switch in the space provided for a single switch made it impossible to provide such a design. It is not believed that the ability to clear or restore one branch of a bifurcated feeder without the necessity of killing and grounding the whole circuit would justify any very expensive refinements.

The precautions taken in the building construction to prevent a failure spreading from one phase to another, or from one section to another, have been entirely successful at least as far as any failures to date are concerned. They have, however, made adequate ventilation more difficult. There is some condensation under certain atmospheric conditions, and in a new station it would be desirable to provide facilities for more rapidly clearing out smoke should a fire occur. Perhaps by the time the next station is built satisfactory breakers without inflammable fluids will be generally available.

Control and Relay Operation

The general control system has been as satisfactory as anticipated. The principle of keeping the number of instruments, control devices, etc., to the minimum really necessary for operation, and have those stand out clearly as well as have each panel distinct, has aided operation. As an aid to general system load dispatching, remote load indicating and totalizing equipment is now being installed to give the load of the principal stations of the Consolidated Gas system in the central system operators' room.

Some study has been given to the advisability of adding automatic voltage control, or at least an automatic means of rapidly increasing excitation in emergency, but these studies and experience indicate that the load and generator characteristics are stable at present. The most trying of these experiences have been the loss of field on the most stable unit in operation at the time, the pulling out of step of the least stable unit, and the sudden tripping out of a 110,000-kw unit due to flashover of its terminals when a cooling radiator sprang a leak. In all cases the remaining units stayed in step and while the voltage dropped momentarily, approximately 60 per cent in the worst case, it was immediately restored.

Some improvements in feeder relaying might be secured by installing the current transformers beyond the reactors rather than in the breaker bushings. This would permit faster feeder relay settings by avoiding the necessity of a time differential between the feeder and selector breakers in case of reactor failure, and would have avoided the possibility of a feeder breaker attempting to open a reactor failure in case of improper timing of relays or breaker tripping. The faster feeder breaker operation was not an advantage when the system was designed due to the necessity of selecting with substation breakers and at present would be advantageous only on purely network feeders. The installation of bushing current transformers in the breakers of the single branch feeders probably made a safer and certainly a much cheaper installation than would have been secured by cutting into the lead-covered feeder cables and installing separate current transformers. A change might have been made when the double ground and test switches were installed by using bushing current transformers in them, but it was believed that the cost of making the changes could not be justified by the improved operation.

Relaying has functioned well. Such failures as have occurred have been cleared with a minimum disturbance to the system. The results are a vast improvement over our old stations operated in 1 or 2 solid busses.

Conclusion

The station was designed as part of a definite distribution system, adapted to equipment and devices available at the time. There were compromises between cost and a closer approach to technical perfection, and choice often had to be made between the advantages and limitations of one design and somewhat different advantages and limitations of another method. But such is always an engineer's job. The station has operated with a high degree of continuity of service and safety to personnel. A review of the experience with this station leads its designers to look with favor toward even greater simplicity and approach toward the unit principle. It is hoped that its design was a small step forward, and that the results of its design and operation may prove helpful in the planning of later station control schemes and equipment that have and will come after it.

Attenuation and Distortion of Waves

The conventional theory explaining the attenuation and distortion of traveling waves is not adequate to explain many peculiarities found to exist in such waves. In this paper there is developed a multi-conductor multi-velocity theory of traveling waves which more completely explains wave behavior. The conventional traveling wave theory is shown to be a special case of this more general theory.

By
L. V. BEWLEY
ASSOCIATE A.I.E.E.

General Elec. Co.,
Pittsfield, Mass.

CATHODE ray oscillograms of artificial lightning surges on transmission lines show many peculiarities which cannot be explained by conventional traveling wave theory. Some of these are: (1) The attenuation is much greater than can be accounted for by the losses, and is less for a surge on all the conductors of the system than for an equal surge on only one of the conductors, (2) as a surge travels along a line a pronounced step may develop in the wave front while (3) a loop of reversed polarity appears at the front of waves induced on adjacent conductors, (4) the attenuation is much greater for the inducing wave than for the induced wave, so that eventually both waves become substantially equal, (5) flat spaces develop on the tail of the surge, (6) the aggregate velocity of waves may be much less than that of light, (7) the coupling varies greatly with distance traveled, (8) voltage and current surges become dissimilar in shape, and (9) the steepness of the wave front may apparently first decrease and then increase.

These and many other facts follow as a natural consequence of the multi-conductor multi-velocity theory of traveling waves developed in this paper. It is shown that attenuation and distortion are largely due to these multi-velocities rather than entirely to losses as generally supposed. These multi-velocities are called into existence by either or both of 2 effects: (1) Zero potential planes for the electrostatic and electromagnetic fields are at quite different depths below the ground surface, and (2) effective conductor radii are different for the 2 fields on account of the corona envelope. In the light of this theory distortion becomes a comparatively simple concept, and such things as the reason why chopped waves attenuate much more rapidly than long waves becomes obvious. Open end adjacent conductors no longer merely "float" in the field of inducing waves, but give rise to powerful and unexpected reactions. The conventional traveling wave theory is a special case of this more general theory and may be delimited by it. In most practical applications the old theory suffices.

Conventional Theories Require Modification

It is ordinarily supposed that the attenuation and distortion of traveling waves are the direct result of energy losses. Conventional transmission line theory based on a single conductor and fixed constants R, L, C, and G will yield no clue to the mechanism of attenuation and distortion, except for the effect of the losses as represented by the series resistance R and shunt conductance G. Attempts have been made to include skin effect in the calculations, and to approximate the discontinuous action

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 29–26, 1934. Manuscript submitted Oct. 6, 1933; released for publication Nov. 13, 1933. *Not published in pamphlet form.*

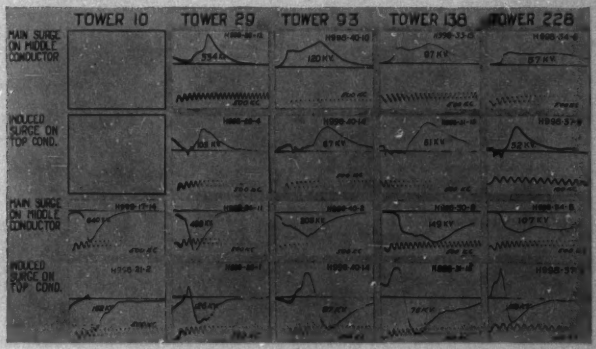


Fig. 1. Impulse tests on transmission lines to study coupling and attenuation

Voltage induced on a parallel conductor free from electrical connection

of corona, but these efforts have led to great mathematical complication, and they have failed to account for the peculiar distortions observed with impulse traveling waves on transmission systems. Moreover, the attenuation chargeable to such energy loss is far too small. When the single conductor theory is abandoned for the more complex multi-conductor theory based on all waves having the velocity of light[1,4,5,6] the results continue to be disappointing; for the linear nature of the equations compels all waves induced on adjacent conductors to be exact replicas of the parent wave, which is quite contrary to the observed facts. Apparently then, the conventional theories require some radical modification to agree with the facts. It is the object of this paper to present such a modification, and to show that on a multi-conductor system the waves move at different velocities, and a large part of attenuation and distortion is due simply to these differences in velocity. Furthermore, these differences in velocity have nothing to do with energy losses. Bekku and Satoh have shown the presence of algebraically different velocities on the completely transposed single and double-circuit 3-phase lines.[2,3] However, they calculated these algebraically different velocities all to be equal numerically to the velocity of light. It has further been shown that, in general, there can exist simultaneously on an n-conductor system waves with n different velocities of propagation.[4,5,6] But in the case of overhead conductors these different velocities all become equal to the velocity of light, provided that the radii of the conductors and the zero potential plane are the same for both the electrostatic and electromagnetic fields. This paper shows that this proviso is untenable in many cases; particularly with respect to attenuation, distortion, and coupling.

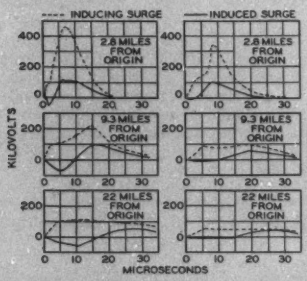


Fig. 2. Curves plotted from oscillograms taken on a transmission line with artificial lightning surges (from Brune and Eaton)

Typical Impulse Tests on Transmission Lines

During the summers of 1930 and 1931 an interesting series of experiments was conducted on the S 19 line of the Consumers Power Company and reported in several A.I.E.E. papers.[7,8] In Figs. 1, 2, and 3 are shown the attenuation and distortion experienced by the main, or parent surge impressed on one conductor, as well as that experienced by the accompanying surge induced on an adjacent conductor. There are 6 points of particular interest disclosed by these oscillograms:

1. As the main surge moves along the line it acquires a pronounced step in its front. That this cannot be due to corona is evidenced by the fact that it is present even when the wave is definitely below the corona level.

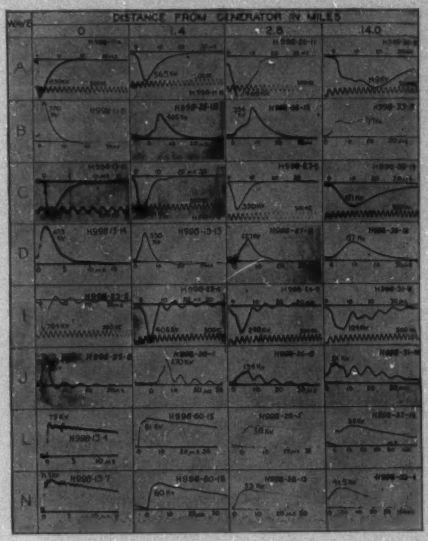


Fig. 3. Attenuation of traveling waves
Waves A, B, I, J, and L applied to one conductor only; waves C, D, and N applied to 3 conductors

2. As the induced surge moves along the line it acquires a pronounced loop of reverse polarity at its front. This loop cannot be due to corona, for it develops even when the main wave is far below the corona level, and for a positive wave—which causes a greater amount of corona—the loop is smaller, or may actually disappear.

3. Both the main and the induced surge become elongated with travel, but the main surge is attenuated much more than the induced surge; so that eventually they are of practically the same size.

4. Short surges, such as those chopped by an insulator flashover, attenuate much more rapidly than long surges. Positive surges suffer a greater attenuation than negative surges.

5. The induced wave is initially greater for a positive than for a negative wave.

6. Equal surges on all 3 conductors attenuate less than an equal surge impressed on only one conductor, but the wave front is flattened much more.

The theory which is developed in this paper explains all of these facts and shows conclusively that they are a natural consequence of different radii of conductors and different zero potential planes for the electrostatic and electromagnetic fields.

In 1930 Foust and Menger[9] developed an empirical formula for attenuation which has proved valuable

1. For all numbered references see list at end of paper.

in certain engineering calculations, but which gives no insight into the mechanism of attenuation.

E. W. Boehne[10] has offered an explanation of the effect of corona on the attenuation and distortion of traveling waves. His theory explains the reduced velocity of the surge and the increased surge impedance, and attempts also to present a plausible reason for the step which develops in the front of the main surge. It does not, however, tell why this same step develops without corona, nor does it explain the peculiarities which appear in the induced surge. Apparently other influences are present.

Brune and Eaton[8] have supplied a somewhat different explanation of the effect of corona. Their theory leads to an attenuation which is roughly linear. They do not attempt to find the reason for the distortion associated with the induced surge,

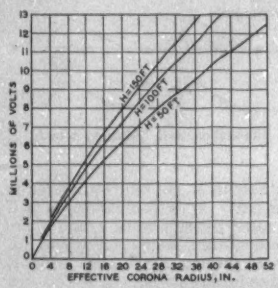


Fig. 4. Effective radius of corona on line conductors

beyond pointing out that the mechanism apparently involves a separation of charge on the isolated conductor.

Effective Radius of Corona Envelope and Equivalent Ground Planes

The effective radius R of the corona envelope surrounding a conductor carrying a high voltage surge was first determined by E. M. Hunter.[11] His method, since used by Fortescue,[12] and by Torok and Ellis,[13] is briefly as follows. The capacitance to ground of a cylindrical conductor of radius R and height H above ground is

$$C = \frac{1}{2 \log (2H/R)}$$

The radius R of the corona envelope is assumed to be that radius at which the gradient is just equal to the critical corona gradient of 76 kv/in. The gradient is

$$g = \frac{2Q}{R} = \frac{2\,CE}{R} = \frac{E}{R \log (2H/R)} = 76 \text{ kv/in}$$

or

$$E = 76\, R \log (2H/R)$$

This equation is plotted in Fig. 4 for representative values of E and H. Now the electrostatic field corresponds to this effective radius of conductor, but not so the magnetic field. The current wave is still restricted to the metallic conductor, although probably concentrated at its periphery due to transient skin effect. Therefore, in calculating the electrostatic coefficients a larger radius must be used than in calculating the inductance coefficients. Furthermore, if the different conductors of a multi-conductor system are carrying surges of different potentials, then the effective corona radius will be different for each conductor. If the voltages are below the corona voltage, then the electrostatic coefficients must be figured on the basis of the metallic conductor.

It is well known that the equivalent zero potential plane with respect to zero sequence and third harmonic currents on power systems is at a considerable depth below the ground plane. This is also true for the comparatively high frequency currents used in telephone practice. The depth of the equivalent image depends upon the resistivity and stratification of the soil, and on the frequency. On the other hand, the zero potential plane with respect to the electrostatic field appears to lie very near or at the ground surface. In conventional traveling wave calculations it has always been assumed that the zero potential plane was the same for both the voltage and current waves, and this plane has habitually been taken as the ground surface. Torok and Ellis[13] have recently published data indicating a relationship between the depth of the equivalent ground plane and the tower footing resistance. But it appears to the author that there is not 1 but 2 zero potential planes, Fig. 5, one of which is associated with the voltage waves (the electrostatic field) and the other with the current waves (the magnetic field). Apparently the zero potential plane for the current wave is at a considerable depth.

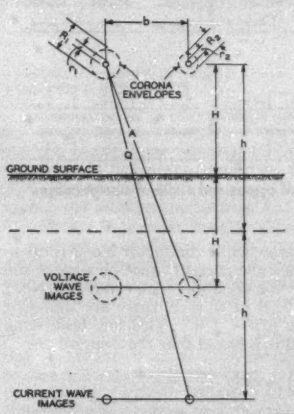


Fig. 5. Corona radii and position of images

The general situation for a 2-conductor system is shown in Fig. 5. The corona radii are shown different for the 2 conductors, since they may be carrying different voltage waves. The electrostatic and electromagnetic coefficients are given in Appendix I.

General Theory

The analysis rests, unfortunately, on the complicated multi-conductor multi-velocity theory of traveling waves.[4,5,6] In Appendix I this has been carried out in detail for the 2-conductor system of Fig. 5, and in Appendix II it has been generalized to apply to any number of conductors.

On the 2-conductor system it is found that there are on each conductor 2 waves with different velocities:

$$e_1 = f_1(x - v_1 t) + f_2(x - v_2 t)$$

$$e_2 = a_1 f_1(x - v_1 t) + a_2 f_2(x - v_2 t)$$

where the velocities v_1 and v_2, and likewise the fixed proportionality factors a_1 and a_2, depend only on the capacitance and inductance coefficients. There are corresponding current equations. The relative magnitudes, shapes, and polarities of the 2 waves $f_1(x - v_1 t)$ and $f_2(x - v_2 t)$ are determined solely from the terminal and initial conditions. For example, suppose a surge $E(t)$ is impressed on conductor No. 1 by

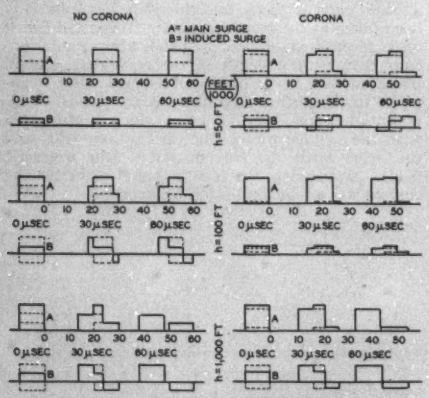


Fig. 6. Effect of corona and depth of current images

an impulse generator, while conductor No. 2 is open-ended. Then since the current must be zero at the open end, $x = 0$, while the 2 waves on conductor No. 1 must add up to $E(t)$ at $x = 0$, there are sufficient data to determine $f_1(x - v_1 t)$. This has been done in Appendix I and it is found that the 2 surges are

$$e_1 = \frac{1}{1-w} E\left(t - \frac{x}{v_1}\right) - wE\left(t - \frac{x}{v_2}\right) = e_1' + e_1''$$

$$e_2 = \frac{1}{1-w} a_1 E\left(t - \frac{x}{v_1}\right) - a_2 wE\left(t - \frac{x}{v_2}\right) = a_1 e_1' + a_2 e_1''$$

where w is a factor involving the circuit constants. Thus at $x = 0$

$$e_1 = E(t)$$

$$e_2 = \left(\frac{a_1 - a_2 w}{1 - w}\right) E(t)$$

Now the 2 component waves are moving at different velocities, so that eventually they part company, and so the ratio

$$\frac{e_2}{e_1} = \text{(coupling factor)}$$

is a variable quantity depending upon how far the waves have traveled and the relative magnitudes and polarities of the component waves. Thus initially

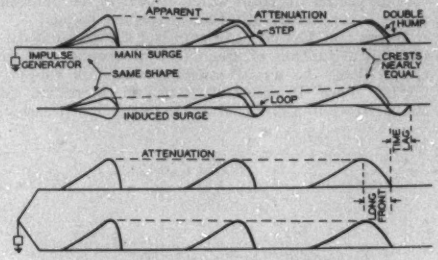


Fig. 7. Typical attenuation and distortion effect

the coupling factor may be 35 per cent while later on it becomes 100 per cent. It is also evident that if e_1' and e_1'' are the same polarity while a_1 and a_2 are of opposite sign, then as the 2 component waves disengage e_1 experiences greater attenuation, while e_2 may actually increase in magnitude! It is also seen that a step will develop in e_1 on account of the faster wave running ahead, while the whole surge becomes elongated, and a negative loop will appear in front of the induced wave on conductor No. 2. It remains to prove by numerical examples that the calculated polarities, velocities, and magnitudes are compatible with the oscillographic records and to show that the effect of corona may be predicted accurately from this theory.

Numerical Examples

The effect of varying the position of the magnetic zero potential plane and the corona envelopes of Fig. 5 is given in Table I, calculated according to Appendix I. The distance between conductors is kept constant at $b = 15$ ft, and likewise the electrostatic zero plane is assumed to remain constant at the ground surface, $H = 50$ ft. The magnetic zero plane is taken at $h = 50$, 100, and 1,000 ft, respectively. When there is no corona the metallic conductor radius is used to calculate both the coefficients. When corona is present the envelope for the main surge is taken as 3 in., which corresponds to 1,370 kv, while that of the induced surge is taken as one inch corresponding to 540 kv. Table I gives complete data on the magnitudes, velocities, and polarities of the 2 wave components on both conductors. These results have been plotted in Fig. 6 for rectangular waves and in Fig. 7 for typical lightning surges.

Table I—Numerical Examples; Effect of Varying h and R of Fig. 5

$b = 15$ ft	No Corona			Corona		
$h_1 = h_2 = h$ (ft)	50	100	1000	50	100	1000
$r_1 = r_2 = r$ (in.)	0.5	0.5	0.5	0.5	0.5	0.5
$(L_{21} = L_{12}) \times 0.5 \times 10^9$	7.775	8.47	10.77	7.78	8.47	10.77
$L_{22} \times 0.5 \times 10^9$	1.89	2.585	4.88	1.89	2.585	4.88
$H_1 = H_2 = H$ (ft)	50	50	50	50	50	50
R_1 (in.)	0.5	0.5	0.5	3	3	3
R_2 (in.)	0.5	0.5	0.5	1	1	1
$K_{11} \times 18 \times 10^{11}$	0.1366	0.1366	0.1366	0.1825	0.1825	0.1825
$K_{22} \times 18 \times 10^{11}$	0.1366	0.1366	0.1366	0.1545	0.1545	0.1545
$K_{12} \times 18 \times 10^{11}$	−0.0333	−0.0333	−0.0333	−0.0492	−0.0492	−0.0492
$l_{11} = (L_{11}K_{11} + L_{12}K_{12}) \times 9 \times 10^{20}$	1.00	1.070	1.307	1.327	1.419	1.729
$l_{22} = (L_{21}K_{21} + L_{22}K_{22}) \times 9 \times 10^{20}$	0.00	0.068	0.306	−0.001	−0.017	0.225
$l_{12} = (L_{11}K_{21} + L_{12}K_{22}) \times 9 \times 10^{20}$	1.00	1.070	1.307	1.110	1.153	1.425
$l_{21} = (L_{21}K_{11} + L_{22}K_{12}) \times 9 \times 10^{20}$	0.00	0.068	0.306	−0.308	0.055	0.361
v_1/(vel. of light)	1.00	0.937	0.787	0.863	0.840	0.726
v_2/(vel. of light)	1.00	0.999	0.999	0.955	0.918	0.892
$\alpha_1 = (1 - v_1^2 l_{11})/v_1^2 l_{12}$	0.244	1.000	1.000	−0.203	0.23	0.762
$\alpha_2 = (1 - v_2^2 l_{11})/v_2^2 l_{12}$	0.244	−1.000	−1.000	2.55	13.65	− 2.11
Ψ	−1.000	−0.568	−0.477	−0.211	−0.006	−0.149
$\alpha_1(v_1)$	0.500	0.638	0.677	0.826	0.994	0.871
$\alpha_2(v_2)$	0.500	0.362	0.323	0.174	0.006	0.129
$\alpha_3(v_1)$	0.122	0.638	0.677	−0.168	0.228	0.664
$\alpha_4(v_2)$	0.122	−0.362	−0.323	0.444	0.080	−0.272
e_1 (initially)	1.000	1.000	1.000	1.000	1.000	1.000
e_2 (initially)	0.244	0.276	0.354	0.276	0.308	0.392
$i_1(v_1)$	0.00107	0.00103	0.00092	0.00229	0.00238	0.00153
$i_2(v_2)$	0.00107	0.00103	0.00092	0.00016	−0.00005	0.00055
$i_3(v_1)$	0.00000	0.00103	0.00092	−0.00096	−0.00019	0.00073
$i_4(v_2)$	0.00000	−0.00103	−0.00092	0.00096	0.00019	−0.00073

A survey of Fig. 6 brings out several important facts:

1. When the current and voltage images coincide and the conductor radii are the same for both the voltage and the current waves, then there is but a single wave moving at the velocity of light. Neglecting losses, neither the main wave nor the induced wave suffer attenuation or distortion.

2. Increasing the depth at which the current images are located, brings into existence waves with 2 different velocities on each conductor. Since these waves travel at different velocities they separate with distance traveled. A step develops at the front of the main surge, while a loop of reversed polarity appears leading the induced surge. As the waves disengage, the amplitude of the main surge decreases, but, neglecting losses, the amplitude of the induced surge may actually increase, so that eventually both surges become practically equal. The separation of the component waves creates the impression of a simple elongation such as is associated with series resistance losses. So far as the author knows, a complete separation of the component waves has not yet been observed in experimental lightning studies, although there are several cathode ray oscillograms of both natural and artificial lightning surges which show the double humps characteristic of this separation. Of course, the elongating effect of series resistance losses will tend to keep the component waves joined.

3. Corona increases the size of the conductors with respect to the electrostatic field. In the calculation of Table I and Fig. 6 it was assumed that the voltage of the main surge was about 1,350 kv and that of the induced surge about 500 kv. By Fig. 4 these potentials correspond to radii of 3 in. and 1 in., respectively. In Fig. 6 it is shown that corona alone causes a step in the front of the main surge and a hump at the front of the induced surge. Thus the effect of corona and of depressed current images are similar on the main surge characteristic, but opposite on the induced surge characteristic. It might therefore be suspected that there are critical corona radii and depths of current images at which the 2 effects will nullify each other. In the case of $h = 100$ and corona on the conductors, this idea is supported by Fig. 6. It is seen that the main surge is practically a single wave, and the relative importance of the faster wave in the induced surge also has been considerably reduced. The principal part of the surge, represented by the slower wave, suffers a considerable reduction in velocity. Thus at 60μ sec the distances traveled are as in Table II.

Table II—Distance Traveled at 60 μsec

h	No Corona	Corona
50 ft	60,000 ft	52,000 ft
100 ft	56,000 ft	50,000 ft
1,000 ft	48,000 ft	43,500 ft

The rectangular waves of Fig. 6 give a clear picture concerning the mechanism of the phenomena, but are not particularly adapted for direct comparison with typical lightning surges. In Fig. 7 is shown a plot using typical lightning surges. Its counterparts among the oscillograms of Figs. 1, 2, and 3 are easily identified. The great variety of surge shapes which appear on transmission lines are not surprising when it is appreciated that the magnitudes, velocities, and polarities of the component waves all affect the resulting shape; nor from this point of view is there any mystery concerning the radical change in shape experienced by a surge as it travels along the line. Another point of some interest which has occasioned comment in the past is the dissimilarity in shape between the voltage and current impulses. This has been explained as due to a "variable surge impedance." In the light of the multi-velocity theory of traveling waves this dissimilarity is to be expected; for the surge impedances of waves with different velocities are different, and consequently the distortion in the current surge will be different than that in the voltage surge.

Physical Concept

This paper would not be complete without a brief physical explanation for the phenomenon of multi-velocity waves. Consider first Fig. 8, which shows a rectangular wave moving along a transmission line over ground having finite resistivity. The ground resistance is represented by a simple network having vertical and horizontal elements. Now at the instant when the advancing wave front reaches a capacitance element all the voltage is consumed by the ground resistance network, the current following paths somewhat as shown in the sketch. There then ensues a transient redistribution of current, at the termination of which the current paths are all horizontal, there are no vertical components of voltage drop, and consequently the surface of the earth is at zero potential, all the voltage being consumed by the capacitance elements of the line. The depth of penetration of the current depends, obviously, upon the resistivity of the soil, and will be deeper the greater that resistivity. Therefore 2 important conclusions are arrived at: (1) the ground surface quickly becomes a zero equipotential surface with respect to voltage images, and (2) the current images are located at greater depths, depending upon the earth resistivity. In general, then, the voltage and current images are not at the same levels, and in consequence of this difference the velocity of propagation $v = 1/\sqrt{LC}$ is slower than normal, because the inductance is greater than it would be if the current image were at the same level as the voltage image. Another effect of the earth resistance is to flatten the wave front; for on account

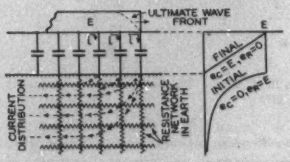


Fig. 8. Current distribution transient

of the redistribution transient, currents continue to flow in the line capacitance elements for some time after the passage of the wave front.

Consider now the effect of introducing a parallel isolated conductor. If the voltage and current images are coincident it merely happens that the voltage induced in the isolated conductor by the currents is exactly equal to that corresponding to its position in the electrostatic field due to the voltages. Under these conditions there is no necessity for a reaction. But if the current and voltage images are not coincident, then the currents tend to induce a different voltage in the isolated conductor than corresponds to its position in the electrostatic field. There can be no resultant current in the isolated conductor (since it is connected to no source) and therefore the only way it can react against these conflicting influences is by a separation of charge. This separation requires time. The mechanism by which it is accomplished is by means of current waves of equal magnitude but opposite polarity traveling at different velocities. Associated with these current waves are corresponding voltage waves, but the surge impedances for the 2 pairs are different.

A trapezoidal surge impressed on one conductor in the presence of another isolated conductor is shown in Fig. 9. The current paths are indicated by arrows. Initially there is no current in the induced surge. After the surge has resolved into its 2 components it is seen that each one of the smaller pair is equal and of opposite polarity, but they involve no net ground current. Consequently they travel at the velocity of light, and do not experience flattening of the front on account of ground resistivity. But those of the larger pair involve heavy ground currents, therefore, travel at a slower speed, and suffer considerable flattening of the wave front. It is obvious that if equal surges were applied to both conductors there would be no further resolution and the surges would propagate as simple, slow velocity waves, but would experience the flattening of the front characteristic of surges carrying ground currents.

The above ideas are illustrated in Fig. 7 for surges of typical shapes when waves are applied to one or both conductors. Notice, in the case of an isolated conductor, how first a step and then a camel's hump develops in the main surge, while a loop appears in the induced surge; the "apparent" attenuation is less for the induced than for the main surge, so that they approach equality; the front of the higher velocity wave is preserved while that of the lower velocity wave is flattened; and the surge is elongated. On the other hand, when equal surges are applied to both conductors only the slow velocity wave exists, but it suffers flattening of the front. However, its attenuation is less, because it

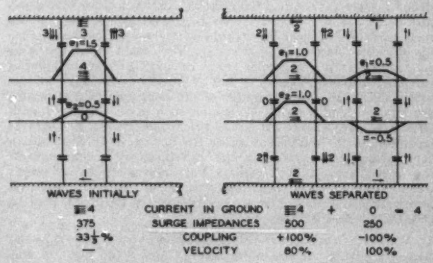


Fig. 9. Resolution of a surge into multi-velocity waves

contains no fast wave component that disengages. Comparing this picture with the oscillograms of Figs. 1, 2, and 3 the agreement is seen to be detailed and exact. In fact, there is hardly any need to remark that *C*, *D*, and *N* of Fig. 3 were for equal waves applied to all the line conductors.

The development of multi-velocity waves on a multi-conductor system is closely analogous to the

development of multi-frequencies in a simple oscillatory circuit when mutually coupled with a number of other such circuits having different independent natural frequencies of oscillation.

Conclusions

The attenuation and distortion of traveling waves are due to 3 principal causes:

1. Multi-velocity waves called into existence by dissymmetry in effective conductor radii and location of the equivalent images for the voltage and current waves, respectively.

2. A slippage effect at higher voltage levels caused by the reduction in velocity of propagation corresponding to the larger diameters of the corona envelopes.

3. Energy losses due to series resistance, skin effect, leakage conductance, and corona.

Of these, the first depends upon the resistivity of the earth and the polarity of the surge. The higher the resistivity the greater the depth to which the equivalent current images are forced, and the more pronounced are both the step which develops in the front of the main surge and the reversed polarity loop leading in the induced surge. On the other hand, the higher the voltage, especially if of positive polarity, the greater the corona envelope diameter and the more the tendency to develop a hump at the front of the induced surge.

But this first factor alone fails in several respects to account for all the observed phenomena. The attenuation is much greater than due to it alone, and the abrupt changes in wave shape called for by it do not always materialize. Rather are the changes in shape gradual. This smoothing process is probably due principally to the variable diameter of the corona envelope, causing the slippage mentioned as the second cause. This may be looked upon in 2 different ways: either as a slowing down of the higher voltage levels on account of the increased corona diameter; or as the yielding of charge to the corona envelope at higher voltage and the reclamation of these charges at lower levels below the corona voltage. The net effect of this action is to reduce the crest and fill in the tail of the surge, and in addition tending to smooth out the contours of the surge.

The energy losses are probably chiefly responsible for attenuation. A surge may start out with an initial potential of 1,000 kv and after traveling a few miles be reduced to 200 kv, or a 5:1 reduction. So far as the separation of the multi-velocity waves is concerned, not more than a 2:1 reduction would be possible on a 2-conductor system; or a 3:1 reduction on a 3-conductor system (assuming all component waves of the same size and polarity); while the reduction in voltage on account of the temporary storage of energy in the space charge is a matter of perhaps 25 per cent. This leaves the greater burden of attenuation on the energy losses. Series resistance tends to elongate a wave, while shunt conductance and corona energy loss tend to contract it. All losses tend to smooth out the irregularities in the surge. Ground resistance flattens the front.

If equal surges are applied to all the conductors of a multi-conductor system, then the resulting surges travel at a single velocity, and consequently the characteristic distortion associated with multi-velocity waves does not materialize. On this account the apparent attenuation is less than when the same surge is applied to only one conductor of the system, but the flattening of the wave front is greater.

Appendix I—2-Conductor System

The differential equations for the 2 conductors shown in Fig. 5 are

$$\left.\begin{aligned}
-\frac{\partial e_1}{\partial x} &= L_{11}\frac{\partial i_1}{\partial t} + L_{12}\frac{\partial i_2}{\partial t}\\
-\frac{\partial e_2}{\partial x} &= L_{12}\frac{\partial i_1}{\partial t} + L_{22}\frac{\partial i_2}{\partial t}\\
-\frac{\partial i_1}{\partial x} &= K_{11}\frac{\partial e_1}{\partial t} + K_{12}\frac{\partial e_2}{\partial t}\\
-\frac{\partial i_2}{\partial x} &= K_{12}\frac{\partial e_1}{\partial t} + K_{22}\frac{\partial e_2}{\partial t}
\end{aligned}\right\} \quad (1)$$

in which

$L_{11} = \frac{2}{10^9}\log\left(\frac{2\,h_1}{r_1}\right)$ = self inductance of No. 1

$L_{22} = \frac{2}{10^9}\log\left(\frac{2\,h_2}{r_2}\right)$ = self inductance of No. 2

$L_{12} = \frac{2}{10^9}\log\left(\frac{a}{b}\right)$ = mutual inductance between No. 1 and No. 2

$K_{11} = \frac{1}{D}\log\left(\frac{2\,H_2}{R_2}\right)$ = capacitance coefficient of No. 1

$K_{22} = \frac{1}{D}\log\left(\frac{2\,H_1}{R_1}\right)$ = capacitance coefficient of No. 2

$K_{12} = \frac{-1}{D}\log\left(\frac{A}{b}\right)$ = capacitance coefficient between No. 1 and No. 2

$$D = \left[\log\left(\frac{2\,H_1}{R_1}\right)\log\left(\frac{2\,H_2}{R_2}\right) - \left(\log\frac{A}{b}\right)^2\right]18 \times 10^{11}.$$

Notice that the effective radii and distances to the zero potential planes for the capacitance coefficients have been taken differently than for the inductance coefficients. Eliminating the currents in eq 1 there results

$$\left.\begin{aligned}
\frac{\partial^2 e_1}{\partial x^2} &= (L_{11}K_{11} + L_{12}K_{12})\frac{\partial^2 e_1}{\partial t^2} + (L_{11}K_{12} + L_{12}K_{22})\frac{\partial^2 e_2}{\partial t^2}\\
\frac{\partial^2 e_2}{\partial x^2} &= (L_{12}K_{11} + L_{22}K_{12})\frac{\partial^2 e_1}{\partial t^2} + (L_{12}K_{12} + L_{22}K_{22})\frac{\partial^2 e_2}{\partial t^2}
\end{aligned}\right\} \quad (2)$$

Let

$$\left.\begin{aligned}
I_{11} &= L_{11}K_{11} + L_{12}K_{12}\\
I_{12} &= L_{11}K_{12} + L_{12}K_{22}\\
I_{21} &= L_{22}K_{12} + L_{12}K_{11}\\
I_{22} &= L_{22}K_{22} + L_{12}K_{12}
\end{aligned}\right\} \quad (3)$$

Then eq 2 may be written as

$$\left.\begin{aligned}
\left(I_{11}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right)e_1 + I_{12}\frac{\partial^2 e_2}{\partial t^2} &= 0\\
I_{21}\frac{\partial^2 e_1}{\partial t^2} + \left(I_{22}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right)e_2 &= 0
\end{aligned}\right\} \quad (4)$$

Assume that eq 4 is satisfied by wave solutions

$$\left.\begin{aligned}
e_1 &= f(x + vt)\\
e_2 &= g(x + vt)
\end{aligned}\right\} \quad (5)$$

Substituting eq 5 in eq 4

$$\left.\begin{aligned}(I_{11}v^2 - 1)\, f''(x + vt) + I_{12}v^2 g''(x + vt) &= 0\\ I_{21}v^2 f''(x + vt) + (I_{22}v^2 - 1)\, g''(x + vt) &= 0\end{aligned}\right\} \quad (6)$$

Integrating each term of eq 6 twice with respect to x, the following relationships are seen to exist

$$g(x + vt) = \left(\frac{1 - v^2 I_{11}}{v^2 I_{12}}\right) f(x + vt) = af(x + vt) \quad (7)$$

$$v^{-4} - (I_{11} + I_{22})\, v^{-2} + (I_{11}I_{22} - I_{12}I_{21}) = 0 \quad (8)$$

Hence by eq 8

$$\frac{1}{v} = \pm\sqrt{\frac{(I_{11} + I_{22})}{2} \pm \frac{1}{2}\sqrt{(I_{11} - I_{22})^2 + 4\, I_{12}I_{21}}} \quad (9)$$

Corresponding to the interior ($\pm$) sign there are 2 numerically different values for the velocity v, and according to the exterior ($\pm$) sign the waves having these velocities may be either forward or backward moving waves. Moreover, by eq 7 waves on the 2 conductors having like velocities are definitely related. Therefore, calling the 2 velocities v_1 and v_2 the complete solution for forward waves may be written

$$\left.\begin{aligned}e_1 &= f_1(x - v_1t) + f_2(x - v_2t)\\ e_2 &= a_1f_1(x - v_1t) + a_2f_2(x - v_2t)\end{aligned}\right\} \quad (10)$$

and from eq 1 the current waves are

$$\left.\begin{aligned}i_1 &= (K_{11} + a_1K_{12})\, v_1f_1(x - v_1t) + (K_{11} + a_2K_{12})\, v_2f_2(x - v_2t)\\ i_2 &= (K_{12} + a_1K_{22})\, v_1f_1(x - v_1t) + (K_{12} + a_2K_{22})\, v_2f_2(x - v_2t)\end{aligned}\right\} \quad (11)$$

where

$$\left.\begin{aligned}a_1 &= \left(\frac{1 - v_1^2 I_{11}}{v_1^2 I_{12}}\right)\\ a_2 &= \left(\frac{1 - v_2^2 I_{11}}{v_2^2 I_{12}}\right)\end{aligned}\right\} \quad (12)$$

From eq 10 and eq 11 the effective coupling may be determined. Fig. 7 shows a wave being impressed on one wire of a 2-conductor circuit. Obviously there can be no current initially on the isolated conductor, so that at $t = 0$, eq 11 gives

$$f_2(x) = -\left(\frac{K_{12} + a_1K_{22}}{K_{12} + a_2K_{22}}\right)\frac{v_1}{v_2}\, f_1(x) = -wf_1(x) \quad (13)$$

This equation shows that the 2 waves have the same shape, but differ in magnitude. Hence for this case eq 10 becomes

$$\left.\begin{aligned}e_1 &= f_1(x - v_1t) - wf_1(x - v_2t)\\ e_2 &= a_1f_1(x - v_1t) - wa_2f_1(x - v_2t)\end{aligned}\right\} \quad (14)$$

Now if the initial wave impressed on the bottom conductor at $t = 0$ is $e_1 = E(x)$ then eq 14 gives

$$E(x) = f_1(x) - wf_1(x) \quad (15)$$

hence

$$f_1(x) = \frac{E(x)}{1 - w} \quad (16)$$

and finally

$$\left.\begin{aligned}e_1 &= \frac{1}{1 - w}\, E(x - v_1t) - \frac{w}{1 - w}\, E(x - v_2t)\\ e_2 &= \frac{a_1}{1 - w}\, E(x - v_1t) - \frac{a_2w}{1 - w}\, E(x - v_2t)\end{aligned}\right\} \quad (17)$$

Thus 2 waves with different velocities but of the same shape (in space) are present on both conductors. If the initial wave is impressed as a function of time $E(t)$ at $x = 0$, then eq 17 must be remodeled as follows:

$$\left.\begin{aligned}e_1 &= \frac{1}{1 - w}\, E\left(t - \frac{x}{v_1}\right) - \frac{w}{1 - w}\, E\left(t - \frac{x}{v_2}\right)\\ e_2 &= \frac{a_1}{1 - w}\, E\left(t - \frac{x}{v_1}\right) - \frac{a_2w}{1 - w}\, E\left(t - \frac{x}{v_2}\right)\end{aligned}\right\} \quad (18)$$

In this case the waves have the same duration as time functions, but are of different lengths and moving at different velocities. They start out together but the faster wave runs ahead and distortion results. For instance, suppose that the 2 waves of e_2 are of opposite polarity and that the negative polarity is the faster and smaller component. Then initially e_2 appears as a complete positive polarity wave, but after a while the negative component has forged ahead where it is no longer nullified, and e_2 then appears more elongated with a negative loop in front, and the main crest hardly at all affected by attenuation, because the negative component is partially detached and therefore does not subtract as much from the positive crest. These possibilities are demonstrated in the text by numerical examples and compared with actual impulse tests on transmission lines.

The more general analysis, applying to an n-conductor system is given in Appendix II.

Appendix II—N-Conductor System

The voltage waves ($e_1, e_2, \ldots, e_n$) on an n-wire multi-conductor system with zero losses are related by the following set of simultaneous differential equations (see chapter VI of reference 6):

$$\left.\begin{aligned}0 &= A_{11}e_1 + J_{12}e_2 + \ldots\ldots + J_{1n}e_n\\ 0 &= J_{21}e_1 + A_{22}e_2 + \ldots\ldots + J_{2n}e_n\\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\ 0 &= J_{n1}e_1 + J_{n2}e_2 + \ldots\ldots + A_{nn}e_n\end{aligned}\right\} \quad (1)$$

in which

$$J_{rs} = (L_{1r}K_{1s} + L_{2r}K_{2s} + \ldots + L_{nr}K_{ns})\, \frac{\partial^2}{\partial t^2} = I_{rs}\frac{\partial^2}{\partial t^2} \quad (2)$$

$$A_{rr} = \left(I_{rr}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right) \quad (3)$$

It has been shown (see chapter VI of reference 6) that these equations are satisfied by wave solutions

$$e = f(x \pm vt) \quad (4)$$

and that there are in general n distinct waves on each conductor. Each wave has a different velocity of propagation, as given by the roots of the following matrix:

$$\left.\begin{vmatrix}B_{11}I_{12} \ldots\ldots I_{1n}\\ I_{21}B_{22} \ldots\ldots I_{2n}\\ \ldots\ldots\ldots\ldots\ldots\\ I_{n1}I_{n2} \ldots\ldots B_{nn}\end{vmatrix} = 0\right\} \quad (5)$$

where

$$B_{rr} = (I_{rr} - v^{-2}) \quad (6)$$

Thus there can exist simultaneously on each conductor of an n-conductor system n pairs of traveling waves of different velocities of propagation ($v_1, v_2, \ldots, v_n$) and each pair consists of a forward and backward wave. Therefore

$$\left.\begin{aligned}e_1 &= [f_{11}(x - v_1t) + F_{11}(x + v_1t)] + \ldots\ldots\ldots\ldots +\\ &\qquad [f_{1n}(x - v_nt) + F_{1n}(x + v_nt)]\\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\ e_n &= [f_{n1}(x - v_1t) + F_{n1}(x + v_1t)] + \ldots\ldots\ldots\ldots +\\ &\qquad [f_{nn}(x - v_nt) + F_{nn}(x + v_nt)]\end{aligned}\right\} \quad (7)$$

The corresponding currents are given by

$$\left.\begin{aligned}i_1 &= \Sigma\, v_r\, [K_{11}(f_{1r} - F_{1r}) + \ldots\ldots + K_{1n}(f_{nr} - F_{1nr})]\\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\ i_n &= \Sigma\, v_r\, [K_{n1}(f_{1r} - F_{1r}) + \ldots\ldots + K_{nn}(f_{nr} - F_{nr})]\end{aligned}\right\} \quad (8)$$

If the effective radii and ground planes of the conductors with respect to the capacitance coefficients are the same as for the inductance coefficients, then eq 5 yields but a single value for the velocity of propagation (equal to the velocity of light) and eqs 7 and 8 then have but a single pair of waves on each conductor. But if

the effective radii and ground planes are different for the capacitance coefficients, then the waves with different velocities exist. However, all the waves of eq 7 are not independent. Substituting eq 7 into eq 1 and equating the terms of waves having the same velocity, there result n simultaneous equations relating the n waves having like velocities, from which any $(n-1)$ of them may be eliminated. Equation 7 may then be rewritten as

$$\left.\begin{aligned}
e_1 &= a_{11}\,[f_1(x - v_1t) + F_1(x + v_1t)] + \ldots\ldots + a_{1n}\\
&\qquad [f_n(x - v_nt) + F_n(x + v_nt)]\\
e_2 &= a_{21}\,[f_1(x - v_1t) + F_1(x + v_1t)] + \ldots\ldots + a_{2n}\\
&\qquad [f_n(x - v_nt) + F_n(x + v_nt)]\\
&\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
e_n &= a_{n1}\,[f_1(x - v_1t) + F_1(x + v_1t)] + \ldots\ldots + a_{nn}\\
&\qquad [f_n(x - v_nt) + F_n(x + v_nt)]
\end{aligned}\right\} \quad (9)$$

where the a coefficients are the proportionality factors between waves with the same velocity, as determined by substituting eq 9 in eq 1 and equating the coefficients of waves with like velocities. The current equations (eq 8) simplify to

$$\left.\begin{aligned}
i_1 &= \Sigma\,(K_{11}a_{1r} + K_1a_{2r} + \ldots + K_{1n}a_{nr})\,v_r\,(f_r - F_r)\\
i_2 &= \Sigma\,(K_{21}a_{1r} + K_{22}a_{2r} + \ldots + K_{2n}a_{nr})\,v_r\,(f_r - F_r)\\
&\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
i_n &= \Sigma\,(K_{n1}a_{1r} + K_{n2}a_{2r} + \ldots + K_{nn}a_{nr})\,v_r\,(f_r - F_r)
\end{aligned}\right\} \quad (10)$$

These, then, are the general equations of traveling waves on a no-loss multi-conductor system. The $2n$ remaining forward and backward waves are determined from the terminal or initial conditions.

References

1. Induktionswirkungen von Wanderwellen in Nachbarleitungen, K. W. Wagner. *E. T. Z.*, v. 35, 1914, p. 639–43; 677–80 and 705–80.

2. Electrical Oscillations in the Three-Phase Aerial Line, S. Bekku. Inst. of Elec. Engrs. of Japan, *Jl.*, Feb. 1923, p. 79–96.

3. Electric Oscillations in the Double-Circuit Three-Phase Transmission Line, Y. Satoh. A.I.E.E. Trans., v. 47, 1928, p. 58–67

4. Critique of Ground Wire Theory, L. V. Bewley. A.I.E.E. Trans., v. 50, 1931, p. 1–22.

5. Traveling Waves on Transmission Systems, I V Bewley. A.I.E.E. Trans., v. 50, 1931, p. 532–50.

6. Traveling Waves on Transmission Systems (a book), L. V. Bewley, John Wiley & Sons.

7. Studies of Traveling Waves on Transmission Lines with Artificial Lightning Surges, K. B. McEachron, J. G. Hemstreet, and W J. Rudge. A.I.E.E. Trans., v. 49, 1930, p. 885–94.

8. Experimental Studies in the Propagation of Lightning Surges on Transmission Lines, O. Brune and J. R. Eaton. A.I.E.E. Trans. v. 50, 1931, p. 1132–8.

9. Lightning Investigation on Transmission Lines. W. W. Lewis and C. M. Foust. A.I.E.E. Trans., v. 49, 1930, p. 917–48.

10. Lightning Investigations (a discussion) E W. Boehne. A.I.E.E. Trans., v. 49, 1930, p. 940–2.

11. The Effect of Corona on the Ground Wire Protection, E. M. Hunter, *G. E. Rev.* v. 33, 1930, p. 100–3.

12. La Foundre et ses Effets sur les Lignes Aeriennes, C. L. Fortescue. *Congrès International de Electricite*, Paris, 1932, v. 6, p. 399–464.

13. Factors Affecting Surge Potentials, J. J. Torok and W. R. Ellis. *Elec. Jl.*, v. 30, 1933, p. 381–7.

Simultaneous Control of Voltage and Power Factor

By
L. F. BLUME
ASSOCIATE A.I.E.E.

F. L. WOODS
APPLICATION PENDING

Both of the General Electric Company, Pittsfield, Mass.

A method of maintaining constant voltage at the load center of a transmission system, utilizing load ratio control equipment in combination with fixed capacitors, is described in this paper. This method combines the desirable performance characteristics of both the synchronous condenser and load ratio control methods, and in some cases results in appreciable savings in over-all system losses.

MAINTENANCE of constant voltage at the receiving bus or load center of a transmission system, independently of wide fluctuations in load, may be accomplished either by means of a synchronous condenser or by the introduction of voltage control apparatus at some convenient point, such as induction regulators or load ratio control.

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 8, 1933. *Not published in pamphlet form.*

The former method maintains constant voltage at the receiving bus, by adjusting line power factor so that line drop between receiving and sending busses remains constant for all loads. The latter method permits line drop to vary with load, but nevertheless maintains constant voltage on the receiving bus by inserting in the system a variable compensating voltage.

Although the 2 methods are radically different in principle, they both are being used extensively. In this paper the essential characteristics of the 2 methods are compared theoretically, primarily for the purpose of indicating how a third method, consisting of the combination of load ratio control and capacitors, may combine advantageously the desirable performance characteristics of the synchronous condenser and load ratio control.

It is shown that: (1) with the use of the combination equipment, appreciable savings in over-all system losses, both at no load and at full load, may be expected in some cases, as compared with either the synchronous condenser or load ratio control; (2) the capacitive kilovoltamperes required in the combination equipment is much less than when the

synchronous condenser is used; and (3) the transformer tap range is less than when standard load ratio control is used. The conclusion is reached that the combination equipment is superior under the following conditions: (1) the increased kilovoltamperes made available to the system by the use of the synchronous condenser is not of sufficient value to justify the extra cost involved; (2) where the advantages inherent in the synchronous condenser by virtue of its being a rotating device are not important; and (3) where the economies resulting from power factor correction justify the increase in first cost as compared with standard load ratio control. In view of the advantages inherently possessed by the combination equipment, obviously there are many practical situations in which this method is to be recommended.

Description of the "Combination Method"

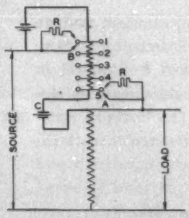
A bank of static capacitors may be so interconnected with a tap changing transformer that the capacitive kilovoltamperes introduced into the circuit is a function of the tap on which the transformer is operating and hence of the load. Figure 1 is the connection diagram of one arrangement, showing an autotransformer with taps in the series winding. By means of contacts *A* and *B* the incoming and outgoing lines may be connected to any of the taps; *A* and *B* are moved alternately and in opposite directions by means of a standard load-ratio-control mechanism. The position of the contacts shown in Fig. 1 (*A* on tap 5 and *B* on tap 1) correspond to maximum buck, in general the no load operating position. In the other extreme position, i. e., maximum boost position, contact *A* will be on tap 1, and contact *B* on tap 5 (Fig. 2) corresponding in general to the full load condition. Capacitors *C* are connected between the series and common windings in such a manner that in the maximum buck position, the voltage across them is zero, while in the maximum boost position, they receive the full voltage of the series winding. Thus, it is evident that at light loads, at which the equipment will be operating at or near its maximum buck position, no leading current will be introduced into the lines. Conversely, at full load, at which the equipment will be operating at or near its maximum boost position, maximum leading current will be introduced into the lines.

By this means, the output voltage can be maintained constant automatically, either at the transformer terminals or at the load center (with the aid of line-drop compensators); and simultaneously, leading current can be introduced into the circuit roughly proportional to the amount of load.

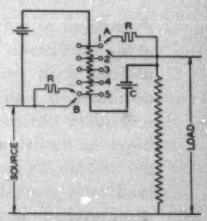
This combination scheme of control has characteristics similar to the synchronous condenser in that increasing leading kilovoltamperes are thrown on the system with increasing load, and at the same time voltage is held constant at the receiver bus. It differs fundamentally from a synchronous condenser in that voltage control is obtained by changing transformer ratio, as well as by changing the leading kilovoltamperes, whereas with the synchronous condenser, voltage control is obtained solely by controlling the amount of reactive kilovoltamperes, leading or lagging, that the condenser introduces into the system. On this account, especially if the synchronous condenser is used for maintaining constant voltage under all load conditions, the resultant power factor will not always be the most desirable. This is especially evident at light loads, under which condition the synchronous condenser is made to circulate lagging reactive kilovoltamperes in the system to prevent excessive voltage from appearing on the receiving bus. Therefore, the combination scheme of control, using variable transformer ratio, together with variable reactive kilovoltamperes, provides, from this point of view, a superior method of holding constant voltage. Furthermore, the kilovoltampere rating of the synchronous condenser for a given condition may be appreciably greater than the maximum leading kilovoltampere rating of the load ratio power factor control, because the former rating depends not only upon the economical power factor at which the system should operate at full load, but also upon the requirements of maintaining voltage constant. Thus it is found, in the example to be discussed, that the leading kilovoltampere rating of the synchronous condenser is about twice the capacitor rating for similar performance.

Elementary Considerations

In order to obtain a simple and direct comparison of the performance characteristics of the different methods, a simple one-way transmission system, equipped in turn with the 3 types of control, will be considered. As an aid to this comparison, it is convenient to use for reference purposes, that current



Maximum "buck" position, minimum voltage across capacitor



Maximum "boost" position, maximum voltage across capacitor

Figs. 1 (left) and 2 (right). Connections of equipment used for load-ratio power-factor control

which may flow through the line without producing any line drop between sending and receiving busses. This *zero-line-drop current* may have any magnitude whatever, but for any particular magnitude its phase angle is determined strictly by the impedance characteristics of the line. It must lead the receiving bus voltage by an angle ϕ (see tabulated list for definition of all symbols) the value of which

may be determined geometrically from the vector diagram, Fig. 3. Under these conditions, the sending and receiving bus voltages E_0 E_R form an isosceles triangle, the base of which is the impedance volts. From this diagram, the angle ϕ by which the zero-line-drop current I_0 leads the receiving bus voltage can be determined readily for any value of transmission line impedance. The angle ϕ can be considered to be made up of the sum of 2 angles, α which is a function of the impedance volts, and β which is a function of the ratio of line reactance to line resistance. The values of α and β are plotted in Fig. 4 as a function of the line characteristics, from which the value of ϕ can be obtained very easily for any value of line constants.

Definition of Symbols

α	= an angle depending on the per cent line impedance
β	= an angle depending on the ratio X/R
ϕ	= $\alpha + \beta$
θ	= power factor angle
θ'	= corrected power factor angle
E_0	= sending end voltage
E_R	= receiving bus voltage
I_0	= zero-line-drop current
I_L	= load current referred to the line
I_L'	= load current referred to the line after power factor has been corrected
Z	= impedance of circuit, including line, transformers, etc., all of which hereafter are referred to as line, expressed in per cent
X	= reactive component of Z
R	= resistance component of Z
Q	= quadrature current to be added to I_L to give I_0
Q_1	= component of Q due to load power factor
Q_2	= component of Q due to line constants
Q_3	= leading quadrature current introduced for power factor correction
Q_4	= quadrature current causing line drop
r	= turn ratio of load ratio control transformer in maximum boost position

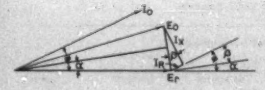


Fig. 3. Vector diagram showing zero-line-drop current

See tabulated list for definition of symbols

As illustrated in Fig. 5, any load current I_L may be resolved into a zero-line-drop current I_0 and a wattless current Q. In other words, line drop may be avoided by combining with the load current a wattless current Q so that the resultant line current I_0 leads the receiver bus voltage by an angle ϕ the value of which is determined from line characteristics as plotted in Fig. 4. This current diagram may vary in value from maximum to zero without introducing line drop or regulation, provided the proper power factor of the line current for zero line-drop always is maintained.

Synchronous Condenser. If, instead of providing the quadrature current Q necessary to maintain the zero-line-drop current, a quadrature current Q_3 (Fig. 6) is added giving a resulting line current I_L', then a line drop is introduced the value of which is determined by Q_4, which is the vector difference between I_L' and I_0. The numerical value of the line drop is equal to Q_4 times the line reactance X. The current Q_4 is necessarily constant to satisfy the condition of constant terminal voltage, taking for granted that the synchronous condenser is operating to maintain constant voltage at the receiving bus for all loads. It is, therefore, independent of load and may be designated as the *line-drop current*. Being constant and independent of the load, it is the lagging current supplied to the line by the synchronous condenser at no load.

Although both current diagrams, Figs. 5 and 6, are applicable to any value of load, their particular usefulness, as far as the present purpose of the paper is concerned, lies in the fact that from them the full load rating of the voltage control equipment may be determined quickly and accurately. For this purpose assume that the current I_L is the rated full load current for which the system is to be designed. Then the value of Q determines the synchronous condenser rating.

Generally, a synchronous condenser is designed to deliver 50 per cent lagging current at no load, in which case the full load leading output is $^2/_3Q$, the no load output is $^1/_3Q$, and the line drop becomes $^1/_3QX$.

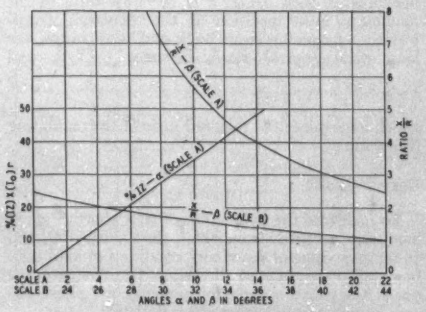


Fig. 4. Curves for determining angles α and β from circuit constants

By the foregoing procedure the currents concerned with the operation of the synchronous condenser have been analyzed into the variable current triangle, consisting of I_L, I_0, and Q, and the constant current Q_4, which determines line drop. The actual current flowing in the condenser, as well as in the system, is determined for both rated load and fractional load by the vector resultant of the variable and constant currents. Thus, assuming that Fig. 6 represents the rated load conditions, then rated current flowing in the line is represented by I_L' and the rated leading current of the synchronous condenser is Q_3. For fractional loads the variable currents are reduced porportionally, but the constant current Q_4 remains unchanged. Thus at 50-per cent load, the resultant currents are illustrated in Fig. 6 *A;* and at no load the current triangle vanishes leaving the constant current Q_4 as the only current flowing in the system.

Load Ratio Control. In this case, the load current I_L is also the line current, and the resulting line

regulation (which is measured by Q, the amount of departure from zero-line-drop current) is neutralized by introducing a compensating voltage, thus holding the receiving bus voltage constant. The total line drop is QrX where r is the turn ratio in the maximum boost position of the regulating transformer. Assuming equal buck and boost range, the load ratio control range becomes $\pm QrX/2$, and the maximum ratio r of the regulating transformer is

$$r = 1 + \frac{QrX}{2} = \frac{2}{2 - QX}$$

which determines the required ratio of the regulating transformer.

Combination Scheme With Capacitor. In the combination of load ratio control with capacitors, we may assume that at full load the capacitors with maximum load ratio control range impressed across them, furnish a leading current Q_3, Fig. 7, sufficient to correct the line power factor to a specified value, say 95 per cent.

The amount of departure of the line current I_L' from the zero-line-drop current is Q_4 and the total line drop is Q_4rX where r is the turn ratio in the maximum boost position of the regulating transformer. Assuming equal buck and boost range, the load ratio control range becomes $Q_4rX/2$, and

$$r = 1 + \frac{Q_4rX}{2} = \frac{2}{2 - Q_4X}$$

which determines the required ratio of the regulating transformer.

Use of Chart

To facilitate the evaluation of Q, a chart (Fig. 8) has been prepared, from which the values of Q_1 and Q_2 for any value of ϕ and any condition of load may be readily determined directly. To illustrate the use of the chart, assume for example, a 3-phase circuit having the following characteristics:

Total line impedance including step-up and step-down transformers (% IZ)	20%
Ratio of line reactance to resistance (X/R)	6
Rated load delivered at receiving bus	100%
Power factor of load	80%
Receiving bus voltage	100%

For 100-per cent load at 80-per cent power factor, zero-line-drop current as determined from the chart is 83 per cent. (Only by successive trials can this value be determined accurately since it is affected by the value of ϕ.) Determine by means of Fig. 4 the angle ϕ, by which the zero-line-drop current leads the receiving bus voltage.

$(\%IZ)\ I_L = 0.20 \times 0.83 = 0.166$ Hence $\alpha = 4.6°$
$X/R = 6$ $\beta = 9.4°$
$\alpha + \beta = 14.0°$

By means of the chart, Fig. 8, the numerical value of the quadrature current Q is determined (Fig. 5) for $\phi = 14°$ and load power 80 per cent, this being made up of $Q_1 + Q_2$, obtained from the chart. Thus

$Q_2 = 20\%$
$Q_1 = 60\%$
$Q = 80\%$

from which the required ratings of the various control equipments can be determined quickly, as previously described.

Where a synchronous condenser having a 50-per cent lagging rating is used, the size of the condenser is $^2/_3Q = 53$ per cent; for full load this corrects the 80-per cent power factor load to $60 - 53 = 7$ per

Table I—Performance Characteristics of the 3 Equipments

Constant voltage maintained under the following conditions: load power factor = 80 per cent; line impedance = 20 per cent; X/R = 6; X = 19.7 per cent

	Full Load Performance	Synchronous Condenser	Load Ratio-Power Factor Control	Load Ratio Control
1.	Load	100%	100%	100%
2.	Load power factor	80%	80%	80%
3.	Line power factor	99.5%	95%	80%
4.	Line impedance	20%	20%	20%
5.	X/R	6	6	6
6.	X	19.7%	19.7%	19.7%
7.	Q, obtained from chart	80%	80%	80%
8.	Leading current introduced	53%	34%	0%
9.	Lagging current effective in producing line drop	27%	46%	80%
10.	Line drop	5.31%	9.50%	17.1%
11.	Line current	80%	87.1%	108.5%
12.	Voltage boost	0%	4.75%	8.55%
	Comparative losses:			
13.	Voltage control apparatus	38	5.3	5.3
14.	Line and transformers	62	78	118
15.	Total system losses	100	83.3	123.3
	No Load Performance			
16.	Line current	28%	0	0
17.	Line drop	5.5%	0	0
18.	Voltage buck	0	−4.75%	−8.55%
	Comparative losses:			
19.	Voltage control apparatus	26.8	1.1	1.1
20.	Line and transformers	15.2	13.4	14.4
21.	Total system losses	42.0	14.5	15.5

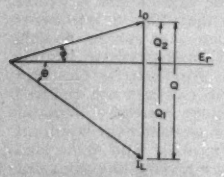


Fig. 5. Vector diagram of variable currents

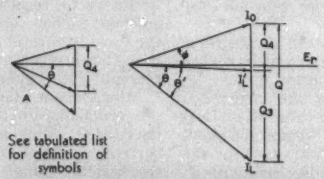


Fig. 6. Vector diagram for a synchronous condenser with 50-per cent lagging rating ($Q_4 = \frac{1}{2} Q_1$)

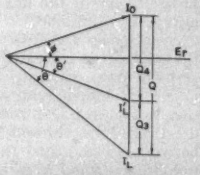


Fig. 7. Vector diagram for load-ratio power-factor control

Fig. 8. Chart for determining rating of control equipment, broken line shows a concrete example of the following procedure:

1. Locate intersection of given load power factor radius with load current arc in the lower half of the chart

2. Project this intersection horizontally and note on the vertical quadrature current scale the quadrature current Q_1 in per cent of load current

3. From Fig. 4 determine values of ϕ equal to $\alpha + \beta$ (the phase angle of the zero-line-drop current) assuming both I_0 and r equal to unity

4. Draw a radius in upper half of chart from origin corresponding to the value of angle ϕ

5. The intersection of the radius just determined with the vertical line drawn through the intersection as determined in (1) gives the magnitude of zero-line-drop current. Its value can be read directly by means of the circular arcs

6. Project the intersection as determined in the preceding paragraph horizontally and read the corresponding value Q_3 on the vertical quadrature current scale

SYNCHRONOUS CONDENSER. Adding the values obtained in (2) and (6) gives $Q = Q_1 + Q_3$, which is the combined leading plus lagging rating of the synchronous condenser expressed in per cent of the assumed load current

LOAD RATIO CONTROL. Maximum ratio of load ratio control equipment necessary to compensate for the line regulation is obtained by substituting in equation $r = \frac{2}{2 - QX}$

COMBINATION EQUIPMENT. When capacitors are added to load ratio control equipment, first determine zero-line-drop current in the same manner as described in (1) to (6) and in addition proceed as follows:

7. Project the intersection as determined in (2) vertically until it meets the radial power factor line corresponding to the power factor to which it is desired to correct, and project this intersection horizontally to the vertical quadrature scale and note its value

8. Subtract this value from the value obtained in (2) to give the current rating of the capacitors (in per cent of assumed full load) required to obtain the desired power factor correction

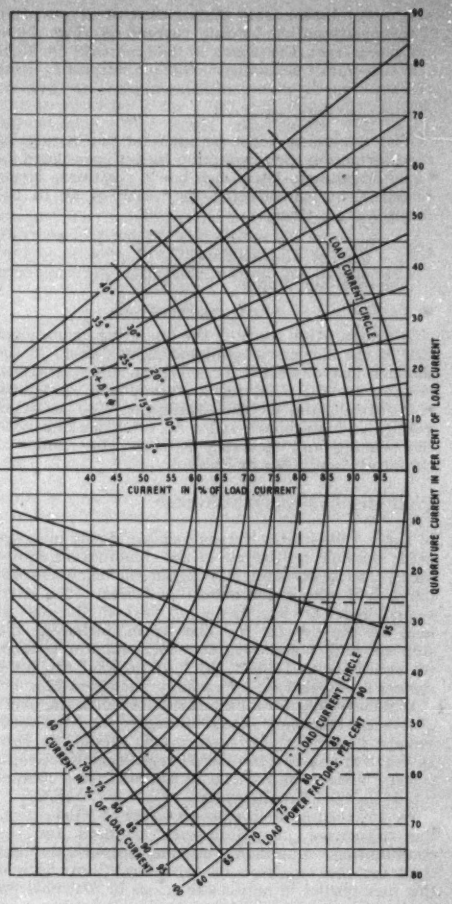
9. Add the value obtained in (9) to the value of Q_1 obtained in (2) to obtain the quadrature current Q_4

10. The maximum ratio of regulating transformer necessary to compensate for the line regulation is obtained by substituting in equation $r = \frac{2}{2 - Q_4X}$

PROCEDURE FOR GREATER ACCURACY. In the above procedure a small error is introduced because in obtaining α and ϕ both I_0 and r are assumed to be equal to unity. This assumption gives values of α and ϕ slightly larger than the correct values, and therefore the equipment ratings so determined are greater than the real values. To correct this error, proceed as follows:

11. Multiply the per cent line impedance by the values of zero-line-drop current and r as obtained above, and use this value in redetermining ϕ. With the new value of ϕ repeat the procedure starting from (4). Note in the case of the synchronous condenser r is always equal to unity

12. In using this chart, it will be found convenient to express all voltages in per cent of the receiving bus voltage which is maintained constant, and all currents in per cent of the assumed uncorrected full load current. All values of line characteristics should be reduced to this base.



cent, which corresponds to a power factor between 99.75 per cent and unity. The lagging rating $^1/_3Q$ = 27 per cent multiplied by line reactance 19.7 per cent determines the line drop; $0.27 \times 0.197 = 0.053$ or 5.31 per cent.

Where load ratio control is used to neutralize line regulation, the maximum ratio required on the assumption that the regulating transformer is designed for equal maximum buck and boost positions, is determined by substituting the value of Q in the formula for r, that is

$$r = \frac{2}{2 - QX} = \frac{2}{2 - (0.80 \times 0.197)} = 1.083$$

The line drop is then

$$0.80 \times 1.083 \times 0.197 = 0.171 \text{ or } 17.1\%$$

Where load ratio-power factor control is used, assume that in the full boost position the capacitive kilovoltamperes introduced is sufficient to improve

the power factor from 80 per cent to 95 per cent. The corresponding leading current Q_3 (Fig. 7) as obtained from the chart is 0.64 − 0.28 = 0.36. The amount of departure of the line current I_L' from the zero-line-drop current is equal to

$$Q_4 = Q - Q_3 = 80 - 36 = 46\%$$

The maximum ratio required for the regulating transformer on the assumption that it is designed for equal maximum buck and boost positions, is determined by substituting the value of Q_4 in the formula for r, that is

$$r = \frac{2}{2 - Q_4X} = \frac{2}{2 - (0.46 \times 0.197)} = 1.05$$

The total line drop is

$$Q_4rX = 0.46 \times 1.05 \times 0.197 = 0.095 \text{ or } 9.5\%$$

A comparative study of the operating characteristics of the 3 types of equipments was made in the manner just described for a typical one-way transmission system involving a step-up and step-down transformer, and on the assumption that constant voltage is maintained under all conditions on both the sending and receiving busses. The results of this study are given in Table I.

Comparison of the 3 Methods

Table I illustrates the appreciable saving in losses made possible by the use of the combination equipment, due to its inherently higher efficiency as compared with the synchronous condenser. The total system losses are less, in spite of the fact that for full load on the system the line losses, including the step-up and step-down transformers, are greater (compare items 14 and 15). At no load the total system losses also are appreciably less (item 21).

It follows that for all intermediate loads, the overall system efficiency should be higher, and the total system losses for any load cycle, should be less. In Fig. 9 are plotted loss curves representing the total system losses from no load to full load for a system rated 12,500 kilovoltamperes.

By correcting the line power factor to 95 per cent, the capacitive kilovoltamperes required for the combination equipment become appreciably less than for the synchronous condenser (item 8) and this fact results in major reductions in first cost for the combination equipment. The assumption tacitly is made here that power factor correction to values greater than 95 per cent generally is not desired for economical reasons, and that it is done in the case of the synchronous condenser because of the necessity of maintaining constant voltage. The difference in the effect on the line current is shown in item 11 of Table I. These differences in line currents are due in part to the difference in the power factor of the resulting line currents, and in part to the turn ratio of the regulating transformer, which, in the maximum boost position corresponding to full load, must be introduced to neutralize the line regulation (item 12).

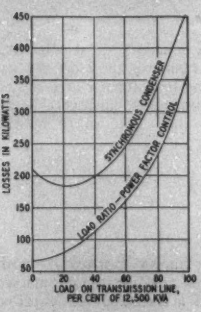


Fig. 9. Comparison of system losses with 2 methods of control

The advantages of minimum line current (item 11) for identical loads, obtained by the use of the synchronous condenser, are obvious, because for a given maximum line current, limited by the current rating of the station equipment, the system is capable of delivering more kilowatts and more kilovoltamperes to the load. The importance of this advantage can be judged only in connection with specific applications, since so much depends upon whether the safe current limits of the system apparatus are approached.

Combination Scheme vs. Load Ratio Control

A general comparison of the advantages of the combination scheme with those of ordinary load ratio control, depends largely on the question of whether for a given application it is economically desirable to improve the line power factor. As the first major cost of the combination equipment consists largely of the capacitor costs, it is obvious that power factor correction must be highly desirable to make the additional cost worth while. In the example cited in Table I, the large increase in efficiency and the large reduction in line current resulting from the addition of capacitors, is so great as to justify a considerable increase in the first cost of the control equipment, as compared with load ratio control.

In general, the desirability of combining load ratio control with capacitors, is made less (1) the higher the power factor of the load, and (2) the lower the reactance between the sending and receiver busses. The latter factor, by reducing the transformer tap range necessary to maintain constant voltage, is effective in reducing the first cost of the load ratio control equipment.

Other Advantages of the Combination Scheme

1. The absence of high speed rotating parts, and the fact that practically no auxiliary equipment is required, makes it possible to install the combination equipments at any convenient point on the line.

2. It becomes possible to use several relatively small units and place them on the system closer to the load centers.

3. On account of the ease with which capacitor units may be added when needed, it is not necessary to install at any given time any greater capacity than actually is needed. The rating of the transformer can be made adequate for future growth, but as the cost of capacitors make up the largest part of the total cost, the initial investment is not increased greatly by the necessity for future load growth.

Joint Use of Poles With 6,900-Volt Lines

A plan has been developed for joint occupancy of poles by power and telephone circuits in the Staten Island, N. Y., area, involving 6,900-volt distribution. The aim of this plan is to secure to the public and to the power and telephone companies over-all safety, convenience, and economy. Results of this coöperative study of joint use are presented in this paper.

By
W. R. BULLARD
MEMBER A.I.E.E.
Elec. Bond and Share Co., New York, N. Y.

D. H. KEYES
ASSOCIATE A.I.E.E.
Am. Tel. and Tel. Co., New York, N. Y.

Abstract

JOINT use of poles has been found mutually advantageous for the distribution of power and telephone services and coöperative work for the purpose of determining mutually satisfactory practices has been carried on for many years. "Principles and Practices for the Joint Use of Wood Poles" were approved in 1926 by the National Electric Light Association and the Bell Telephone System. At that time, it was found necessary to place some limitations on the joint practices. In order to obtain fully acceptable joint practices, the Joint Subcommittee on Development and Research[1] has carried on a number of studies of the problems in specific areas. The study described in this paper was made for Staten Island, New York, and was concerned with the economics and relative safety of certain phases of power and telephone distribution. The study covers estimated plant requirements for the period from 1932 to 1950, and is based upon estimates of growth of population and service requirements through this period.

Previous studies made by the power company indicated the desirability of supplying the load either by extending the existing 2,300-volt delta system or by changing to a 6,900-volt delta system. Factors which influence the effects which may be experienced in event of contact between the power and telephone circuits are given and evaluated for the particular situation.

The study indicates that in view of conditions which exist in Staten Island and features which would be incorporated in the design and operation of the 6,900-volt system, the safety of joint construction at the higher voltage can be made comparable with that of the 2,300-volt joint construction now existing. The study also shows that substantial economies would be obtained by the use of the 6,900-volt system.

This is an example of the satisfactory solution by coöperative effort of a mutual problem of distribution. The solution arrived at and the conclusions drawn are dependent, as is always the case, upon the local conditions, but the method of attack is felt to be generally applicable to problems of this type.

Full text of a paper recommended for publication by A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 27, 1933; released for publication Nov. 14, 1933. *Not published in pamphlet form.*

1. This work now being carried on jointly by the Edison Electric Institute and the Bell Telephone System.

Introduction

The public requires both power and telephone service, and the problem of distributing these to the same customers involves factors which are so closely interrelated that to arrive at an economically sound solution, coöperative consideration must be given to the requirements of both. In built-up areas where both distribution plants are aerial, joint use of poles in accordance with mutually acceptable practices, is usually preferable to separate pole lines in respect to safety, public relations, and over-all economy.

The problems of joint use of poles received consideration by the Joint General Committee of the National Electric Light Association and Bell Telephone System, and as a result of its early work, that committee published a report dated February 15, 1926, entitled "Principles and Practices for the Joint Use of Wood Poles by Supply and Communication Companies." These principles and practices were intended as a basis on which electric supply companies and communication companies could work out their joint use problems mutually, and among other items, recommend that each party should:

"Be the judge of the quality and requirements of its own service, including the character and design of its own facilities."

"Determine the character of its own circuits and structures to be placed or continued in joint use, and determine the character of the circuits and structures of others with which it will enter into or continue in joint use."

"Coöperate with the other party so that in carrying out the foregoing duties, proper consideration will be given to the mutual problems which may arise and so that the parties can jointly determine the best engineering solution in situations where the facilities of both are involved."

In order to extend this work, the joint subcommittee on development and research is conducting studies of types of plant, methods of construction, and protection practices. Mutually accepted practices for joint use at the lower distribution voltages are well established. However, many of the present day joint use problems relate to the use of higher distribution voltages. These studies include assembly of data to permit the various factors to be weighed, and development of additional or improved methods and devices to meet the present and future requirements. This paper describes briefly the

first of a series of field studies being made in co-operation with operating power and telephone companies. This study was made possible through the coöperation of the New York Telephone Company and the Staten Island Edison Corporation.

Basis of Study

The engineers of the Staten Island Edison Corporation in connection with their system planning had conducted extensive studies of their distribution problem to determine the system that would most economically provide satisfactory electric service. As a result of these studies they determined that either a 6,900-volt delta system or a 2,300-volt delta system would best meet their conditions, the former proving the more economical provided satisfactory joint use of poles could be arranged. Furthermore, local conditions generally make it impracticable to erect more than one pole line on a street. Where such dual lines have been built in the past, it is generally necessary to consolidate them at such time as the poles in either line become defective and require replacement. An exception to this rule is the case of wide streets where it is necessary to place street lighting on both sides. Since mutually acceptable practices for joint use at the higher voltages were not available, the joint subcommittee was invited to coöperate in the study of the over-all economies and protection practices applicable to the power and telephone systems, with a view to assisting in finding the best engineering solution for this case.

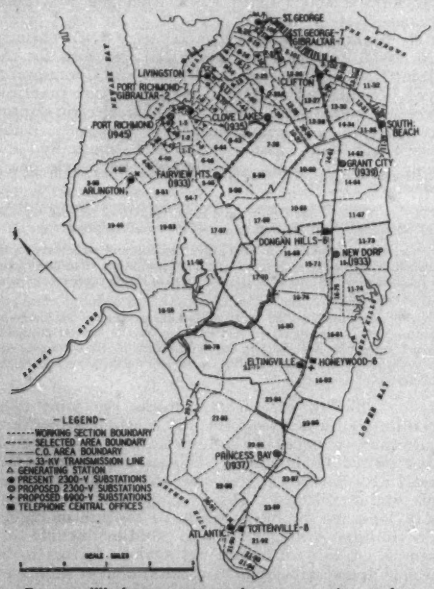


Fig. 1. Working sections, substations, and central offices in Staten Island

General Conditions

Staten Island is 1 of the 5 boroughs of the City of New York. It is located to the southwest of the center of the city and is separated from the New Jersey Coast by a channel averaging about 0.5 mile wide. The island is about 7.5 miles wide and 14 miles long, with an area of about 57 sq miles. Due to the lack of direct transportation to the rest of the City, the development is as yet largely suburban except for a small urban area at the north and a large industrial area along the north and west shores.

The present 2,300-volt joint use plant is of a good average grade of construction. In general, 40-ft poles are used with a span length of 100 ft. The span lengths are largely controlled by local restrictions and street lighting requirements. Joint use has been extensively used throughout the island between telephone circuits and the 2,300-volt circuits.

Power System

At present in Staten Island there are 1 generating station and 6 distribution substations, including 1 at the generating station. The locations of these substations are shown on Fig. 1.

There are now 3 voltages employed in Staten Island—33,000 volts for transmission between the generating station and several of the substations, 6,900 volts for some substation supply but mainly for primary supply to large industries and to a minor extent for other distribution, and 2,300 volts for the remainder of the distribution system throughout the island.

The present distribution transformers are mostly between 5 and 25 kva. They are fused on the primary side for transformer failure, but not for overload. The tendency is to use the 25 to 50-kva sizes and longer secondaries for most cases in new construction. Lightning arresters are used for the protection of all transformers fed from open wire. There are many shade trees on the island, but adequate clearance for the primaries is maintained.

The present substation transformers have 3-section secondary windings which are now connected in parallel for 2,300-volt operation and which can be connected in series for 6,900-volt operation. All of the newer switching gear is suitable for either 2,300-volt or 6,900-volt operation.

The street lighting is a series system using incandescent lamps. Constant current transformers are pole-mounted, supplied from 2,300-volt primary circuits kept separate from the general distribution system.

The power secondaries are generally grounded to the water system on customers' premises.

Telephone System

There are 5 central office buildings on Staten Island, each of which contains a common battery

exchange. The locations of these offices also are given on Fig. 1.

The use of underground cable along main feeder routes is rather extensive, the minimum amount terminated at any one office being 2,000 ft. In general, aerial cables extend from the underground terminals to the limits of each central office area, there being very little open wire. The maximum length of aerial cable is approximately 3 miles, but the average length is materially less.

The many shade trees require the more frequent use of terminals than is the general practice on the aerial cables in order to minimize the number of runs of drop wire along the cables.

Subscribers in the aerial cable territory are served by drop wire between their premises and the aerial cable terminals. Where the drop wire enters a subscriber's premises it is provided with a protector. This protector consists of 7-amp fuses, and carbon block protector gaps from the lines to ground. Telephone protectors are generally grounded to the water system on subscribers' premises.

Growth

The first step in obtaining the requirements for the power and telephone system throughout the period of the study was to arrive at an estimated population growth for the island. Data as to the residence and business development and present usage of the 2 services in the area were studied, together with local and economic factors which were instrumental in effecting past growth or have an influence on the future.

From these factors the number of residence and commercial electric meters was estimated. Taking into account the fact that the power company is promoting electric range and water-heating loads in addition to the other increases in the use of electric power, the load per meter was obtained. A combination of these estimates gives the load for which the distribution system must be designed. The area studies give the distribution of load in various sections of the island.

The telephone study employed the family as a unit and is based upon United States and other census records as to past performance, divided in accordance with the various subdivisions of the study area. The forecast of the future utilization of the telephone was made based on the projection of the various factors and subdivided for the areas.

The detailed methods employed and the results obtained in these growth studies would require more space than could be allotted in this paper.

A section of the island consisting of approximately 13 sq miles, representative of conditions throughout the island, except for a congested underground section, was selected for detailed study. For carrying out the study this selected area was further divided into 14 small working sections.

Power in Selected Area

Maps of the selected area were prepared, showing the location and sizes of all the distribution transformers required to serve the estimated loads. On such a map a layout of primary lines was made for the 6,900-volt plan consisting of 6 feeders radiating from the Eltingville substation. On a similar map the 2,300-volt plan was shown, using 2 substations, 1 at Eltingville with 8 feeders and 1 at New Dorp with 5 feeders. Service requirements and load distribution in this territory make desirable the use of large transformers and extensive secondaries rather than smaller transformers and shorter secondaries. It was recognized that some saving might be effected by using for the 2,300-volt system smaller transformers and less extensive secondaries, but this saving was not considered sufficient to offset the advantages of the large transformers in this territory. Due to these considerations, the assumed locations and sizes of transformers were the same for both voltage systems.

The primary circuits were designed for the same regulation limits in both plans, namely, plus or minus 2 per cent at the load centers and plus or minus 3 per cent at points of maximum variation. Each feeder with its branches was laid out geographically to serve certain distributed loads. The size of wire required between substation and load center to give the desired regulation then was computed. When the specified regulation could not be obtained without going to undesirably large wire sizes, regulators were specified. Sizes larger than No. 4/0 were generally avoided for mechanical reasons, but some larger sizes are now in place and additions were made in certain cases. Single-phase regulators were specified, 2 or 3 on a feeder depending upon the amount of regulation required.

The power loss in the primary wires was estimated for each circuit from the yearly effective load current and the resistance from substation to load center, plus a small allowance for branches. The effective current was determined by comparison with load curves from actual circuits serving similar types of loads and the resistances were computed. Losses in the branches are generally very small since the wire, for mechanical reasons, is usually of such size that the current density is low.

The total amount of primary wire required for each system was determined from the maps. From the circuit lengths the numbers of crossarms and insulators were estimated. Two lightning arresters were assumed per distribution transformer. The plans were made so as to use, as far as possible, the wire and cross-arms now in place. The average length of the assumed 6,900-volt circuits (including branches) was approximately 3 times that of the 2,300-volt circuits.

Distribution transformer losses would be somewhat higher on the 6,900-volt system. The total for each plan was estimated, assuming core losses to be constant for the full year and the effective yearly average copper loss to be 0.2 times the full-load copper loss. This same factor was used in finding the primary line losses.

Regulator losses were found to be slightly greater in the 2,300-volt plan because of the greater number used. The 2,300-volt regulators have 1.6 per cent core loss and 2.4 per cent copper loss at full load as

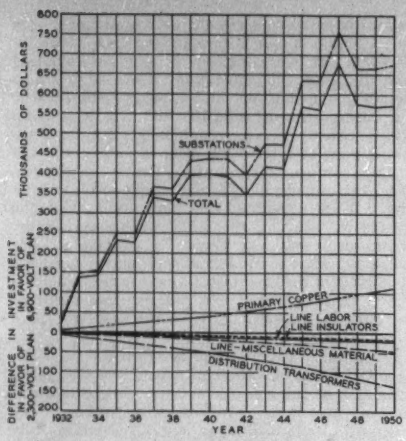


Fig. 2. Difference in investment between 2,300-volt and 6-900-volt plans for the whole Island

compared with 2 per cent core and 3 per cent copper loss in the 6,900-volt regulators. Core losses were assumed constant and copper losses were multiplied by 0.2 as for the transformers.

In both plans the Eltingville substation was used because it is now in operation and there is plenty of room for expanding it. It is necessary to add only the distribution voltage equipment as the present 33-kv equipment is ample. The substation is so located that it will serve some territory outside the selected area.

The 2,300-volt plan requires a new substation at New Dorp. This was necessary since it would be uneconomical to supply the power required for this whole area from Eltingville at 2,300 volts. All equipment for the proposed New Dorp substation was for outdoor mounting to be operated by supervisory control from St. George.

Power System on Whole Island

In order to project the study to include costs of the 2 plans for the whole island, peak loads were calculated for each working section on the island based upon the estimated population at intervals up to 1950. The ratio of load to population at each date was assumed to be the same as in the selected area.

The total line costs were assumed to be in direct proportion to the load served, based upon costs calculated in the selected area. Since additions to the primary system are made in comparatively small units, the investment at any time can be assumed to be proportional to the load served.

The change-over from 2,300 volts to 6,900 volts would require the gradual removal from the system of 2,300-volt transformers, line insulators, and some other equipment. The scrap value of all equipment that was not suitable for use on the 6,900-volt system was credited.

The 6,900-volt plant required no new substations but the total additions to present substations were estimated on the basis of the load requirements in the areas served which were calculated for each year so that the date of installation of additional equipment could be determined. The conversion to 6,900 volts would, of course, be gradual as required by the load growth.

The 2,300-volt plan required 6 new substations by the end of the study period. The dates of installation of new 2,300-volt substations were determined by comparing the cost of feeding a given group of working sections year by year with long feeders and regulators from existing substations against the cost of serving it from a new substation.

The methods used for estimating the losses in the primary wires, distributing transformers, and regulators have been indicated in the study of the selected area. Substation transformer losses were less in the 6,900-volt plan due to the larger sizes of the units, the principal saving being in the core losses. It was found that the increased cost of copper losses in the 2,300-volt substation transformers would be approximately offset by the decreased transmission line losses in the 2,300-volt plan. This difference in transmission loss was due to the tapping off of load at more substations closer together than in the 6,900-volt plan.

Line losses and distribution transformer losses were projected over the whole island and their growth estimated by assuming them to be directly proportional to the load served, based upon the relation between load and losses determined in the selected area. Losses in regulators and substation transformers, however, were added for each unit on the proposed date of its installation.

Table I shows the difference in investment of the various items for the 20-year period. In Fig. 2 is shown the accumulated difference in the capital expenditure year by year.

Table II shows the total difference in power loss in the various parts of the system for the 2 voltages. The accumulated power loss year by year is shown by Fig. 3.

Table I—Net Savings in Investment to 1950

	Favor of 6,900 Volts	Favor of 2,300 Volts
Substations	$674,000	
Primary copper	114,000	
Line insulators		$ 16,500
Line labor		20,000
Distribution trans.		135,000
Miscellaneous		45,500
Total	$788,000	$217,000
Grand total (see item 1 in "Results of Study")	$571,000	

The material and labor costs used were obtained by averaging costs for the period from 1926 to 1931. The present views on slower growth in population and changes which have taken place in costs of labor and material are factors of major importance, and fundamental in the study. These changes would reduce the total savings which the study shows, but should not alter appreciably the percentage difference in cost of the 2 power distribution systems. However, there is a definite indication that when increases are required in the capacity of the distribution substations and feeders on Staten Island, the gradual conversion to the 6,900-volt system in general accordance with the study herein outlined would result in substantial economies.

Table II—Net Savings in Power Loss to 1950

	Favor of 6,900 Volts	Favor of 2,300 Volts
Distribution lines	18,291,000 kwhr	
Substation transformers	14,005,000 kwhr	
Regulators	5,373,000 kwhr	
Distribution trans.		13,651,000 kwhr
Total	37,669,000 kwhr	13,651,000 kwhr
Grand total	24,018,000 kwhr	

Items, on which it was evident that the costs would be approximately the same in both systems, such as power supply, secondaries, customers' services, etc., were omitted from the comparisons.

Pole costs were not included in this study since they would be approximately the same for the 6,900-volt system as for the 2,300-volt system owing to the following:

1. There would be no appreciable difference in the number of poles jointly used because the total length of pole lines from substations to all distribution transformers was approximately the same for the 2 systems.

2. There would be no difference in the height of poles jointly used because the clearance between power and telephone attachments is the same for 6,900 volts as for 2,300 volts.

3. The existing pole sizes meet the strength requirements provided in the National Electrical Safety Code where 6,900-volt joint use is mutually agreed upon.

It was recognized that the costs of operating the 2 systems probably would be different but experience to evaluate this difference was lacking. However, all information available indicated that any increase in operation and maintenance would be small compared to the saving in favor of the 6,900-volt system.

Telephone System in Selected Area

Telephone plant layouts consisting of the aerial cable necessary to serve the estimated number of subscribers in this area were made on maps to the same scale as the power layouts. Two layouts were made for the telephone system to be used with the 6,900-volt power distribution in the selected area; one plan, attaching telephone cables to lines carrying primary wires, as would ordinarily be done with lower voltage primaries, and a second plan, avoiding joint use with primary circuits as far as practicable. There was found to be very little difference in the 2 plans as the power distribution lines had been laid out to avoid telephone routes as far as possible.

The telephone cable layout was superposed on each of the power distribution plans in turn to show the extent of the joint use requirements in the selected area.

Telephone System on Whole Island

This study was extended to cover the whole island by comparing each of the remaining sections with one in the selected area having similar characteristics. The total number of lines in 1950 was estimated for each section and the number of lines requiring protectors was found by assuming that the ratio of these lines to total lines was the same as that in the selected section used for comparison.

A comparison of plans for attaching and avoiding attachment showed that there is relatively little difference in the amount of plant involved. However, the total number of poles required for the latter arrangement would be somewhat greater.

Relative Safety of 2,300- and 6,900-Volt Delta Distribution Systems

The factors requiring consideration in a study of relative safety of various joint use plans are discussed in Provisional Report No. 6 of the Joint Subcommittee on Development and Research, entitled "The Coördination of Power and Communication Systems in Respect to the Joint Use of Poles" (National Electric Light Association Bulletin of December, 1931, p. 815). The plans assumed that the type of plant to be used in the future would be similar to that now used.

The voltage which can be impressed by contact on telephone wires and apparatus inside of buildings, while higher with 6,900 volts than with 2,300 volts, is limited since a favorable relationship between the power and telephone impedances is obtained due to the general use of low resistance grounds for the telephone services on the subscribers' premises.

With either voltage, without coördinative measures, currents as large as 400 amp might continue indefinitely in case of double faults on the power system. If one of these faults should involve the telephone plant, the current would be enough to burn off the cables either at the point of contact or at other locations. The burning off of the cable would eliminate the beneficial effect of the low resistance ground on the sheath and make it possible to impress

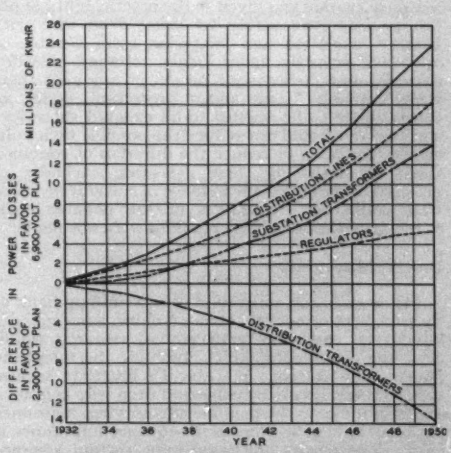


Fig. 3. Difference in power losses between the 2,300-volt and 6,900-volt plans for the whole Island

full phase voltage on drop wire and fuses. Tests and field experience show that the probability of fuses holding over is greater with 6,900 volts impressed than with 2,300 volts. The higher voltages which could be impressed on telephone cable might result in more failures involving many telephone circuits. If a power wire should fall on a drop wire, the insulation of the drop wire under condition of double fault might be subjected to as much as 6,900 volts. This might result in more failures of drop wire insulation than if the voltage were limited to 2,300 volts. A number of typical possible faults involving such a system and telephone plant are illustrated in Table III, and the results indicated.

Based on the above, there is little doubt that if the voltage were raised to 6,900-volts ungrounded delta without additional coördinative measures the hazard of joint use would be increased over that obtaining with 2,300-volts delta. Consideration therefore was directed to finding some practicable means for obviating the increase in hazard.

Separate Pole Lines

Completely separated aerial plants for the 2 utilities would be impossible on account of local conditions and restrictions. In addition, under the conditions in Staten Island, joint poles would usually permit a safer and more satisfactory arrangement of telephone drop and secondary service wires.

Telephone Measures

The protection used at each subscriber station consists of 7-amp fuses (Bell system code 11-*C*) and carbon block protector gaps, of 3-mil spacing (Bell system code Nos. 26 and 27) grounded to the city water system.

Consideration was given to the practicability of obtaining improved safety by using drop wire with heavier insulation and telephone fuses capable of operating properly under higher voltages, provided material and devices and means of applying them were available. This added protection would, of course, have to be applied to all exposed subscriber stations and would not reduce the possible high voltage on the cable or reduce the duration of contacts. Costs for installing these measures, exclusive of material, based upon the number of stations involved were estimated. Estimates of the possible costs of material that would be required were not made.

Power Measures

The use at each substation of a grounding bank of transformers of not less than 15 ohms zero-sequence impedance combined with ground relaying would clear the circuits for faults involving the telephone plant. The sketches of Table IV illustrate several types of fault involving cable and drop wire contacts, and also indicate the possible effects when a grounding bank having 38 ohms zero-sequence impedance is used. The results are based upon certain assumptions as to circuit lengths, grounding conditions, etc., as found in Staten Island and may not apply in other localities. It will be noted from these sketches that:

1. Faults involving telephone plant are quickly cleared, except in some cases when the cross is with the end of a broken wire away from the substation.
2. The voltage which can be impressed on telephone cable is limited to about 1,000 volts.
3. In general, the maximum voltage that can be impressed on drop wire insulation is 4,000 volts.
4. The maximum voltage across a fuse is generally limited to 4,000 volts, but in any case will be less than 6,900 volts.
5. Ground fault currents, in general, will not exceed 300 amp and usually will be cleared in less than 5 sec.

The exact condition which can occur will, of course, be somewhat affected by the impedance of the grounding transformer. Where a grounding bank is used, the circuit will be interrupted promptly by the initial fault to the telephone plant, which largely eliminates the possibility of it being involved in a double fault. Tests as well as field experience show that under the above conditions, the possibility of fuses holding over is not great. In addition to this, with water pipe grounds, the currents resulting, in case of contact, should always be sufficient to clear the circuit in a very short time. In case of contact with cable, the rapid interruption of the circuit will prevent the parting of cable and messenger. This maintains a low impedance through the telephone plant to ground and therefore limits the voltage which can be impressed on the telephone plant.

Design Features

In order to obtain the safety conditions outlined above, the committee considered the following features of construction and design necessary:

1. Construction in accordance with the National Electrical Safety Code.
2. Telephone circuits, except drop loops running from terminals to subscribers' premises carried in lead sheath cable.
3. Aerial telephone cables bonded to the messengers and to the underground cables.
4. Telephone station grounds of low impedance.
5. The power distribution system grounded through grounding banks with zero-sequence impedance of not less than 15 ohms. These banks to be installed in each 6,900-volt substation and continuously maintained in service to provide neutral point grounding for all feeders.
6. Ground relays installed and continuously maintained in service at such points so that: (1) any primary distribution circuit in case of fault to the telephone plant will be deenergized promptly, and usually within 5 sec; and (2) the current which can flow continuously through the ground connection without relay operation should be kept as small as practicable and not exceeding 100 amp.

Results of Study

A summary of the results of this study follows:

The difference in total investment between the 2,300-volt and 6,900-volt systems at the end of the study period would be about $570,000 in favor of the 6,900-volt system. This difference is influenced by the fact that the pole plant and substation equipment now installed are largely suitable for 6,900-volt operation. In other situations, where extensive replacements of either or both of these items were required substantial difference in relative economy might be expected.

The difference in power losses in favor of the 6,900-volt system would amount to 24,000,000 kwhr by the year 1950.

Table III—Results of Contact Between 6,900-Volt Isolated-Delta Circuit and Telephone Plant

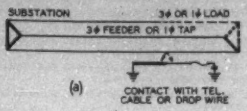
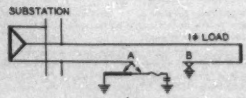
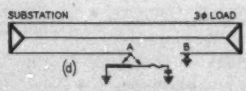
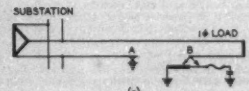
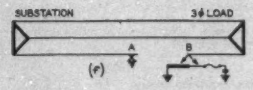
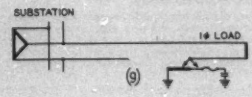
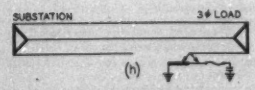
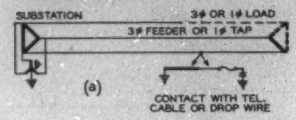
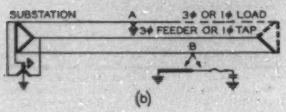
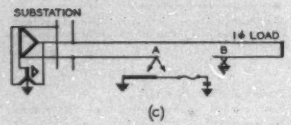
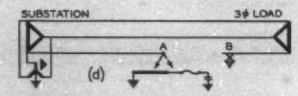
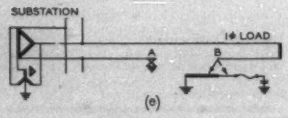
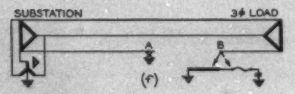
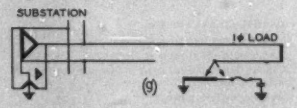
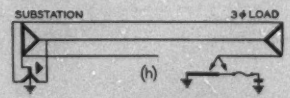
Circuit Diagram	Results of Contact With Cable Sheath or Messenger	Results of Contact With Telephone Drop Wire
 (a)	Fault current less than one amp No relay operation Volts on telephone cable negligible Duration until trouble is cleared The only hazard in this situation would be the removal of wire from contact without proper precautions	Protector blocks operate Fault current less than one amp No relay operation No fuse operation Voltage of telephone loop negligible Duration, until trouble is cleared Voltage available to break down insulation on drop wire, 4,000 volts Only hazard would be removal of wire from contact without proper precautions
(b)	If total impedance of 2 faults and circuit between them is less than 23 ohms, 300 amp overload relay trips, or less than 17 ohms, 400 amp overload relay trips. (Modified by load current.) Duration, up to several seconds if relay operates; otherwise until trouble is cleared Assuming fault A at bus and B at a distance, with 5 ohms in power circuit and 5 ohms in telephone cable, I = 690 amp, voltage of cable = 3,450 volts Maximum voltage of cable without circuit interruption approximately 2,000 volts (400 amp × 5 ohms) Maximum fault current near substation limited by short-circuit capacity of substation	Protector blocks operate If total impedance of 2 faults and circuit between them is less than 690 ohms, telephone fuse blows, with 6,900 volts across it; or 23 ohms, 300 amp overload relay trips; or 17 ohms, 400 amp overload relay trips. (Modified by load current.) Duration up to several seconds if relay operates otherwise until trouble is cleared Voltage available to break down insulation on drop wire, 6,900 volts. Maximum current in drop wire about 1,500 amp Maximum voltage 6,900 if not limited by cable, for example, if it burns off and drop wire remains in contact
 (c)	Fault current somewhat less than load current No relay operation Duration, until trouble is cleared As this current can be nearly as great as the load current, without interruption, a poor contact will cause messenger to part and burn sheath and cable conductors. If sheath burns away, 6,900 volts on conductors will cause other cable troubles	Protector blocks operate Fault current somewhat less than load current. Will operate fuse if 10 amp or more. No relay operation Duration, until trouble is cleared Voltage available to break down drop wire insulation 6,900 volts. Volts on drop wire if fuse is not blown, negligible. If fuse operates, maximum voltage across it is 6,900 volts unless limited by cable breakdown
 (d)	Same as above except voltage may be only 6,000 instead of 6,900 if load is balanced	Same as above except voltage may be only 6,000 instead of 6,900 if load is balanced
 (e)	Fault current somewhat less than load current No relay operation Duration, until trouble is cleared As this current can be nearly as great as the load current, without interruption, a poor contact will cause messenger to part and burn sheath and cable conductors. If sheath burns away, 6,900 volts on conductor will cause other cable troubles	Protector blocks operate Fault current somewhat less than load current. Will operate fuse if 10 amp or more. No relay operation Duration, until trouble is cleared Voltage available to break down drop wire insulation, 6,900 volts. Volts on drop wire if fuse is not blown, negligible If fuse operates, maximum voltage across it is 6,900 volts unless limited by cable breakdown
 (f)	Same as above except voltage may be only 6,000 instead of 6,900 if load is balanced	Same as above except voltage may be only 6,000 instead of 6,900 if load is balanced
 (g)	Fault current less than one amp Duration, until trouble is cleared No relay action Voltage of telephone cable, negligible Possible hazard in case of attempt to remove contact without proper precautions	Protector blocks operate Fault current less than one amp Duration, until trouble is cleared Voltage available to break down drop wire insulation, 4,000 volts No relay or fuse action Possible hazard in case of attempt to remove contact without proper precautions
 (h)	Same as above	Same as above

Table IV—Results of Contact Between 6,900-Volt Delta Circuit With Grounding Bank* and Telephone Plant

Circuit Diagram	Results of Contact With Cable Sheath or Messenger	Results of Contact With Telephone Drop Wire
	Fault current up to about 300 amp Relay will clear circuit in less than 5 sec on any cable contact Voltage on telephone cable about 800 volts maximum, for worst impedance conditions in Staten Island. This does not occur with maximum fault current, however Relay operation independent of load	Protector blocks operate Fault current up to about 300 amp Relay will clear circuit in less than 5 sec on any drop wire contact unless fuse clears first Voltage available to break down drop wire insulation, 4,000 volts If fuse operates, maximum voltage across it is 4,000 volts Relay operation independent of load
	If contact at *B* occurs, relay clears in less than 5 sec If contact at *A* occurs first and is less than 70 ohms, it will clear circuit; if greater, fault will remain on until *B* fault occurs Voltage on telephone cable, 800 volts maximum as above Relay operation practically independent of load Maximum current about 300 amp	Protector blocks operate If contact at *B* occurs, relay will clear circuit in less than 5 sec, unless fuse clears first. If contact at *A* occurs first and is less than 70 ohms it will clear circuit, if greater, fault will remain on until *B* fault occurs Voltage available to break down drop wire insulation approximately 4,000 volts Voltage across fuse approximately 4,000 volts Relay operation practically independent of load
	Fault current up to about 300 amp maximum Relay clears circuit in less than 5 sec on contact at *A* Circuit may be cleared by fault *B* if fault impedance is low and if single-phase load beyond *B* is about 650 kva or more Volts on telephone cable about 800 volts maximum as above	Protector blocks operate Fault current up to about 300 amp maximum Relay clears circuit in less than 5 sec on contact at *A* unless fuse clears circuit Circuit may be cleared by fault *B* if fault impedance is low and if single-phase load beyond *B* is about 650 kva or more If fault *B* occurs first, voltage available to break down drop wire insulation, or voltage across fuse after it blows, may be approximately 3,400 to 4,600 volts in case of very large load beyond *B*, but will generally be approximately 4,000 volts
	Same as above, except requires about 1,000 kva 3-phase load to trip circuit through fault at *B*	Same as above, except requires about 1,000 kva 3-phase load to trip circuit through fault at *B*
	Fault current at *B* may reach 50 amp and clear circuit if single-phase load is about 650 kva or more; or current at *A* will clear circuit if impedance is 70 ohms or less Maximum current without tripping, 50 amp Maximum voltage on cable about 250 volts	Protector blocks operate Fault current at *B* may reach 50 amp and clear circuit if single-phase load is about 650 kva or more; or fuse may clear circuit; or current at *A* will clear circuit if impedance is 70 ohms or less Maximum current without tripping, 50 amp Voltage available to break down drop wire insulation, 4,000 volts or more, approaching 6,900 volts as impedance from bus to ground through *A* approaches zero. However, higher voltages remain on for less than 5 sec
	Same as above, except requires about 1,000 kva 3-phase load to trip circuit through fault at *B*	Same as above, except requires about 1,000 kva 3-phase load to trip circuit through fault at *B*, and voltage on drop wire may be from 2,000 to 4,000 volts; or 6,000 to 6,900 volts when impedance at *A* is zero
	Fault current less than 60 per cent of load current previous to fault, and may operate relay if load is 650 kva single-phase or more If load is not sufficient to trip circuit on ground current, fault will remain on	Protector blocks operate Fault current less than 60 per cent of load current previous to fault, and may operate relay if load is 650 kva, single-phase or more; or fuse may clear circuit. Voltage across fuse, 4,000 volts. Voltage to break down drop wire insulation, 4,000 volts
	Fault current less than $^1/_3$ of balanced 3-phase load current; may operate relay if load is about 1,000 kva or more If load is not sufficient to trip circuit on ground current, fault will remain on	Protector blocks operate Fault current less than $^1/_3$ of balanced 3-phase load current; may operate relay if load is about 1,000 kva or more; or fuse may clear circuit Voltage across fuse 2,000–4,000 volts Voltage to break down drop wire insulation 2,000–4,000 volts

* Consisting of 3 transformers rated at 100 kva each; reactance, 38 ohms per transformer. Secondaries connected delta. Ground relay set for minimum tripping current of 50 amp

The cost of the grounding transformers and ground relays for the 6,900-volt distribution system would be about $12,000.

The application to the telephone system of alternative safety measures considered would cost substantially in excess of the cost of the power system measures and does not appear justified in this case. Therefore, the cost of the telephone plant would be about the same in joint use with either power system.

With the additional protective measures provided for the 6,900-volt distribution system, the safety of joint use would compare favorably with that obtained under present conditions.

The adoption of the higher voltage in the power system appears, therefore, to provide the best engineering solution in this case and joint use of facilities apparently may be entered into in all instances in Staten Island where the 2 services should preferably be placed on the same poles.

The joint subcommittee is continuing its studies in other areas since the results of this study are not necessarily applicable where different conditions might influence the results to an important extent.

The authors wish to express their appreciation to the members of their project committee and particularly to Mr. L. F. Fox and Mr. A. A. Williamson of the New York Telephone Company and Mr. J. H. Lytle of the Staten Island Edison Corporation for their assistance and coöperation in carrying out the study upon which this paper is based.

Investigation of Rail Impedances

Measurements of impedance made on 5 sizes of rails and on 2 types of bonds are reported in this paper; the investigation covered a range of current per rail of 20 to 900 amp, and frequencies of 15 to 60 cycles per second. Results are given in a form convenient for engineering use, and include information for applying corrections for bond impedance and for temperature.

By
HOWARD M. TRUEBLOOD
MEMBER A.I.E.E.

GEORGE WASCHECK
NONMEMBER

Both of the American Tel. & Tel. Co., New York, N. Y.

PRINCIPAL results of experimental work, done in 1929 and 1930, to determine impedances of railroad rails over a range of frequencies and currents are given in this paper. The results are divided in a general way into 2 groups: one having to do with certain questions of general interest concerning rail characteristics (Figs. 3 to 8, and Tables I to VI), while in the other the data is presented in convenient form for engineering use (Figs. 9 to 15, and Table VII).

Full text of a paper recommended for publication by the A.I.E.E. committee on transportation, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1933. Manuscript submitted Oct. 10, 1932; released Nov. 9, 1932. *Not published in pamphlet form.*

A feature of the investigation is the detailed exploration of the electromagnetic field on and near the surfaces of the rails, the object of which was to put methods of calculating the impedances of circuits involving rails on a satisfactory basis. This part of the work has resulted in suggesting a practical meaning for the term "internal reactance" as applied to rails. This is explained and the term is adopted tentatively and used in setting forth results, which, however, are given also in form suitable for use in methods of calculation which involve "total" reactance.

Measured total reactances of the rail checked within 1 per cent the sum of the observed "internal" reactance and the calculated "external" reactance. In calculating external reactances results show that for traffic rails of usual design it should be satisfactory to assume the rail to be equivalent to a cylindrical conductor, the circumference of which is equal to the rail periphery.

Brief discussions are given of the methods and results of the investigations of bond impedance and of temperature effects. Data respecting the chemical, electrical, and magnetic properties of the rails are given, the degree of similarity among the different rail samples is discussed, and single curves for the resistance and the internal reactance of the "best representative rail" are shown.

Internal Reactance

Some explanation perhaps is needed with respect to "internal" reactance as the term is used in this paper. The usual engineering calculation of the reactance of a circuit involving parallel straight conductors proceeds from the assumption that the magnetic field due to the current in a single wire is strictly circular and coaxial with the wire, even in the close neighborhood of the wire. Usually the total reactances "to infinity" appear as the self-reactances in the computation, there being no point in distinguishing between internal and external reactance under the assumption of exact circular symmetry. Although the idea of internal reactance is clear and self-defining only for round wires where circular symmetry obtains, the practical need for the concept, or

for something equivalent, appears only when the field departs radically from circular symmetry as in the case of a railroad rail carrying current. A common procedure in such situations is to imagine the rail or other irregular conductor replaced with an "equivalent" conductor.[1] This latter is a straight round wire of zero internal reactance and of such a diameter that its external reactance "to infinity" is the same as the total reactance of the actual conductor. The fixing of the radius of the equivalent conductor of course requires a knowledge of the total reactance of the actual conductor, which, in the case of a steel rail, usually is inferred from measurements of its reactance out to a parallel wire sufficiently remote to insure that the field at this wire and at all points beyond is sensibly circular.

This method of handling the problem is convenient and for all ordinary purposes it is sufficiently accurate. By itself, however, it does not assure the reliability of any calculated results for circuits involving conductors closer to the rail than the wire used in the measurements from which the total reactance of the rail is inferred, and of course does not touch the question of the shape of the field in the near vicinity of the rail. There are practical situations in which the latter may be important. An example is the self-impedance of a rail with ground return, where the separation between the surfaces of the conductors forming the 2 sides of the circuit (the rail and the earth) is of the order of the height of the rail itself. To apply the formula given by Carson,[2] which contains a term representing internal impedance, requires that a meaning be assigned to this term in the case of the rail.

Considerations of this nature suggest that generally it would be convenient to conceive the reactance of such conductors as rails to be made up of 2 parts: (1) a part, which may be called *internal*, depending upon the material and geometry of the conductor itself, and varying with such conditions as temperature, saturation, etc., much as does the resistance; (2) a part to be calculated on the circular symmetry assumption, as with round wires, which, in contrast with the other, may be called *external*.

In adopting this point of view in the present paper, the internal reactance has been taken as the reactive component of the longitudinal electric intensity at the point of the rail periphery where it is a maximum. The line of the magnetic field that touches the periphery at this point, and is elsewhere outside of the periphery, is then the boundary separating internal and external reactance. This line is sufficiently nearly circular in shape to allow calculation of the external reactance, with the precision needed for engineering purposes, outward from a circle of specifiable radius that is centered on an axis of current concentration at a specifiable position in the rail (see Figs. 5 and 6). "Internal" as used in this way, of course, does not mean within the substance of the rail, part of the magnetic field concerned being outside the latter. The usage is appropriate, however, in that it signifies close association with the rail itself. It is also a *useful* way of extending the idea of internal reactance in a round wire to the complicated case of the rail, whereas it is difficult to see how the reactance associated with the field in the interior of the rail alone could be of practical value in calculations.

It is not intended to imply that the use of the equivalent conductor or total reactance method should be superseded by one based upon these concepts of internal and external reactance; on the contrary, the results of the experiments are given (in Fig. 14) in a form suitable to the former.

[1] References are at the end of the paper.

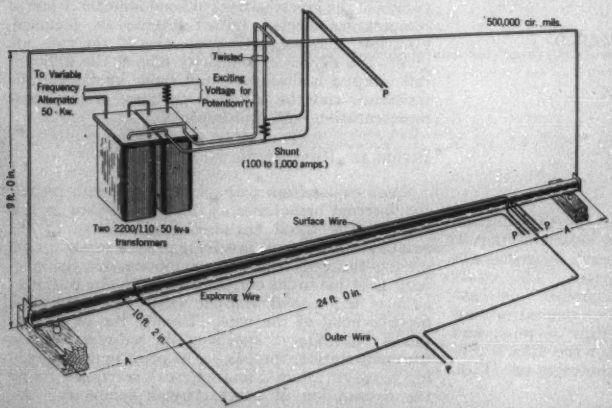


Fig. 1. Diagram of circuit arrangements for impedance measurements on single rails

P, leads (all in twisted pair) to measuring terminals of potentiometer. Dimension "A": for 60-lb rail, 3 ft; for 85- and 100-lb rails, 4 ft 6 in.; for 130-lb rail, 5 ft

Experimental Methods

The circuit arrangement used for most of the work is shown diagrammatically in Fig. 1, as set up for measurements on single rail samples. Where a bond was under investigation the same circuit dimensions were maintained by wrapping the bare cable once around the rail and brazing at the top and the upper surface of the base on each side. All conductors provided for measurement of rail voltage were connected to the rail by soldering to 2 small brass potential taps which were soldered to the web of the rail halfway between the base and top. Tests showed that the distance between adjacent current and potential terminals was ample for the elimination of end effects.

The voltage measuring conductors may be divided into 3 groups, the first consisting of No. 18 B.&S. gauge wires with enamel and single cotton insulation, stretched parallel to the rail axis along the rail surface and touching it, but insulated from it except at the ends. These are called "surface wires" in the following, and the resistances, reactances, etc., measured with them are called "surface resistances," etc. There were 7 positions for these wires in the routine testing, as shown by small letters in Fig. 2. The second group, called "exploring wires," were similar to the surface wires, except that they were held in close proximity to the rail surface instead of against it. They were used only in measurements on the 60- and 130-lb rails, in positions shown in Figs. 5 and 6. The third group was represented by a single No. 12 B.&S. gauge wire (hereafter called the "outer wire") parallel to the rail at a distance of about 10 ft, the ends being connected to the potential lugs by means of wires at right angles; the whole circuit formed, with the rail, a rectangular loop in a plane perpendicular to that of the test current loop.

In an earlier set-up used in measurements on the 90-lb rail and some of those on the 130-lb rail, the planes of the current supply and outer voltage loops made an angle of approximately 108°. In this arrangement, three lengths of 90-lb rail were used, welded together by the thermite process. The same sample of 130-lb rail was tested with both this and the final arrangement of the test circuits, and agreement within 2 per cent was obtained.

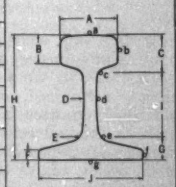
Measurements of rail current and voltages were made with an a-c potentiometer developed according to the design of E. C. Wente.[3] The potentiometer is of the null type, with a precision of at least $^1/_2$ per cent in magnitude and 0.2 degree in angle. A low frequency amplifier and a low pass filter were used in the detector circuit, and values of resistance, reactance, and impedance given throughout this paper are those corresponding to the fundamental frequencies. Close checks were obtained on measurements of magnitude by the potentiometer and by a vacuum tube voltmeter.

Temperatures were measured with 2 thermometers at the $^1/_3$ points of the rail sample, with bulbs laid against the bottom of the web (*e* position, Fig. 2) and covered with putty. The average of the 2 thermometer readings was taken as the temperature of the sample. Frequency was measured with a frequency meter of the vibrating reed type.

Rail Samples

Rails used in the tests were loaned by the Virginia Electric and Power Company, the Chesapeake and Ohio Railway, and the Richmond, Fredericksburg, and Potomac Railway, whose courtesy is gratefully acknowledged. There was only 1 sample of the 85-lb rail and 1 of the 100-lb rail, 2 each in the 60- and 130-lb sizes and 3 samples of the 90-lb rail. All samples were new, except the 2 60-lb rails. These had been

	60 lb. Rail	85 lb. Rail	90 lb. Rail	100 lb. Rail	130 lb. Rail
A	$2\,^5/_{16}$	$2\,^1/_2$	$2\,^1/_2$	$2\,^{13}/_{16}$	3
B	$^7/_8$	$1\,^1/_8$	$1\,^7/_{16}$	$1\,^1/_4$	$1\,^9/_{16}$
C	$1\,^1/_8$	$1\,^3/_8$	$1\,^9/_{16}$	$1\,^9/_{16}$	$1\,^7/_8$
D	$^1/_2$	$^1/_2$	$^5/_8$	$^{11}/_{16}$	$^3/_4$
E	$^5/_8$	$^5/_8$	$^3/_4$	1	1
F	$^3/_{16}$	$^1/_4$	$^5/_{16}$	$^3/_8$	$^9/_{16}$
G	$^3/_4$	$^7/_8$	1	$1\,^1/_{16}$	$1\,^1/_4$
H	$4\,^3/_{16}$	$5\,^1/_8$	5	6	$6\,^5/_8$
I	$2\,^9/_{16}$	$2\,^7/_8$	$2\,^7/_{16}$	$3\,^1/_2$	$3\,^1/_2$
J	$4\,^1/_4$	$5\,^3/_{16}$	$4\,^3/_4$	$5\,^9/_{16}$	$5\,^9/_{16}$
Penmeter	$18\,^1/_2$	$22\,^3/_8$	$21\,^3/_8$	$24\,^5/_8$	$25\,^3/_4$
See Note	f	f	f	a	a



Note
Small letters in the table show location of measuring wire (see diagram above) for measurements of resistance and internal reactance.
Dimensions in inches

Fig. 2. Dimensions of test rails and locations of surface wires for routine tests

Table I—Comparison of Surface Impedances of 2 Supposedly Similar Rail Samples

Rail Weight, Lb Per Yd	Frequency, Cycles Per Second	Current in Rail, Amperes	Point of Measurement*	Surface Reactance** Regular Sample	Surface Reactance** Check Sample	Surface Reactance** Per Cent Difference	Surface Resistance** Regular Sample	Surface Resistance** Check Sample	Surface Resistance** Per Cent Difference
60	25	75	f	0.775	0.875	12.9	0.830	0.920	10.9
			e	0.550	0.645	17.3	0.800	0.875	9.4
		700	f	1.21	1.25	2.8	1.81	1.87	3.3
			e	1.00	1.04	4.0	1.78	1.85	3.9
60	60	75	f	1.34	1.48	10.4	1.27	1.41	11.0
			e	0.890	1.01	13.5	1.18	1.32	11.9
		700	f	1.96	2.05	4.6	2.82	2.88	2.1
			e	1.50	1.55	3.3	2.78	2.84	2.2
130	25	75	a	0.565	0.610	8.0	0.500	0.530	6.0
			e	0.340	0.395	16.2	0.451	0.490	8.7
		700	a	0.911	1.01	11.0	1.26	1.32	4.8
			e	0.668	0.765	14.5	1.23	1.28	4.1
130	60	75	a	0.990	1.10	11.1	0.790	0.860	8.9
			e	0.530	0.600	13.2	0.700	0.750	7.2
		700	a	1.52	1.74	14.5	1.99	2.01	1.0
			e	0.990	1.20	20.2	1.90	1.94	2.1

* See Fig. 2. ** In milliohms at 70 deg F for 24 ft of rail.

Table II—Chemical Analyses of Rails

Element	Average Content, Per Cent: First Group	Average Content, Per Cent: Second Group
Mn	0.97	0.80
S	0.090	0.034
Si	0.007	0.18
P	0.072	0.024
Cu		0.005
Ni		0.01
C	0.50	0.56

Table III—Magnetic Characteristics of Rails

Rail Weight, Lb Per Yd	Permeability, c.g.s. Units: Initial: Magnitude	Initial: Range (%)	Maximum: Magnitude	Maximum: Range (%)	Induction for Maximum Permeability, Gausses
60	90	6	535	9	7,000
85	95	23	615	30	7,300
90	90	5	509	16	6,600
100	65	0 ∞	386	9	6,300
130	70	0 ∞	356	5	6,000

in service, but, while somewhat rusty, they showed only slight evidence of wear.

The 3 90-lb samples were welded end-to-end as already mentioned, and the length of rail between potential terminals included all of the middle and most of the end rails. The results thus represent averages for the 3 rails. To determine the character of the welds, one of them was sawed through when the assembly was taken apart. The weld appeared to be practically perfect; hence, there was no reason for suspecting that the welded joints might have caused irregularities.

Most of the measurements on the 60- and 130-lb rails were made on one sample; check measurements were made on the other at a low and a high current, and at 25 and 60 cycles. Comparisons are shown in Table I. To a large extent, differences such as those shown should average out in a long stretch of rail. In contrast with these variations, a single sample was found to be remarkably uniform. Thus with the 130-lb rail at 25 cycles, the surface impedance of the middle 12 ft differed in magnitude from half of the result for the full 24 ft by not more than 1.5 per cent for any of the 7 regular surface wire positions (Fig. 2) and the difference in the angle did not exceed 1° in any case. This was with rail currents of 200 and also 400 amp. Equally consistent results were noted at 60 cycles.

If all rail samples may be considered similar, the resistance and internal reactance each multiplied by the rail perimeter should be approximately the same, respectively, for all samples, at fixed frequency and fixed current per inch of periphery. Computation of these 2 products showed that, on the whole, the deviations of their values for the 85- and 100-lb rails from averages taken over all samples were about the same as for other rail sizes for which more than one sample was available; that is, the evidence from this study is that the 85- and 100-lb samples were of as representative a character as the others,

Table IV—Specific Resistance of Rails

Weight of Rail, Lb Per Yd	Specific Resistance at 70 Deg F μohms-Cm³/Cm	Temperature Coefficient Per Deg F (70 to 160 Deg F)
60	19.8	+0.144
85	18.9	0.150
90	21.4	0.131
100	21.7	0.152
130	22.0	0.146
Means	20.8	+0.146

and results from the former are given without attempt at correction because of their possible non-representative character.

Chemical, Magnetic, and Electric Properties of the Rails

Chemical analyses of the material in the rails classify them into 2 groups, characterized primarily by silicon content and to a smaller extent by content of sulphur and phosphorus. The first group (low silicon) comprises the 60-, 85-, and 90-lb rails; the second group, the 100- and 130-lb rails. The principal features of the chemical analyses (average of 3 rails for the first group and of 2 rails for the second) were as shown in Table II.

For the magnetic tests, samples were machined from the head, the web, and the base of a rail of each size tested. The more significant results are given in Table III.

Figures for both permeabilities are for the particular machined sample giving the largest value. Figures for range represent extreme variations among different machined samples.

Measurements of the specific resistance and its temperature coefficient gave the results shown in Table IV.

Temperature coefficients are expressed as percentages of the resistance at 70 deg F. The coefficient was found to be constant over the range indicated within the precision of the measurements.

The laboratory determinations of chemical, electrical, and magnetic properties were made by the Bell Telephone Laboratories, Inc.

Bonds

Two kinds of bonds were tested. The first, called the "short" bond, consisted of stranded twin conductor equivalent in conductance to No. 4/0 B.&S. gauge copper and about 7 in. long. In practice and as in these tests, the ends of the bond were brazed to the heads of the rails on either side of the joint, a single bond being used. The second bond, called the "long" bond, was of the expanded terminal type, and consisted of a single stranded conductor 33-in. long with conductance equivalent to No. 3/0 B.&S. gauge copper; this bond had sleeves at each end for insertion into $^3/_4$-in. holes in the web of the rail, expansion against the inside of the hole being accomplished by a steel pin driven into the sleeve. Two bonds of this type, one on each side of the rail, were

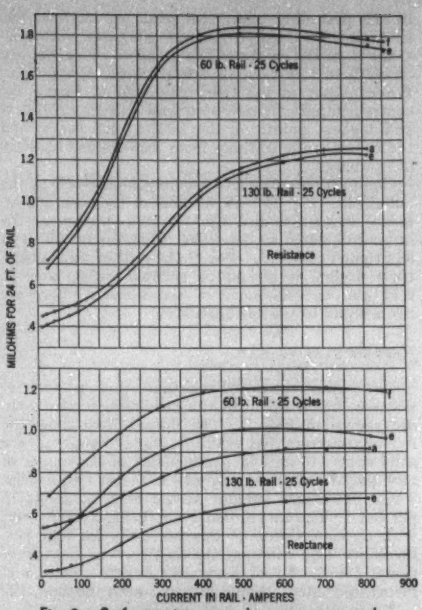


Fig. 3. Surface resistance and reactance at regular positions of surface wires where they were maximum and minimum; temperature, 70 deg F

Small letters indicate locations of surface wires (See Fig. 2)

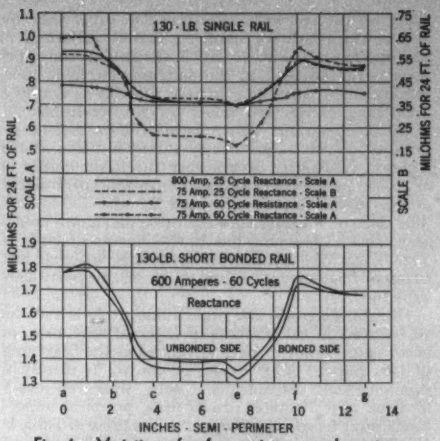


Fig. 4. Variation of surface resistance and reactance around rail periphery at constant rail current; temperature, 70 deg F

Small letters refer to positions shown in Fig. 2

utilized for each joint. Standard fishplates arranged in the usual way (one on each side of the rail) were used for joints with both types of bonds, the long bonds being between the fishplate and the rail.

Tests for the effects of bonds were made only on the 60-lb (short bonds only) and 130-lb rails (both types of bonds). Measurements were made at all 4 frequencies and over the whole range of current.

Results and Discussion

Results in form for practical use are given in Figs. 9 to 15, inclusive, and in Table VII. In the curves, the internal reactance is the surface reactance at that one of the 7 regular measuring positions where it was largest, and the resistance is the surface resistance at the same point. For the 100- and 130-lb rails, this is position *a*, Fig. 2; for the others, it is position *f*. The resistance was found to be practically identical with the resistive component of the voltage drop as measured in the outer wire. Within the precision of the measurements, the 2 components of surface impedance had their maxima at the same peripheral position (see Fig. 4) as would be expected from theoretical considerations.

From a more general point of view, features having sufficient interest to warrant discussion include the field at the surface and in the immediate vicinity of the rail, the degree of concordance of results from the various rail samples, the effects of bonds, and temperature effects.

Field on the Surface and in the Vicinity of the Rail—Internal Reactance

Surface resistance and reactance were measured for all samples at all currents at the maximum and minimum points, *f* (approximately) and *e* for the 60-, 85-, and 90-lb rails, *a* and *e* for the 100- and 130-lb rails. Typical results are shown in Fig. 3. The differences in resistance were small for all rails, running from about 2 per cent at high currents to about 8 per cent at low currents, whereas the surface reactance differed at the 2 extreme points by as much as 2 to 1 for the large rails at low currents. Typical results of more detailed examinations of the field around the periphery, with 11 points of observation in addition to the 7 regular ones, are shown in Fig. 4. The secondary maxima appearing in these curves at or near point *f* become the principal maxima for the 3 smaller rails (for which no curves are shown). In the 85-lb rail surface reactance at 40 cycles and 500 amp, for example, the *f*-maximum exceeds the *a*-maximum by about 2 per cent. The effect of a bond in distorting the field around the periphery is shown in the 2 lowest curves of Fig. 4. In obtaining these curves, the surface wires were placed over the fishplates on both sides in passing the joint. A comparison of results with wire *d* under, and then over, the fishplate showed that considerable flux threaded the fishplate.

In Figs. 5 and 6 are shown the results of measurements of reactance in the vicinity of the rail. The

data are plotted without adjustment other than for temperature and for small accidental variations in rail current. The flattening of the field at the upper corners of the head in the diagrams for 60-lb rails, confirmed by iron-filing figures, possibly is due to a hardening of the rail under service conditions.

As the diagrams show, the maximum surface reactance, which as previously stated is taken as the internal reactance, occurs near the lower corner of the base in the 60-lb rail and (substantially) at the center of the top of the head for the 130-lb rail. The lines of the field through these maximum points (*e.g.*, the 1,100-μ ohm line in the 75-amp diagram of Fig. 6) are the boundaries separating internal and external reactance according to the scheme previously explained.

In each diagram, the broken-line circle is the one to be used in calculations of external reactance, in accordance with the ideas advanced at the beginning of this paper. This circle, of course, is merely a mathematical convenience; and, while its exact location and diameter are of little practical importance, that figures agreeing as well as those of Table V should be obtained for samples so different and for so wide a range of conditions is of interest. The center of each circle is located halfway between the 2 points in which the line of the magnetic field separating internal and external reactance, as described in the preceding paragraph, cuts the vertical line through the rail axis. The radius is taken as the distance from the center to the point at which the line of the field just mentioned touches the rail contour. For example, in the right-hand half of Fig. 5 the center is (approximately) halfway between the lowest and highest points on the 1,250-μ ohm curve, and the radius is the distance from this center to the tip of the base.

Comparisons of reactive voltages observed in the outer wire (Fig. 1) with the sum of the observed internal reactance and the external reactance, the latter calculated as described, show discrepancies of less than 1 per cent. For traffic rails of usual structural design, it should be entirely satisfactory to take the circumference of the external reactance circle equal to the rail periphery.

Representative Rail

Composite curves for resistance and internal reactance, based upon all the rails used in the tests, are shown in Fig. 7. The dotted lines show the maximum errors that would be made in applying the solid curves to find the components of impedance of any tested sample at any of the 4 test frequencies. These deviations amount at the most to about 15 per cent. The curves could not be used, however, with an expectation of this precision, for high-permeability high-conductivity rails such as the exceptional 100-lb rail of Kennelly, Achard, and Dana mentioned later. Using a least square method, the

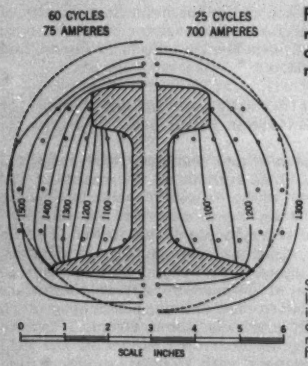


Fig. 5. Magnetic field in vicinity of 60-lb. rail at 70 deg F

Small circles show locations of exploring wires. Figures on curves represent reactance in μohms for 24 ft of rail

Table V—Circle for Calculating External Reactance of Rails

Rail Weight, Lb Per Yd	Frequency Cycles Per Second	Rail Current, Amperes	Location of Center of Circle*		Diameter of Circle*	
			h, inches	h/H	d, inches	$\pi d/p$
130	60	75	2.75	0.42	7.75	0.94
	60	700	2.75	0.42	7.75	0.94
	25	75	2.80	0.42	7.60	0.93
	25	700	2.65	0.40	7.95	0.96
60	60	75	2.20	0.52	6.05	1.03
	60	700	2.10	0.50	5.90	1.00
	25	75	2.10	0.50	5.90	1.00
	25	700	2.10	0.50	5.90	1.00

*h = distance of center of circle above bottom of flange.
d = diameter of circle.
H = height of rail.
p = perimeter of rail.

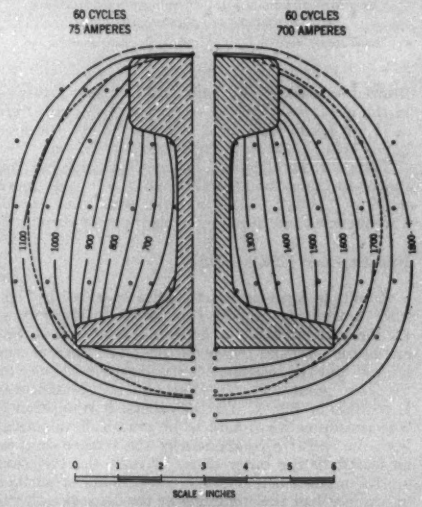


Fig. 6. Magnetic field in vicinity of 130-lb rail at 70 deg F

Small circles show locations of exploring wires. Figures on curves represent reactance in μohms for 24 ft of rail

values of the exponent of the frequency appearing in the ordinates were found to be 0.47 for the resistance and the 0.62 for reactance. The values used in plotting the curves, $^1/_2$ and $^2/_3$, respectively, are more convenient in using the curves and are sufficiently accurate considering the character of the data.

Effects of Bonds

To determine the effects of bonds, the surface impedance of 24 ft of rail, made up of 12 ft each of 2 similar rails having the bond between them, was measured. From the result, an impedance equal to the average impedance of the 2 rails, 24 ft of each, was subtracted; the result was the bond impedance. This method, while obviously capable of improvement for refined investigations, was sufficiently accurate for engineering purposes and saved a good deal of time.

The short-bond tests showed differences in the impedance of the bond as applied to the 2 sizes of rail tested (60- and 130-lb). The impedance on the whole was somewhat larger for the 130-lb rail, but for both components the sign as well as the magnitude of the difference depended upon frequency and current. These differences, while they were frequently substantial fractions of the bond impedance itself, were small parts of the impedance of a rail bonded at usual spacings; thus, for practical purposes, the results could be averaged, as shown in the 8 curves of the upper part of Fig. 15. The maximum error in the use of these curves for either rail with bonds at 33-ft intervals, is estimated at 3 to 4 per cent in resistance, and 1.5 per cent in reactance.

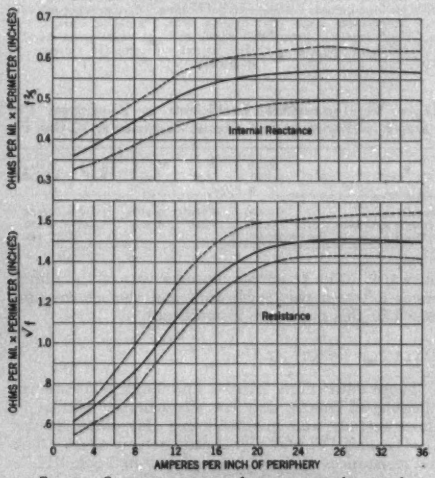


Fig. 7. Composite curves of resistance and internal reactance at 70 deg F for single continuous rail

Curves are based on results from 9 test samples at 4 frequencies. Dashed curves are envelopes of maximum deviations, all samples and frequencies

The short-bond resistance showed well-marked maxima with respect to rail current at all frequencies and the reactance showed similar, though flatter, maxima. The maximum was found to occur uniformly at a smaller current for the 60- than for the 130-lb rail, and, with a single exception, the magnitude of the maximum was increased when the frequency was raised. The resistance and reactance of long bonds were found in every case to exceed corresponding quantities for short bonds, the variation with rail current being like that for short bonds, but with broader maxima.

Since the long-bond data were taken only for the 130-lb rail, it seemed best to express the long-bond impedance in terms of its ratio to the short-bond impedance; this is done in the 2 lower curves of Fig. 15, which apply to all 4 frequencies. It is estimated that the maximum error in the calculated resistance of a length of rail, bonded with long bonds at usual intervals, arising from the use of these lower curves, would not exceed 1.5 per cent. The estimated maximum error in calculating the resistance of a length of long-bonded rail, due to the combined inaccuracies in both sets of curves in Fig. 15, is then about 5 per cent. The precision in internal reactance is possibly not quite so good, owing to inaccuracies involved in taking the lowest curve of Fig. 15 as fully representative. These statements concerning precision apply to extreme cases of deviations of individual measurements from the curves of Fig. 15, at currents chosen to give an unfavorable ratio of bond impedance to continuous rail impedance. In the average case, the errors would be much smaller, perhaps half as large. It is probable that variations due to the condition and tightness of fishplates,[4] imperfect contacts in the case of pin-type bonds, etc., are larger than this in practice.

Temperature Effects

To systematize collection of temperature data, so-called "heat runs" were made, covering all rails except the 90-lb size. In these tests, alternating currents of suitable values were run through the samples to heat them. Particularly in measurements at large currents (700 to 900 amp) with low ambient temperatures, fluctuations in rail temperature were unavoidable; but even in extreme cases the variation in temperature while a set of readings was being made was seldom more than 1.5 deg F. The considerable stretch of time covered by the experiments (conducted during intervals of another investigation) afforded a wide seasonal range of ambient temperatures and made it possible to secure satisfactory checks on the adequacy of the scheme of using ordinary thermometer readings for the rail temperature. The character of these checks may be seen in Fig. 8.

The main results may be stated as follows:

1. The rate, in ohms per degree, at which rail a-c resistance or rail internal reactance increases with rising temperature is substantially constant from 30 to 120 deg F (0 to 50 deg C) and is substantially the same whether the temperature changes affect the entire rail, or are effected by methods that concentrate the generation of heat in a superficial layer.

2. There is no consistent variation in the coefficients with magnitude of rail current, with frequency, or with size of rail.

3. Over-all averages of observations at all frequencies, all currents, and all temperatures are shown in Table VI.

4. The temperature coefficient at the position of minimum electric intensity on the rail periphery is consistently larger than at a position of maximum or large electric intensity, especially for the 130-lb rails.

5. For the 60-lb bonded rail, the temperature coefficients are very nearly the same as for continuous rails. For 130-lb rails, with both short and long bonds, however, the temperature coefficients are both higher (running up toward 0.2 per cent on the average) than for continuous rails.

Comparisons With Other Results

Kennelly, Achard, and Dana[5] made impedance measurements on 10 traffic rail samples of 5 different weights per yard, most of the work being at 25 and 60 cycles. The 100-lb rail used in the present tests ran from 0.5 to 6 per cent lower than the lowest of their 4 similar 100-lb rails in skin-effect resistance-ratio and in total reactance. A fifth 100-lb rail investigated by them, of high permeability and low resistance, showed differences from the other 4 as large as 80 per cent in resistance. Their results from 2 90-lb rails agree well with those obtained from the authors' 90-lb sample; results from their single 60-lb rail are more divergent from those of this paper. On the whole, one may say that for rails of the same size and of comparable permeability and resistivity characteristics, their results agree with the results given here about as well as the results from different samples of similar rails in either set of experiments taken by itself.

The work of E. R. Benda,[6] published in 1931, did not come to the authors' notice until after the present experiments had been completed. Experimenting on a single rail sample, evidently with ideas similar to those underlying the work with which the present paper is concerned, he found minimum resistive and reactive components both at position *e* of Fig. 2, as in all rails tested by the authors, with the maximum reactive component at *a*, as in the present 100- and 130-lb rails. The maximum resistive component, at position *f* as with the present 60-, 85-, and 90-lb rails, was practically the same as at *a*.

From field explorations like those illustrated in Figs. 5 and 6, Benda located the centroid of total rail current about 0.3 of the distance from bottom of base to top of head, and found that the magnetic field became practically circular at a distance from this centroid equal to about 1.35 times the radius of an "equivalent conductor," defined as the circular conductor of circumference equal to the rail periphery with axis coinciding with the current centroid. (Note that this is not the same as the "equivalent conductor" previously mentioned.) The reactance at the surface of this conductor, calculated from the observed reactance at the point at which the magnetic field becomes circular, was found to be the same as at the top of the head, where it is a maximum. This led Benda to suggest that this reactance be taken as the internal reactance of the rail, and thus that the external reactance be calculated from the surface of the "equivalent conductor" outward. The practical consequences of the differences between this suggestion and the scheme proposed in this paper are insignificant.

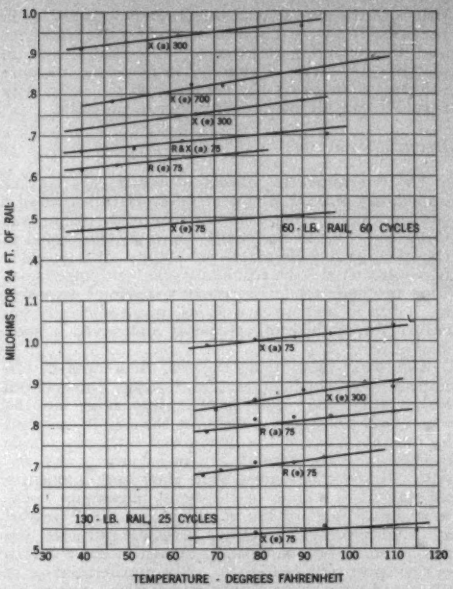


Fig. 8. Variation of surface reactance and resistance with temperature

Dots represent observations made after the rail had been left for long periods without artificial heating. Circles represent observations made after heating with alternating current. Small letters in parentheses signify point of measurement on rail periphery (see Fig. 2). Figures represent rail current in amperes

Table VI—Temperature Coefficients as Percentages Per Deg F, of Resistance and Internal Reactance at 70 Deg F

	60-Lb Rail	85-Lb Rail	100-Lb Rail	130-Lb Rail	Mean, All Rails
Resistance	0.139	0.156	0.210	0.147	0.153
Internal Reactance	0.117	0.150	0.183	0.130	0.132
Mean, resistance, and reactance					0.142

Data for Practical Use

These data (Figs. 9 to 15, and Table VII) are applicable, of course, only to rails generally similar to those tested; and in considering this point, Tables II, III, and IV, and Fig. 2 may be consulted. The d-c resistances of the rails are shown in Table VII.

Curves for the 90-lb rail are in effect means of results from 3 samples, as already explained; those for the 60- and 130-lb rails represent means from 2 samples of each of these sizes. Curves for the 85- and 100-lb rails are from single samples, believed to

Table VII—D-C Resistances of Rails

Rail Weight, Lb Per Yd	Resistance at 70 Deg F, Ohms Per Mile
60	0.0869
85	0.0558
90	0.0587
100	0.0524
130	0.0420

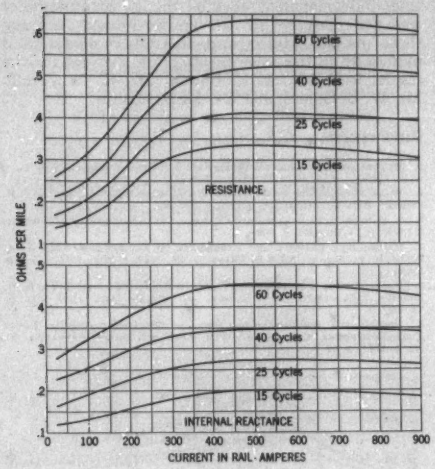


Fig. 9. 60-lb rail

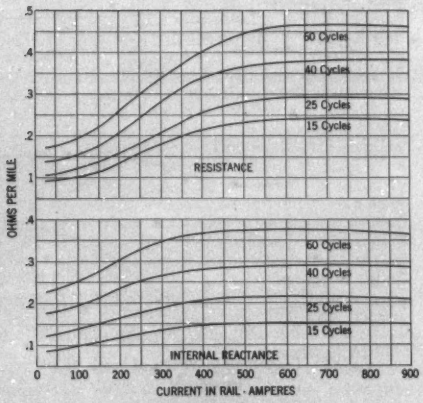


Fig. 12. 100-lb rail

Figs. 9 to 13. Resistance and internal reactance of single continuous rails at 70 deg F

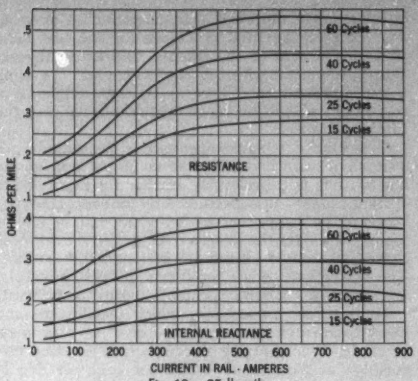


Fig. 10. 85-lb rail

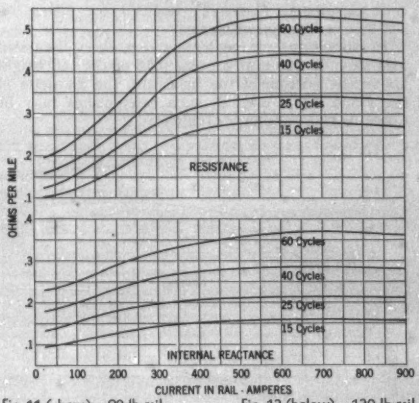
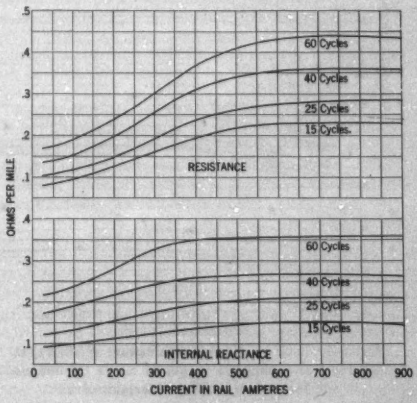


Fig. 11 (above). 90-lb rail

Fig. 13 (below). 130-lb rail



be of a fairly representative character. Curves of Fig. 14 give the total reactance for the test rails, that is, the sum of the internal and external reactances, the latter with infinite flux-radius. In using these curves, it should be noted that temperature corrections should be based on the internal, not the total, reactance.

Correction for bond impedance is the same for all weights of rail; it is about 16 or 18 per cent at the largest, but is considerably smaller for most of the current range. It is given directly for short (U-type) bonds in the 8 upper curves of Fig. 15, and, by applying to these data the factors indicated in the 2 lowest curves, for pin-type bonds (33 in. long in these tests). The corrections, given for bonds at 33-ft intervals, are, of course, inversely proportional to the interval.

Temperature corrections, which usually are not likely to amount to more than 7 or 8 per cent, may be made, after applying the correction for bond impedance, at the rate of +0.14 per cent per deg F excess of temperature above 70 deg F (+0.25 per cent per deg C above 21 deg C) for either resistance or internal reactance.

In calculating external reactance, the rail-current axis may be taken at a point 0.45 of the rail height above the bottom of the base, and the diameter of the circle to be used in such calculations may be taken as rail periphery divided by π.

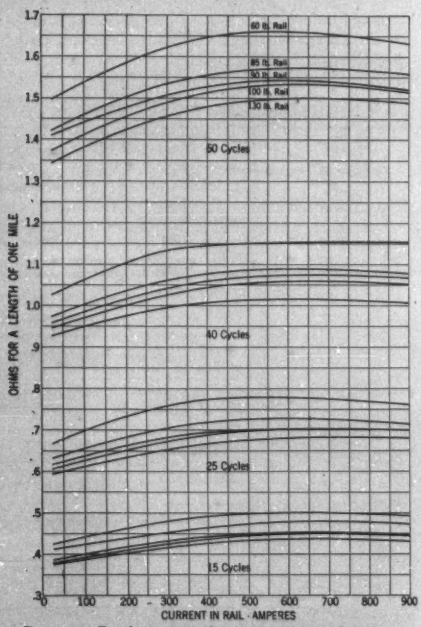


Fig. 14. Total reactance (return current at infinity) at 70 deg F of a one-mile length of single continuous rail, for each of 5 different weights of rail

The curves of Fig. 7 may be useful where the rail is of a size different from, but is otherwise generally similar to, those tested, or where the frequency is different from one of the test frequencies (though, of course, not widely different). This figure also should be of some value in judging what precision may be expected in using data from these rails in estimates concerning other similar rails.

Mr. C. P. Bartgis, Mr. H. Ferris, and Mr. J. H. Harding assisted in the greater part of the field tests. Development work on the a-c potentiometer was done largely by Mr. H. R. Moore. Among those whose advice and assistance contributed materially in the experiments or in working up the results were Mr. A. E. Bowen, Mr. K. E. Gould, Mr. W. L. Gaines, and Mr. K. L. Maurer.

References

1. Regulation and Inductive Effects in Single-Phase Railway Circuits, A. W. Copley. *Elec. Jl.*, v. 17, 1920, p. 326–41.

2. Wave Propagation in Overhead Wires With Ground Return, J. R. Carson. *Bell Syst. Tech. Jl.*, v. 5, 1926, p. 539–54.

3. A Vacuum-Tube Alternating-Current Potentiometer, E. C. Wente. A.I.E.E. Jl., v. 40, 1921, p. 900–4.

4. Railbonding Practice and Experience on Electrified Steam Railroads, H. R. Brown. A.I.E.E. Trans., v. 49, 1930, p. 1299–1314. (See p. 1305.)

5. Experimental Researches on the Skin Effect in Steel Rails, A. E. Kennelly, F. H. Achard, and H. S. Dana. *Jl.* Franklin Inst., v. 182, 1916, p. 135–90.

6. Beitrag zur Bestimmung des Inneren Scheinwiderstandes Einer Eisenbahnschiene, E. R. Benda. *Wiss. Veröff. a.d. Siemens-Konzern*, v. 10, No. 1, 1931, p. 91–7.

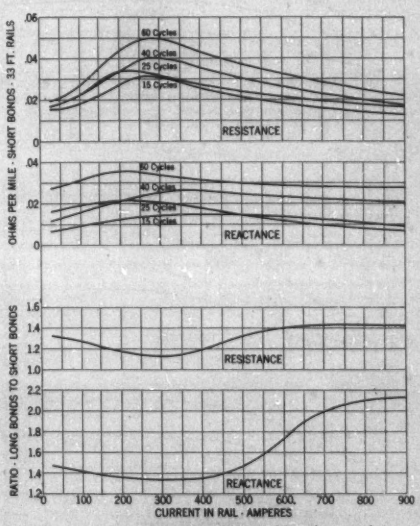


Fig. 15. Corrections for effects of bonds on rail impedance

The 2 groups of 4 curves each give, for short bonds, corrections to be added to the resistance and the reactance per mile of a single continuous rail, bonds being assumed at 33-ft intervals. The 2 lower curves give the factors by which the corrections for short bonds should be multiplied, to obtain corrections for long bonds

Counterpoises for Transmission Lines

Counterpoises are recommended for protecting electric power transmission lines against damage from lightning surges where other methods do not reduce the tower footing surge impedance to the desired level. In this paper a physical explanation of the theory of counterpoises is given together with an analytical solution of parallel counterpoise problems. Of the 2 types studied, the parallel counterpoise is shown to be the more effective.

By
CHARLES L. G. FORTESCUE
FELLOW A.I.E.E.

Westinghouse Elec. and Mfg. Co.
E. Pittsburgh, Pa.

CONSTANT PROGRESS in an art can be made only by the development of a working theory. It is not necessary that such a theory be presented in full perfection. This statement applies with particular force to an art such as the protection of electric power transmission lines against lightning where confirmation by statistical data on experimental lines takes many years. One of the major problems of protecting transmission lines against direct strokes of lightning is related intimately to the earth conditions of the right-of-way over which the line passes.

After the direct stroke theory was announced in 1929, many engineers found that poor performance on many existing lines was attributable mainly to high tower footing resistance. In many cases it was found almost impossible to effect sufficient reduction of this resistance by means available at that time. The counterpoise, consisting of cables connected to the line towers and buried in the ground offers a solution to this difficulty. Counterpoises in general are of 2 types: the "crow's foot" consisting of cables extending radially from the corners of the towers; and the parallel type consisting of cables extending from the towers parallel to the line.

In this paper both the crow's foot and parallel types of counterpoises are analyzed from a theoretical standpoint, and a mathematical analysis of parallel counterpoise problems is given. An example illustrating the method of calculating the protection level of a line equipped with a parallel counterpoise also is given. From the studies upon which this paper is based the following general conclusions may be drawn:

1. Where the earth resistivity is low, no special measures may be required to obtain tower footing surge impedances of 10 ohms or less; the tower foundation structures provide the necessary surface "leakance."

2. Where the earth has fairly low resistance, the normal tower surge impedance may be reduced economically by the use of driven grounds.

3. Where the resistivity of the earth is high, driven grounds have been found to be inadequate and sometimes impractical. For such cases the remedy now is indicated to be the use of counterpoises.

4. Counterpoises have been analyzed and classified as follows: (a) those consisting of wires at right angles to the direction of the line which have the effect only of lowering the surge impedance of the tower footings; (b) those consisting of wires parallel to the direction of the line which have the effect of not only reducing the surge impedance of the tower footings, but also reducing by mutual coupling the difference of potential between line conductors and the tower top. The parallel counterpoise is, therefore, the most effective type, and methods of calculation are presented for the first time that allow analysis of this type of problem.

5. Where a cross-wire counterpoise is used in combination with a parallel counterpoise, its surge impedance should be considered independently of the parallel counterpoise and in parallel with the normal tower footing surge impedance; their resultant surge impedance then should be used in the calculations in place of the normal tower footing surge impedance.

6. To obtain the optimum effect with a given length of wire, where the earth resistivity is not very high, but too high to be taken care of by driven grounds, it may be advantageous to extend the counterpoise for only a portion of the distance between towers. Where the resistivity is very high, however, the counterpoise should be extended for the whole distance.

7. For a projected line tests may be required to predetermine what method of auxiliary grounding will be necessary. For practical estimating purposes, where a line is to be erected on ground with high resistivity a parallel counterpoise consisting of 2 or more wires extending from tower to tower may be considered to make the line equivalent to one having tower footing surge impedances of 10 ohms, and the clearances and insulation can be calculated on that basis. This value of 10 ohms has yet to receive confirmation, but to the author's best knowledge it is a fair value to use at present in projecting a line.

Review of Past Developments

Since this paper is a further extension of the theory of protection of transmission lines against direct lightning strokes and necessarily depends on much of the theory already established, a brief review of past developments of this theory seems in order.

The paper by Fortescue, Atherton, and Cox entitled "Theoretical and Field Investigations of Lightning," presented at the A.I.E.E. winter convention in 1929 (see A.I.E.E. TRANS., v. 48, 1929, p. 449–68) was among the first papers relating to the intensive field investigation of lightning with the cathode-ray oscillograph started in the summer of 1928. It presented for the first time before the Institute the conception of the lightning channel as a highly conducting path, after it had become established, having a surge impedance of decreasing value in the direction of the point of stroke. In that paper the theory of the direct stroke as the cause of outages on high voltage transmission lines first was advanced, which theory now has become generally accepted. Based on the ideas presented in that paper, by the

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 22–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 13, 1933. *Not published in pamphlet form.*

end of 1929 4 principles of protection were established:

1. Proper configuration of ground wires to shield the line conductors against direct strokes.

2. The importance of maintaining low values of tower footing resistance or surge impedance at every tower.

3. Adequate insulation coördinated with the clearance between line and tower taking into account wind deflection.

4. Sufficient distance in the middle of the span between line conductors and ground wires to prevent side flash to the conductors when a stroke occurs at the middle of the span.

Although these principles were established as the result of laboratory work in 1929, nothing definite was known regarding the probable magnitude of the direct lightning stroke when it strikes a line. The lightning investigations were continued for the purpose of obtaining as much information as possible on this point. In 1931 2 of the highest surges ever recorded on a transmission line were obtained at Ogemaw on the Arkansas Power and Light Company system. One of these showed a maximum value of 5,000 kv after traveling about $4^1/_2$ miles. It is estimated that had the wood poles not broken down on the front of the wave, the lightning stroke probably would have reached a value of 20,000 kv. As a result of the laboratory work done in 1930 and the previous years, 20,000 kv was decided on as the probable magnitude of severe lightning strokes with the reservation that exceptionally severe strokes might reach even higher values, but were so exceedingly rare that it would not be practical to design lines to withstand these values.

The portable lightning generator used at Stillwater, N. J., contributed a great deal to this progress in showing the importance of the surge impedance of the tower and the reflections set up in the tower after a lightning stroke. The effect of this surge impedance was expressed in the form of curves and added to the theory; it was presented in a discussion by J. J. Torok, of the 1931 lightning papers presented at the A.I.E.E. North Eastern District meeting, Rochester, N. Y., May 6–9, 1931. The effect of corona in increasing the coupling between ground wires and line wires at midspan and in reducing the clearance necessary to prevent side flash due to a direct stroke at midspan was added in 1932. The complete theory taking into account the surge impedance of the towers, the consequent reflections in the tower structure, and the effect of corona on the coupling factors was given in a paper presented by the author before the International Electrical Congress at Paris in June 1932, entitled "La Foudre et ses Effets sur les Lignes Aeriennes."

Counterpoise Tests at Stillwater

The preceding introduction outlines the progress of the art of protection of transmission lines against direct lightning strokes up to the present time, and points out the various influences that contributed to this development. It may be seen that the present theory presumes the ability to obtain low tower footing resistance at all points of the line right-of-way. As soon as the direct stroke theory was announced in 1929 many utility engineers found that poor performance on many existing lines was due mainly to high tower footing resistance, and set about to remedy this condition. In many cases, it was found almost impossible to effect sufficient reduction by the means available at that time. It was decided, therefore, to include in the test schedule at Stillwater in the summer of 1929 an investigation on artificial means for obtaining satisfactory grounds for tower footings. This work was done on the 220-kv Roseland-Bushkill line of the Public Service Electric and Gas Company of New Jersey, which was being installed at that time and of which a length of 9 miles with ground wires omitted was made available for these tests. An account of this investigation is given in the paper by Conwell and Fortescue entitled "Lightning Laboratory at Stillwater, New Jersey," presented at the A.I.E.E. winter convention of 1930 (see A.I.E.E. Trans., v. 49, 1930, p. 872–6) and the discussion by A. S. Brookes in which further data was added. Although it was impossible to carry the work to completion, some interesting results, contained in Table I of that paper, were obtained. Based upon a surge impedance of 450 ohms for the line and a corona radius of $^1/_6$ ft, which corresponds to a potential of 500 kv, the depth of the ground plane appears to be about 50 ft below the surface of the earth. The buried cable, which was connected to the footings of towers 39, 40, and 41, reduced the tower footing surge impedance from 83 to 44.2 ohms at tower 39; from 128 to 26.4 ohms at tower 40; and with tower 41 alone connected to the buried cable its tower footing impedance was reduced from 46 to 18.8 ohms. The reduction in surge impedance of tower 39 indicates that the buried cable had a surge impedance of 95 ohms; for tower 40, it was 33 ohms; and for tower 41, 32 ohms. It may be observed that they are fairly consistent. The surge impedance in parallel with tower 41 is somewhat less than half that in parallel with tower 39, although practically the same as that at tower 40. It may be supposed that the surge impedance at tower 40 is affected by reflections from tower 41 and that the low surge impedance of tower 41 is due to a higher leakage factor at that portion of the right-of-way.

Obviously, the data is too meager to do much with in the way of generalization; but if a factor K be taken to represent the effect of the capacitance and "leakance" of the buried cable, its value appears to be between 8 and 16, which would not be excessive for a wire in earth of fairly low resistivity. The equivalent surge impedance obtained in this manner has, of course, no real existence as a constant, but changes in value with time and the duration of the applied potential. This explains why the d-c measurement frequently gives values that are too low. For instance, if a constant electromotive force be applied to an infinite cable in a homogeneous medium of low resistivity, the current will build up exponentially and in time will approach a constant value; the $r = E/I$ thus obtained is the equivalent of the footing resistance as measured by d-c means. The surge impedance as measured by a surge generator with a steep wave is an average transient value and is ap-

plicable with a fair degree of approximation to the relative short surges produced by lightning.

General Discussion of Counterpoises

For purposes of discussion a "crow's foot" will be considered as a counterpoise in which 4 wires extend radially from the tower footing at an angle of 45° with the direction of the line. The "parallel counterpoise" shall be considered as one or more wires extending in each direction from the tower footing parallel to the transmission line. The parallel counterpoise does not necessarily extend from tower to tower; as a matter of fact, in some cases it should not do so. The first thing to find out in discussing these 2 types of counterpoises is whether there is any appreciable reduction of the surge impedance in multiple with the normal tower footing surge impedance, by using the crow's foot arrangement, using 2 wires in each case. In the crow's foot arrangement, since the wires are at right angles to each other, there will be no mutual surge impedance between the 2. Considering 2 of the radial conductors of the crow's foot, if the effective radius of one conductor from the standpoint of corona is 0.166 ft and the depth of the earth plane is 50 ft, the surge impedance of the 2 in multiple will be

$$\frac{1}{2} \cdot \frac{60}{\sqrt{K}} \log_e \frac{100}{0.166} = \frac{192}{\sqrt{K}}$$

Consider 2 parallel conductors of the parallel counterpoise having the same effective radius 40 ft apart, the geometric mean radius of the 2 will be $\sqrt{0.166 \times 40} = 2.58$, and the joint surge impedance will be

$$\frac{60}{\sqrt{K}} \log_e \frac{104}{2.58} = \frac{222}{\sqrt{K}}$$

Considering the same arrangements but assuming 200 ft for the equivalent depth of the earth plane for high resistivity earth, the equivalent surge impedance may be computed in a similar manner for the crow's foot counterpoise as

$$\frac{1}{2} \frac{60}{\sqrt{K}} \log_e \frac{400}{0.166} = \frac{234}{\sqrt{K}}$$

and for the parallel counterpoise as

$$\frac{60}{\sqrt{K}} \log_e \frac{400}{2.58} = \frac{302}{\sqrt{K}}$$

From the foregoing calculations it may be assumed, therefore, as far as the surge impedance that operates in parallel with the normal tower footing surge impedance is concerned, that for the same amount of wire there is a slight advantage in favor of the crow's foot counterpoise. If 8 radial wires be used in the crow's foot arrangement, the surge impedance is approximately equal to $^1/_4$ that of the foregoing parallel counterpoise. From this fact may be formed some idea of the reduction in tower footing surge impedance that may be effected by going as far as is practicable with the crow's foot arrangement. If the resistivity of the soil is very high, K may be assumed equal to 4. This will give 37.5 ohms approximately, using the higher value of earth resistivity. Since in such a case the normal tower footing surge impedance is likely to be not less than 200 ohms and may approach 1,000, it may be seen that such a counterpoise would reduce the effective tower footing surge impedance to 31.6 ohms for a normal 200-ohm footing; this is too high a value to give adequate protection, the requirement being 10 ohms or less for a well insulated line. In moderately low resistivity soil K may be assumed equal to 9. Using the first example, 18.25 ohms is obtained as the surge impedance, which may be effective provided the normal tower footing is fairly low; however, under these conditions driven grounds probably would be still more effective and more economical.

The values of K used in the preceding paragraph for low resistivity soils are estimated. There is little or no data available, as far as the author is aware, on the surge impedance of counterpoises. Some data recently has been presented on counterpoises which indicate rather high soil resistivity. Where the resistivity of the soil is very high, the surge impedance of a counterpoise may be less than the resistance obtained by d-c measurements, so that d-c measurements in general are not a measure of the effectiveness of a counterpoise system. Data obtained at Stillwater is too meager and was obtained with a small surge generator. It is believed that a large capacity generator of at least 2,000,000 volts should be used so as to obtain the effects of corona in the soil, which it is believed would reduce the surge impedance materially. Whatever effectiveness has been obtained with crow's foot grounds, is believed to have been due very largely to the parallel counterpoise effect. There is no sharp line of demarcation between the 2 types of counterpoises, both to some extent having the same features in common.

In his discussion of the 1930 paper by Conwell and Fortescue, A. S. Brookes gives a curve showing the reduction of surge impedance of a given tower for different lengths of connected cable; which is reproduced in Fig. 1. To interpret this curve it must be remembered that as the cable length is increased in soil of fairly low resistivity the attenuation of the current due to leakage becomes greater and greater. The potential measured at the tower is the resultant

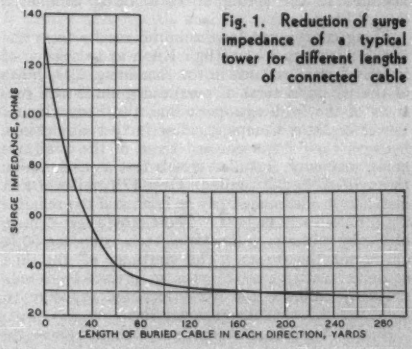


Fig. 1. Reduction of surge impedance of a typical tower for different lengths of connected cable

of all the reflections that take place in the buried cable and of the effects of the attenuation. If the curve of surge impedances given is assumed to be asymtotic to the effective surge impedance of the tower footing with a very long counterpoise, this would indicate a surge impedance of approximately 32 ohms for a buried cable extending in both directions from a tower footing, which value seems very low.

Practical Experience With Lines Indicating Counterpoise Effects

Some 66-kv lines with overhead ground wires built along the right-of-way of railroads have shown exceptionally good performance. With the usual insulation and clearance for such lines, their performance cannot be accounted for by the low tower footing surge impedance alone and must, therefore, be credited to the counterpoise effect due to paralleling rails. A notable example illustrating this correspondence is a $12^1/_2$-mile 69-kv line paralleling a railroad, which has a record of one outage in 15 years though exposed to lightning storms of the usual severity experienced in that region.

During the first 3 lightning seasons of operation, that is 1926 to 1928, inclusive, of the Wallenpaupack-Siegfried 220-kv line of the Pennsylvania Power & Light Company, a considerable number of lightning flashovers was experienced with a disproportionately high percentage of this total concentrated at High Knob, a terrain prominence and the point of highest elevation of the line about 12 miles from Wallenpaupack. High Knob is a hill of solid rock, with a thin layer of soil where not entirely exposed. Realizing the necessity of augmenting the protection afforded by the overhead ground wires, after weighing such experience as they could gather from operating companies and results from lightning research in the high voltage laboratories and in the field, Mr. Nicholas Stahl, chief engineer of the Pennsylvania Power & Light Company, and Mr. A. E. Silver, consulting electrical engineer of Electric Bond & Share Company, recommended the installation of a buried counterpoise over a distance of $2^1/_2$ miles at High Knob. This counterpoise, consisting of 2 continuous No. 2/0 B.&S. gauge copper wires, was installed in the spring of 1929, being completed during May.

Being encouraged by the initial results from the buried counterpoise at High Knob and desirous of improved performance in the remaining $22^1/_2$ miles of the 25 miles total of overhead ground wire sections of the Wallenpaupack line, the Pennsylvania Power & Light Company, after further discussions between their engineers and those of the Westinghouse company, installed crow's feet at each tower throughout the $22^1/_2$ miles. Over $17^1/_2$ miles of this installation was made early in 1930, and the remaining 5 miles early in 1931. These crow's feet consist of buried cables in 4 directions, each extending 50 ft out from the tower. The portions of the line equipped with these 2 types of artificial grounds probably embrace the worst localized exposure to lightning on the Wallenpaupack line.

Results to date since the completion of these respective installations, from the information that the writer has obtained, are as follows: The $2^1/_2$-mile portion of the line over High Knob equipped with the buried longitudinal counterpoise, has not had one insulator assembly flashed by lightning. The $22^1/_2$ miles of the line equipped with crow's feet have had a substantial reduction of flashed insulators, compared with previous experience. Table I brings out this comparative performance in more detail.

Table I—Flashed Insulator Assemblies on a 25-Mile Section of the Wallenpaupack-Siegfried 220-Kv Line

Year	Parallel	Crow's Foot	Station Protective Gaps
1930	0	2	4
1931	0	1	4
1932	0	2	2
1933	0	0	1

While $2^1/_2$ miles of line statistically is not enough to draw any definite conclusion from, even though it shows a perfect record over 5 lightning seasons, the performance of this portion of the line when compared with the $22^1/_2$-mile portion equipped with crow's foot counterpoises is quite significant; and when considered in the light of experience with other existing lines, which appear to owe their high record to parallel counterpoise effects, the result is quite convincing. Doubtless the performance of the $22^1/_2$-mile portion still could be improved by using more wire in the counterpoises, but from theoretical considerations the possible improvement does not appear to be sufficient to bring it to a par with the portion of the line over High Knob equipped with parallel counterpoise.

Physical Explanation of Theory of Parallel Counterpoise

Theory of counterpoises has been a matter of speculation for the last 3 or 4 years. The surge impedance of the counterpoise in which is included the effect of distributed inductance, capacitance, and leakance has been recognized as playing an important part in its effectiveness. Corona formation undoubtedly also plays a large part by increasing the capacitance and leakage and probably reducing the inductance. It has been shown that in respect of surge admittance a parallel counterpoise with 2 wires 40 ft apart extending parallel from the towers a given distance in both directions is not materially different from a crow's foot counterpoise of 4 wires extending radially the same distance at an angle of 45° with the direction of the line. To explain the theory of the parallel counterpoise effect, the overhead ground wires and the buried counterpoise wires running parallel to the line should be considered as in effect a transmission system of comparatively low surge impedance, the tower being merely the cross connection between the parallel wires of the system. The conductors must be considered as a second parallel system insulated from the first sys-

tem, but mutually coupled with the first system through the mutual surge impedance between ground wires and line wires, and counterpoise wires and line wires.

Obviously any surge currents passing through the ground wires and counterpoise wires will raise the potential of the line conductors (through the mutual surge impedance between these and the line conductors) bringing the potential of the line wires closer to the potential of the system comprising the ground wires and line wires. The difference of potential between the ground wires and the counterpoise wires is determined by the surge impedance of the tower and the reflections therein. When the counterpoise is absent and the tower footing surge impedance is high, the ground wires and tower will be raised to a high potential above true zero when the tower is struck, because the surge impedance of the ground wires and tower footing is not low enough to keep the potential down. The potential of the line wires also will be raised through the mutual surge impedance between overhead ground wires and line wires, but not enough to prevent flashover of the insulator due to the difference of potential between line wires and ground wires.

The addition of the parallel counterpoise wires now will be considered. First of all, the surge impedance of the counterpoise will reduce the potentials of line and ground wire in the same proportion so that the difference of potential between them will be reduced proportionately. This would be the only effect of a counterpoise having the same surge impedance as the parallel counterpoise, but extending radially from the tower at right angles to the line; in effect, it functions by lowering the tower footing surge impedance. In the case of the parallel counterpoise, this lowering of the potential by reduction of tower footing surge impedance is obtained and, in addition, the current in the counterpoise through the mutual surge impedance between counterpoise and line wires will raise the potential of the latter so that it more nearly approaches that of the ground wire and tower top; consequently, the difference of potential between line wire and tower will be reduced greatly, and with adequate insulation will not cause a flashover. These phenomena are illustrated by experiences in the Adirondack Mountain (N. Y.) region where lightning punctured cables buried in soil of high resistivity. It was found that cables having no outer metallic covering were affected, but armored cables were not. One remedy that was effective was to place wires in the same trough about a foot or 2 above the cable. A better remedy was to place a light stranding of wires over the whole cable. The action of the counterpoise and ground wires is similar to that of the metallic stranding over the cable except that in the latter case the coupling is very high so that the difference of potential between the inner conductor and the outer stranding is very small.

Different Types of Counterpoises

It will be clear now to those who have followed the reasoning in this paper that there are 2 distinct types of counterpoise effects: that due to wires radiating from the towers at right angles to the line, and that due to wires radiating from the towers in a direction parallel to the line, the former having the effect of merely increasing the surge admittances of the tower footing by adding its surge admittance to that of the natural surge admittance of the tower. The latter not only increases the surge admittance of the tower footing by practically the same amount as the former for a given length, but also through its mutual surge impedance and the current passing through it, raises the potential of the line conductor to a value approaching more nearly that of the overhead ground wires thereby reducing the stress on the line insulation. This effect must not be considered small; indeed, it is quite large because of the large amount of current in the surge passing into the counterpoise. It seems proper to point out now that in soil of comparatively low resistivity, in order to get a large part of the benefit of a parallel counterpoise, the counterpoise wires need not extend from tower to tower. The weak point of the transmission line from an insulation standpoint is usually the line insulator and, fortunately, at that point the full coupling effect due to the counterpoise is realized. Beyond the tower the insulation strength rapidly increases, so that if the difference of potential increases because of attenuation of the surge current in the counterpoise, this need not cause concern as there is ample insulation strength away from the tower. However, the portion of the counterpoise parallel with the line should be long enough so that what current is reflected will be small and will have attenuated to a negligible amount before it reaches the tower.

Analytical Solution of the Parallel Counterpoise Problem

In the preceding few paragraphs, it has been attempted to explain the mechanism of the parallel counterpoise in simple terms so that those who do not care to take the time to follow out the analytical solution may form a clear idea of what it does. Appendix I presents the analytical solution based upon a homogeneous medium, by the theory of multiple circuits considering the lines as being distortionless. In actual practice the medium is not homogeneous and some correction must be used to obtain the approximate values of surge impedances and mutual surge impedances. For the overhead ground wires and line wires, the usual convention has been used based upon the distance of the wires from their images considering the medium as air. Considering the effect of the surge propagated in the counterpoise, which is buried in the earth, a suitable value of K is used so that its surge impedance is the surge impedance that would be obtained if the sole medium were air, divided by $\sqrt{K}$. In considering its mutual surge impedance to the line conductors and the overhead ground wires, the field due to the surge current flowing therein is conceived to consist of 2 parts, one of which moves with the velocity of light and is porportional to s, where s is less than unity, and has surge impedance and mutual surge impedance pro-

portional to unity; and a second portion moving with velocity $V/\sqrt{K}$ whose magnitude is proportional to $\sqrt{K} - s$, where v is the velocity of light. The current due to the combined natural surge admittance of the footing and that of a cross counterpoise, if any, is included and is taken to be proportional to m. Calling the current concerned in these effects I_1, I_K, and I_s, respectively,

$$I_1 : I_K : I_s :: s : \sqrt{K} - s : m$$

$$\therefore I_1 = \frac{s}{m + \sqrt{K}} (I_1 + I_K + I_s)$$

$$I_K = \frac{\sqrt{K} - s}{m + \sqrt{K}} (I_1 + I_K + I_s)$$

$$I_s = \frac{m}{m + \sqrt{K}} (I_1 + I_K + I_s)$$

Now I_s has no mutual surge impedance, and the mutual surge impedance of I_K is proportional to $1/\sqrt{K}$ while that of I_1 is proportional to 1. Therefore, the mutual surge impedance of the total current $I_1 + I_K + I_s$ is proportional to the factor

$$\frac{s}{m + \sqrt{K}} \times 1 + \frac{\sqrt{K} - s}{m + \sqrt{K}} \times \frac{1}{\sqrt{K}} + \frac{m}{m + \sqrt{K}} \times 0$$

This is equal to

$$\frac{(s + 1)\sqrt{K} - s}{m + \sqrt{K}} \cdot \frac{1}{\sqrt{K}}$$

If the surge impedance due to the section of line and counterpoise on one side of the tower be considered, then to determine m, $2Z_G$, where Z_G is the normal tower footing surge impedance, must be used thus

$$2Z_G = \frac{Z_1}{m}$$

so that

$$m = \frac{Z_1}{2Z_G}$$

The value of Z_G is supposed to be known and, unless a cross counterpoise is used, is dependent only on the normal tower footing surge impedance; Z_1 is the surge impedance of the parallel counterpoise considering the medium to be homogeneous and air.

The K used in the preceding discussion should be the true specific inductive capacity of the soil. This will vary over a wide range. The value for pure distilled water is about 70; therefore K would be expected to be high for deep alluvial or marshy soil, possibly 9 or more. For light dry sandy soil, K may be low, but moisture is always present in alkaline earths and salts so that K is not expected to be less than 4. In general, the value of the apparent surge impedance is affected not only by K but also by the leakance. Fortunately, where leakance is high K also is high and one tends to offset the other. However, for short steep waves resistance and leakance affect the surge impedance very little, so that the proper value of K may be obtained by tests made on buried counterpoises using a surge generator giving a steep front wave. Resistance has a tendency to increase the surge impedance while leakance has a tendency to decrease it, so that they offset each other to a certain extent; when they completely balance each other, the circuit is distortionless In the present problem it is not necessary to consider the attenuation due to leakance and resistance nor the distortion because the values involved are at the threshhold of the ground wire and counterpoise system. It should be noted that the working theory applies not only to the parallel counterpoise, but also to the cross counterpoise and any combination of the 2 types. The surge impedance of the cross counterpoise is to be considered as independent of the parallel counterpoise and in multiple with the normal tower footing surge impedance.

While the author does not attempt to justify on theoretical grounds the approximation given in the previous paragraph, it appears to be consistent and is flexible and easy to use; furthermore, it works in well with the analytical theory and is believed to give conservative results. Possibly further study will develop a more scientific way of arriving at an approximation. In Appendix II is worked out a numerical example by this method using $s = 1$.

Prospective Tests

Since so much depends on the mutual surge impedance between the counterpoise and overhead lines, tests are under way on a line built near the Trafford laboratory of the Westinghouse company for the purpose of measuring some of these values. It is hoped that by the time this paper is presented some data will be available that will be of help in determining the proper constants to use in applying the analytical solution to practical problems.

Appendix I—The Parallel Counterpoise

One of the difficulties of problems of this kind is to provide adequate nomenclature for all the quantities involved. Since there will be a change of value of all surge currents and electromotive forces every half-period, it will be necessary to distinguish between the values of a given current during the intervals. The currents in the ground wires and counterpoises all will be traveling positively; in the tower will be both positively and negatively traveling surges that must be taken into account; while in the lightning channel both kinds exist, but only the positively traveling waves need be taken into account. Currents and electromotive forces will be designated by giving them a subscript S for the lightning channel, A and B for the ground wire and counterpoise, C for the line, and T for the transmission tower. The half-period is designated by the Greek letter Tau (τ) and the values occurring during the τth half-period will be designated by adding the letter τ to the subscript, thus $\hat{E}_{A\tau}$, $\hat{E}_{T\tau}$, $\hat{E}_{B\tau}$, $\hat{E}_{T\tau}$, etc. A positively traveling wave will be designated by placing the sign "}" over the symbol, thus $\hat{E}_{T\tau}$ and a negatively traveling wave by placing the sign in reverse as "{," example $\hat{E}_{T\tau}$. A positive traveling wave resulting from reflection at the beginning of the τth period would be designated $\hat{I}_{A\tau}$, $\hat{I}_{B\tau}$, etc., similarly negative traveling waves will be designated $\hat{I}_{T\tau}$, $\hat{I}_{B\tau}$, etc.

There are 3 general terminal conditions to be accounted for.

1. Junction of lightning channel, tower, and ground wires.
2. Junction of tower footing and counterpoise.
3. Junction of tower, channel, and ground wire for negatively traveling waves in the tower only.

At the beginning of the first half-period no electromotive force is impressed at the junction of the tower footing and counterpoise so

that for the potential of the transmitted surge on the ground wire and tower in multiple

$$\hat{E}_S + \hat{E}_S = \text{transmitted potential}$$

$$\hat{E}_S = -I_{S1}Z_S$$

The transmitted current is

$$I_{S1} + I_{S1} = I_{A1} + I_{T1}$$

$$-I_{S1}Z_S = I_{S1}Z_S - I_{A1}Z_S - I_{T1}Z_S$$

$$\hat{E}_S + \hat{E}_S = \hat{E}_S - I_{S1}Z_S$$

$$= \hat{E}_S + I_{S1}Z_S - I_{A1}Z_S - I_{T1}Z_S$$

$$= 2\hat{E}_S - I_{A1}Z_S - I_{T1}Z_S$$

Therefore,

$$2\hat{E}_{S1} - I_{A1}Z_S - I_{T1}Z_S = Z_{AA}I_{A1} + Z_{AB}I_{B1}$$

or

$$\hat{E}_{S1} = \left(\frac{Z_S}{2} + \frac{Z_{AA}}{2}\right)I_{A1} + \frac{Z_{AB}}{2}I_{B1} + \frac{Z_S}{2}I_{T1}$$

$$2\hat{E}_{S1} - I_{A1}Z_S - I_{T1}Z_S = Z_TI_{T1}$$

or

$$\hat{E}_{S1} = \frac{Z_S}{2}I_{A1} + \left(\frac{Z_S}{2} + \frac{Z_T}{2}\right)I_{T1}$$

At the junction of the tower and counterpoise there is no impressed surge, and the surge impedance of the tower is Z_T so that the complete set of equations is

$$\hat{E}_S = \left(\frac{Z_S}{2} + \frac{Z_{AA}}{2}\right)I_{A1} + \frac{Z_{AB}}{2}I_{B1} + \frac{Z_S}{2}I_{T1}$$

$$\hat{E}_S = \frac{Z_S}{2}I_{A1} + \left(\frac{Z_S}{2} + \frac{Z_T}{2}\right)I_{T1}$$

$$0 = \frac{Z_{AB}}{2}I_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I_{B1}$$

By eliminating I_{T1}, these are reduced to

$$\left.\begin{aligned} \frac{Z_T}{Z_S + Z_T}\hat{E}_S &= \left(\frac{Z_SZ_T}{2(Z_S + Z_T)} + \frac{Z_{AA}}{2}\right)I_{A1} + \frac{Z_{AB}}{2}I_{B1} \\ 0 &= \frac{Z_{AB}}{2}I_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I_{B1} \\ I_{T1} &= \frac{2E_S}{Z_S + Z_T} - \frac{Z_S}{Z_S + Z_T}I_{A1} \end{aligned}\right\} \quad (1)$$

At the junction of counterpoise and tower,

$$I_{T1} - I_{B1} = 0$$

$$I_{T1} = I_{B1}$$

Therefore,

$$\left.\begin{aligned} \hat{E}_{T1} &= Z_TI_{T1} \\ \hat{E}_{T1} &= -Z_TI_{T1} = -Z_TI_{B1} \end{aligned}\right\} \quad (2)$$

At the beginning of the second half-period there are 2 sets of equations to solve in which portions of I_{A1} designated by I'_{A1} and I''_{A1} and portions of I_{B1} designated by I'_{B1} and I''_{B1} are involved independently. They are

$$\left.\begin{aligned} 0 &= \left(\frac{Z_SZ_T}{2(Z_S + Z_T)} + \frac{Z_{AA}}{2}\right)I'_{A1} + \frac{Z_{AB}}{2}I'_{B1} \\ \hat{E}_{T1} &= \frac{Z_{AB}}{2}I'_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I'_{B1} \end{aligned}\right\} \quad (3)$$

$$\hat{E}_{T1} = \left(\frac{Z_T}{2} + \frac{Z_{AA}}{2}\right)I''_{A1} + \frac{Z_{AB}}{2}I''_{B1} - \frac{Z_T}{2}I''_{B1}$$

$$\hat{E}_{T1} = \frac{Z_T}{2}I''_{A1} - \left(\frac{Z_T}{2} + \frac{Z_S}{2}\right)I''_{B1}$$

$$0 = \frac{Z_{AB}}{2}I''_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I''_{B1}$$

By eliminating I''_{B1},

$$\left.\begin{aligned} \frac{Z_S}{Z_S + Z_T}\hat{E}_{T1} &= \left(\frac{Z_SZ_T}{2(Z_S + Z_T)} + \frac{Z_{AA}}{2}\right)I''_{A1} + \frac{Z_{AB}}{2}I''_{B1} \\ 0 &= \frac{Z_{AB}}{2}I''_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I''_{B1} \end{aligned}\right\} \quad (4)$$

Adding eqs 3 and 4

$$\left.\begin{aligned} \frac{Z_S}{Z_S + Z_T}\hat{E}_{T1} &= \left(\frac{Z_SZ_T}{2(Z_S + Z_T)} + \frac{Z_{AA}}{2}\right)I_{A1} + \frac{Z_{AB}}{2}I_{B1} \\ \hat{E}_{T1} &= \frac{Z_{AB}}{2}I_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I_{B1} \end{aligned}\right\} \quad (5)$$

Since there are no induced potentials in the tower structure nor in the channel, at the junction of the tower channel and ground wire transmitted potential is

$$\hat{E}_{T1} + \hat{E}_{T2} = (I_{T2} - I_{T1})Z_T$$

By the principle of continuity of current at a junction point, the current flowing toward this point $-(I_{T1} + I_{T2})$ must be equal to the current flowing from it $(I_{A1} - I_{B1})$ or

$$-I_{B1} = -(I_{A1} + I_{T1} + I_{T2})$$

but since there are no induced potentials in the channel, the potential at the junction

$$\hat{E}_{T1} + \hat{E}_{T2} = -Z_SI_{B1} = -Z_S(I_{A1} + I_{T1} + I_{T2})$$

or

$$(I_{T2} - I_{T1})Z_T = -Z_S(I_{A1} + I_{A1}) - Z_SI_{T1}$$

Therefore

$$I_{T2}(Z_S + Z_T) = -Z_S(I_{A1} + I_{T1}) + Z_TI_{T1}$$

or

$$I_{T2} = -\frac{Z_S}{Z_S + Z_T}(I_{A1} + I_{T1}) + \frac{Z_T}{Z_S + Z_T}I_{T1}$$

Therefore

$$\hat{E}_{T2} = -\frac{Z_S + Z_T}{Z_SZ_T}(I_{A1} + I_{T1}) + \frac{Z_T^2}{Z_S + Z_T}I_{T1} \quad (6)$$

At the junction of the tower and counterpoise,

$$I_{T1} + I_{T2} - I_{B1} = 0$$

$$I_{T2} = -(I_{T1} - I_{B1})$$

$$\hat{E}_{T2} = -I_{T2}Z_T = (I_{T1} - I_{B1})Z_T \quad (7)$$

It may be observed now that the cycle of operations has been established so that the next equation will be the same as eq 5 with $\hat{E}_{T2}$, $\hat{E}_{T1}$, I_{A1}, I_{B1}, or

$$\left.\begin{aligned} \frac{Z_S}{Z_S + Z_T}\hat{E}_{T2} &= \left(\frac{Z_SZ_T}{2(Z_S + Z_T)} + \frac{Z_{AA}}{2}\right)I_{A1} + \frac{Z_{AB}}{2}I_{B1} \\ \hat{E}_{T2} &= \frac{Z_{AB}}{2}I_{A1} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I_{B1} \end{aligned}\right\} \quad (8)$$

$$\left.\begin{aligned} I_{T2} &= -\frac{Z_S}{Z_S + Z_T}(I_{T1} + I_{A1}) + \frac{Z_T}{Z_S + Z_T}I_{T1} \\ I_{T2} &= -(I_{T1} - I_{B1}) \\ \hat{E}_{T2} &= -\frac{Z_SZ_T}{Z_S + Z_T}(I_{T1} + I_{A1}) + \frac{Z^2_T}{Z_S + Z_T}I_{T1} \\ \hat{E}_{T2} &= -I_{T2}Z_T = (I_{T1} - I_{B1})Z_T \end{aligned}\right\} \quad (9)$$

The equations after the first may be expressed in the general form

$$\left.\begin{aligned} \frac{Z_S}{Z_S + Z_T}\hat{E}_{T(r-1)} &= \left(\frac{Z_SZ_T}{2(Z_S + Z_T)} + \frac{Z_{AA}}{2}\right)I_{Ar} + \frac{Z_{AB}}{2}I_{Br} \\ \hat{E}_{T(r-1)} &= \frac{Z_{AB}}{2}I_{Ar} + \left(\frac{Z_T}{2} + \frac{Z_{BB}}{2}\right)I_{Br} \end{aligned}\right\} \quad (10)$$

$$
\left.\begin{aligned}
I_{T_r} &= -\frac{Z_S}{Z_S+Z_T}(I_{T(r-1)}+I_{A_r})+\frac{Z_T}{Z_S+Z_T}I_{T(r-1)}\\
I_{T_r} &= -(I_{T(r-1)}-I_{B_r})\\
\hat{E}_{T_r} &= -\frac{Z_SZ_T}{Z_S+Z_T}(I_{T(r-1)}+I_{A_r})+\frac{Z^2_T}{Z_S+Z_T}I_{T(r-1)}\\
\hat{E}_{T_r} &= -Z_TI_{T_r}=Z_T(I_{T(r-1)}-I_{B_r})
\end{aligned}\right\}\quad(11)
$$

It may be observed further that eqs 1 and 2 are identical in form to eqs 5, 8, and 10 except for the terminal voltage which is the lightning potential $\hat{E}_S$. Therefore, it will be convenient to express the currents in terms of the admittances corresponding to the impedances in these equations. Designating them by Y_{AA}, Y_{BB}, and Y_{AB},

$$
\left.\begin{aligned}
Y_{AA} &= \frac{\dfrac{Z_T}{2}+\dfrac{Z_{BB}}{2}}{\left(\dfrac{Z_SZ_T}{2(Z_S+Z_T)}+\dfrac{Z_{AA}}{2}\right)\left(\dfrac{Z_T}{2}+\dfrac{Z_{BB}}{2}\right)-\left(\dfrac{Z_{AB}}{2}\right)^2}\\
Y_{BB} &= \frac{\dfrac{Z_SZ_T}{2(Z_S+Z_T)}+\dfrac{Z_{AA}}{2}}{\left(\dfrac{Z_SZ_T}{2(Z_S+Z_T)}+\dfrac{Z_{AA}}{2}\right)\left(\dfrac{Z_T}{2}+\dfrac{Z_{BB}}{2}\right)-\left(\dfrac{Z_{AB}}{2}\right)^2}\\
Y_{AB} &= -\frac{\dfrac{Z_{AB}}{2}}{\left(\dfrac{Z_SZ_T}{2(Z_S+Z_T)}+\dfrac{Z_{AA}}{2}\right)\left(\dfrac{Z_T}{2}+\dfrac{Z_{BB}}{2}\right)-\left(\dfrac{Z_{AB}}{2}\right)^2}
\end{aligned}\right\}\quad(12)
$$

$$
\left.\begin{aligned}
I_{A1} &= Y_{AA}\frac{Z_T}{Z_S+Z_T}\hat{E}_S\\
I_{B1} &= Y_{AB}\frac{Z_T}{Z_S+Z_T}\hat{E}_S\\
I_{T1} &= \frac{2E_S}{Z_S+Z_T}-\frac{Z_S}{Z_S+Z_T}I_{A1}=\frac{Z_S}{Z_S+Z_T}\left(\frac{2\hat{E}_S}{Z_S}-I_{A1}\right)\\
I_{T1} &= I_{B1}\\
\hat{E}_{T1} &= Z_TI_{T1}\\
\hat{E}_{T1} &= -Z_TI_{T1}=-Z_TI_{B1}
\end{aligned}\right\}\quad(13)
$$

$$
\left.\begin{aligned}
I_{A2} &= Y_{AA}\frac{Z_S}{Z_S+Z_T}\hat{E}_{T1}+Y_{AB}\hat{E}_{T1}\\
I_{B2} &= Y_{AB}\frac{Z_S}{Z_S+Z_T}\hat{E}_{T1}+Y_{BB}\hat{E}_{T1}\\
I_{T2} &= -\frac{Z_S}{Z_S+Z_T}(I_{T1}+I_{A2})+\frac{Z_T}{Z_S+Z_T}I_{T1}\\
I_{T2} &= -(I_{T1}-I_{B2})\\
\hat{E}_{T2} &= -\frac{Z_SZ_T}{Z_S+Z_T}(I_{T1}+I_{A2})+\frac{Z^2_T}{Z_S+Z_T}I_{T1}\\
\hat{E}_{T2} &= -Z_TI_{T2}=Z_T(I_{T1}-I_{B2})
\end{aligned}\right\}\quad(14)
$$

$$
\left.\begin{aligned}
I_{A_r} &= Y_{AA}\frac{Z_S}{Z_S+Z_T}\hat{E}_{T(r-1)}+Y_{AB}\hat{E}_{T(r-1)}\\
I_{B_r} &= Y_{AB}\hat{E}_{T(r-1)}+Y_{BB}\hat{E}_{T(r-1)}\\
I_{T_r} &= -\frac{Z_S}{Z_S+Z_T}(I_{T(r-1)}+I_{A_r})+\frac{Z_T}{Z_S+Z_T}I_{T(r-1)}\\
I_{T_r} &= -(I_{T(r-1)}-I_{B_r})\\
\hat{E}_{T_r} &= -\frac{Z_SZ_T}{Z_S+Z_T}(I_{T(r-1)}+I_{A_r})+\frac{Z^2_T}{Z_S+Z_T}I_{T(r-1)}\\
\hat{E}_{T_r} &= -Z_TI_{T_r}=Z_T(I_{T(r-1)}-I_{B_r})
\end{aligned}\right\}
$$

The complete solution for I_A and I_B is

$$
\left.\begin{aligned}
I_A &= \Sigma I_{A_r}\\
I_B &= \Sigma I_{B_r}
\end{aligned}\right\}\quad(16)
$$

each term being added at the beginning of its period. Expressions for the other currents are similar.

Appendix II—Method of Calculating Protection Level

In this example the counterpoise wires are considered at ground level; they consist of 2 No. 2/0 B.&S. gauge wires 50 ft apart extending parallel to the line in both directions, and 2 No. 2/0 wires at right angles 50 ft apart but extending only in one direction. This latter connects to the parallel counterpoise of another line 200 ft away, but its mutual surge impedance with the first line has been ignored. The ground plane is assumed to be 200 ft below the earth's surface. The ground wires consisting of two $^3/_8$-in. steel cables 50 ft apart average 298 ft above the ground plane. The corona radius of the ground wires for the maximum potentials encountered will be approximately 1 ft, and the geometrical mean radius of the ground wires taking into account corona and their spacing will be approximately 3.3 ft. The same corona radius is assumed for the counterpoise wires and their geometrical mean radius is approximately 2.87 ft. The geometrical mean distance between ground wires and line wires is 46.9 ft, between ground wires and counterpoise 103.3 ft, and between line wires and counterpoise 68.4 ft. It is assumed that the normal tower footing surge impedance is 400 ohms. In these calculations K is assumed equal to 4 which is believed to be a conservative value, and S is taken equal to 1.

To obtain the value of m

$$Z_G = 400 \text{ ohms}$$

$$Z_1 = 60 \log_e \frac{400}{2.87} = 298$$

It is desired also to include with the ground resistance the effect of a cross counterpoise having a surge impedance equal to $Z_{12} = Z_1/\sqrt{K} = 149$ ohms. This will be denoted by Z'_G.

$$Z'_G = \frac{400 \times 149}{549} = 108.5 \text{ ohms}$$

Therefore

$$m = \frac{Z_1}{2Z'_G} = \frac{298}{217} = 1.375$$

Taking $S = 1$

$$\frac{(1+S)\sqrt{K}-S}{m+\sqrt{K}}\cdot\frac{1}{\sqrt{K}} = \frac{3}{3.375}\cdot\frac{1}{2} = 0.444$$

$$
\begin{aligned}
Z_{11} &= 60 \log_e \frac{596}{3.3} &&= 312\\
Z_{22} &= 30 \log_e \frac{400}{2.87} &&= 149\\
Z_{12} &= 0.444 \times 60 \log_e \frac{498}{103.3} = 0.444 \times 94.4 &&= 42\\
Z_{12} &= 0.60 \log_e \frac{559}{46.9} &&= 149\\
Z_{22} &= 0.444 \times 60 \log_e \frac{461}{68.4} = 0.444 \times 114.5 &&= 50.9
\end{aligned}
$$

From these the following are obtained:

$$
\begin{aligned}
Z_{AA} &= && 156 \text{ ohms}\\
Z_{BB} &= \frac{74.5 \times 108.5}{183.0} = && 44.2\\
Z_{AB} &= && 21\\
Z_{AC} &= && 74.5\\
Z_{BC} &= && 25.45
\end{aligned}
$$

$$
\begin{aligned}
\frac{Z_{AA}}{2} &= 78 & \frac{Z_S}{Z_S+Z_T} &= \frac{2}{3}\\
\frac{Z_{BB}}{2} &= 22.1 & \frac{Z_T}{Z_S+Z_T} &= \frac{1}{3}\\
\frac{Z_{AB}}{2} &= 10.5 & \frac{Z_SZ_T}{Z_S+Z_T} &= 66.67 \text{ ohms}
\end{aligned}
$$

$Z_S = 200$ ohms

$Z_T = 100$ ohms

$\frac{Z_T^2}{Z_S - Z_T} = 33.33$ ohms

$\frac{Z_S Z_T}{2(Z_S + Z_T)} = 33.33$ ohms

$\frac{Z_S Z_T}{2(Z_S + Z_T)} + \frac{Z_{AA}}{2} = 111.33$ ohms

$\frac{Z_T}{2} + \frac{Z_{BB}}{2} = 72.1$ ohms

$\frac{Z_{AB}}{2} = 10.5$ ohms

Product of first 2 of above 3 quantities is $111.33 \times 72.1 = 8{,}025.0$
Square of last $= 110.2$

Difference $7{,}914.8$

$Y_{AA} = \frac{72.1}{7914.8} = 0.0091$

$Y_{BB} = \frac{111.33}{7914.8} = 0.0141$

$Y_{AB} = -\frac{10.5}{7914.8} = -0.00133$

For the calculations an arbitrary value $\dot{E}_S = 1{,}000{,}000$ volts will be taken. $\frac{2E_S}{Z_S} = 10{,}000$ amp.

$\frac{Z_T}{Z_S + Z_T}\dot{E}_S = 333{,}333$ volts

$\dot{I}_{A1} = 3{,}030$ amp

$\dot{I}_{B1} = -444$ amp

$\dot{I}_{T1} = 6{,}667 - 2{,}020 = 4{,}647$ amp

$\dot{I}_{T1} = -444$ amp

$\dot{E}_{T1} = 464{,}700$ volts

$\dot{E}_{T1} = 44{,}400$ volts

$\frac{Z_S}{Z_S + Z_T}\dot{E}_{T1} = 29{,}600$

$\dot{I}_{A2} = 269.5 - 618 = -348.5$

$\dot{I}_{B2} = -39.4 + 6{,}560 = +6{,}520.6$

$\dot{I}_{T2} = -\frac{2}{3}(-222 - 349.5) = 381$

$\dot{I}_{T2} = -(4{,}647 - 6{,}520.6) = 1{,}873.6$

$\dot{E}_{T2} = 38{,}100$

$\dot{E}_{T2} = -187{,}360$

$\frac{Z_S}{Z_S + Z_T}\dot{E}_{T2} = -125{,}000$

$\dot{I}_{A3} = -1{,}139 - 50.7 = -1{,}189.7$

$\dot{I}_{B3} = +166.3 + 537 = +703.3$

$\dot{I}_{T3} = -\frac{2}{3}(936.8 - 1{,}189.7) = 168.5$

$\dot{I}_{T3} = -(381 - 703.3) = 322.3$

$\dot{E}_{T3} = 16{,}850$

$\dot{E}_{T3} = -32{,}230$

$\frac{Z_S}{Z_S + Z_T}\dot{E}_{T3} = -21{,}480$

$\frac{Z_S - Z_T}{Z_S + Z_T} = \frac{1}{2}\frac{Z_S}{Z_S + Z_T}$

$\frac{Z_T(Z_S - Z_T)}{Z_S + Z_T} = 33.33$ ohms

$\frac{2}{Z_S + Z_T} = 0.00667$ mho

$\dot{I}_{A4} = -195 - 22.4 = -217.4$

$\dot{I}_{B4} = +28.6 + 237.5 = +266.1$

$\dot{I}_{T4} = -\frac{2}{3}(161.2 - 217.4) = 37.5$

$\dot{I}_{T4} = -(168.5 - 266.1) = 97.6$

$\dot{E}_{T4} = 3{,}750$

$\dot{E}_{T4} = -9{,}760$

$\frac{Z_S}{Z_S + Z_T}\dot{E}_{T4} = 6{,}520$

$\dot{I}_{A5} = -59.3 - 5.0 = 64.3$

$\dot{I}_{B5} = +8.7 + 52.8 = +61.5$

$\dot{I}_{T5} = -\frac{2}{3}(488 - 64.3) = 10.35$

$\dot{I}_{T5} = -(37.5 - 61.5) = 24.0$

$\dot{E}_{T5} = 1{,}035$

$\dot{E}_{T5} = -2{,}400$

$\frac{Z_S}{Z_S + Z_T}\dot{E}_{T5} = -1{,}600$

$\dot{I}_{A6} = -14.5 - 1.4 = -15.9$

$\dot{I}_{B6} = +2.1 + 14.6 = 16.7$

$\dot{I}_{T6} = -\frac{2}{3}(12 - 15.9) = 2.6$

$\dot{I}_{T6} = -(10.35 - 16.7) = 6.35$

$\dot{E}_{T6} = 260$

$\dot{E}_{T6} = -635$

$\frac{Z_S}{Z_S + Z_T}\dot{E}_{T6} = -423$

$\dot{I}_{A7} = -3.8 - 0.35 = -4.15$

$\dot{I}_{B7} = +0.56 + 3.66 = 4.22$

$\dot{I}_{T7} = -\frac{2}{3}(3.17 - 4.15) = 0.655$

$\dot{I}_{T7} = -(2.6 - 4.22) = 1.62$

$\dot{E}_{T7} = 65.5$

$\dot{E}_{T7} = -162$

$\frac{Z_S}{Z_S + Z_T}\dot{E}_{T7} = -108$

$\dot{I}_{A8} = -0.98 - 0.081 = -1.07$

$\dot{I}_{B8} = 0.14 + 0.92 = 1.06$

DATA OBTAINED BY CALCULATIONS

$\dot{I}_{A1} = 3{,}030$ amp	$\dot{I}_{B1} = -444$	$Z_{AA} = 156$ ohms	$Z_{AC} = 74.5$ ohms
$\dot{I}_{A2} = -349$	$\dot{I}_{B2} = 6{,}521$		
$\dot{I}_{A3} = -1190$	$\dot{I}_{B3} = 703$	$Z_{BB} = 44.2$	$Z_{BC} = 25.45$
$\dot{I}_{A4} = -217$	$\dot{I}_{B4} = 266$	$Z_{AB} = 21.0$	
$\dot{I}_{A5} = -64$	$\dot{I}_{B5} = 61$		
$\dot{I}_{A6} = -16$	$\dot{I}_{B6} = 17$		
$\dot{I}_{A7} = -4$	$\dot{I}_{B7} = 4$		
$\dot{I}_{A8} = -1.0$	$\dot{I}_{B8} = 1.0$		

The tabulated results of carrying out the additions to obtain $\dot{I}_A$, $\dot{I}_B$, $\dot{E}_A$, $\dot{E}_B$, $\dot{E}_C$, and $\dot{E}_A - \dot{E}_C$ are given in Table II. It may be seen that for a stroke of 20,000,000 volts the maximum value of

$_A - \hat{E}_C$ which is 20 times the value given in the table will be 2,000,000 volts reached in 1 μsec which is reduced to approximately 1,140,000 volts at the end of 2 μsec. Taking a time lag of 3 μsec and using Fig. 2, it is found that the number of standard insulators required to withstand the voltage is between 17 and 18.

Table II

Values Obtained Are Per 1,000 Kv of Stroke Potential

	Amperes		Kilovolts			
t	$\hat{i}_A$	$\hat{i}_B$	$\hat{e}_A$	$\hat{e}_B$	$\hat{e}_C$	$\hat{e}_A - \hat{e}_C$
0	0	0	0	0	0	0
0.1	303	−44	46	4	21	25
0.2	571	563	101	36	57	44
0.3	720	1,241	139	70	85	54
0.4	847	1,946	173	104	113	60
0.5	969	2,557	207	138	140	67
0.6	1,088	3,369	241	172	167	74
0.7	1,207	4,082	274	206	194	80
0.8	1,326	4,750	307	238	220	87
0.9	1,445	5,463	340	272	246	94
1.0	1,566	6,225	375	308	275	100
1.1	1,349	7,087	359	341	281	79
1.2	1,174	7,025	332	336	266	65
1.3	1,130	6,987	323	332	262	61
1.4	1,100	6,929	317	330	258	59
1.5	1,097	6,866	315	327	257	59
1.6	1,084	6,791	312	323	254	58
1.7	1,072	6,720	308	319	251	57
1.8	1,068	6,649	306	316	249	57

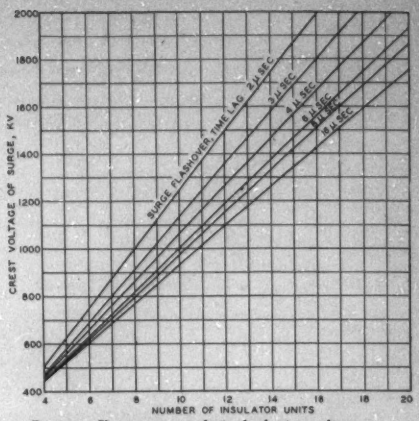


Fig. 2. Characteristics of standard 10-in. diam. insulator units with $5^3/_4$ in. spacing; $1^1/_2 \times 40$-μsec positive wave

Corrected to the following atmospheric conditions: absolute humidity, 6.5 grains per cu ft; relative density, 1.0

Power Limits of a Transmission System

By
W. S. PETERSON
MEMBER A.I.E.E.

Bureau of Power & Light of the City of Los Angeles, Calif.

This article presents a practicable and comparatively simple means of determining the ability of an electric power transmission system to withstand any type of short circuit at any single point of the system without losing synchronism. The method is one that enables an engineer without much special training in handling stability problems to obtain quite accurate solutions with a reasonable expenditure of time.

A SIMPLE and accurate method of calculating the power limit of a transmission system under dynamic conditions is presented; rotor movements of the synchronous machinery at each end of the line are taken into account, both during and after the short circuit. From such calculations curves may be constructed to show the permissible duration of any type of short circuit at any single point in the system as a function of the load being carried previous to the short circuit. Circuit conditions before and after the short circuit need not be alike; that is, certain sections of line can be considered switched out as would be the case in order to clear the short circuit.

Calculations of this nature find their greatest usefulness in the design of long distance high voltage transmission lines where the principal limitation in design and performance is power limit or stability. By their use, the following important choices are facilitated:

1. Selection of proper speed of oil circuit breakers.
2. Selection of most advantageous characteristics of other equipment such as generators and transformers, by indicating to what extent equipment of especially low reactance should be used.
3. Decision as to the number of sectionalizing points that may be necessary on a given transmission line.

Based upon a paper "Calculation of Dynamic Power Limit of Transmission System During Three-Phase Faults" originally presented at a meeting of the A.I.E.E. Los Angeles Section, Feb. 17, 1931; and subsequently awarded the 1931 A.I.E.E. Pacific District prize for best paper. Since its original presentation this paper has been revised, extended, recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. *Not published in pamphlet form.*

4. Conclusion as to the proper load rating of the transmission system.

Fundamental Principles

A transmission system is essentially 2 groups of synchronous machinery, electrically connected together by a transmission line, and having loads taken off at points between the 2 groups of generators (or generator and motor or condenser) and usually quite close to those at the receiving end. When a short circuit occurs, the electrical output of each of the 2 groups is changed immediately. However, as the governing mechanism of the generators and the external torque requirements of the motors or synchronous condensers do not change immediately, there is a difference between the externally applied shaft torque and the internal electrical torque. The difference between these 2 values, for a given group, causes it to accelerate or retard as the case may be. At the conclusion of the short circuit, the machine voltages have new angular relations which cause the transmission of synchronizing power from one group to the other. This power may have to be transmitted over a circuit of changed constants because of the switching that took place to eliminate the short circuit. It is necessary to determine whether the machine rotors have swung beyond angles for which the synchronizing power is adequate to control the mechanical oscillations of the synchronous machines.

Power relations between the machines or between either machine and the point of short circuit can be expressed in terms of the voltages at those various points, the angles between the voltages, and the general circuit constants of the circuit connecting them. The most familiar form of expressing this relationship is the power angle diagram, where the power transmitted between 2 points of constant voltage is given as a function of the vector angle between the voltages.

In the power angle diagrams for this article the generator voltage is assumed to be that which in-

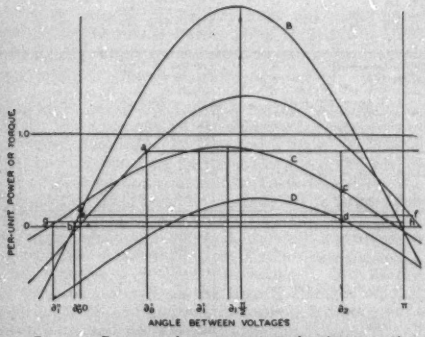


Fig. 1. Power-angle or torque-angle diagram of a typical transmission system

Table I—Calculation Form to Test Stability of Transmission System for 3-Phase Short Circuits

1. E_g	=	1.020	35. d_{Bn}	=	1.046
2. E_r	=	1.000	36. d_{Bn}	=	0.057
3. E_a	=	1.283	37. 35×9	=	−0.021
4. b_{Ln}	=	0.0657	38. 36×10	=	0.031
5. b_{Ln}	=	0.7815	39. $37 + 38$	=	0.010
6. $\sqrt{b_{Ln}^2 + b_{Ln}^2}$	=	0.7845	40. d_{Cn}	=	0.3401
7. $4/6$	=	0.0838	41. d_{Cn}	=	0.3176
8. $\theta_{Ln} = \cos^{-1} 7$	=	1.4867	42. 40×14	=	−0.2602
9. b_{Bn}	=	−0.0199	43. 41×15	=	0.5318
10. b_{Bn}	=	0.5500	44. $42 + 43$	=	0.2716
11. $\sqrt{b_{Bn}^2 + b_{Bn}^2}$	=	0.5503	45. a_{Cn}	=	1.453
12. $9/11$	=	0.0362	46. a_{Cn}	=	0.750
13. $\theta_{Bn} = \cos^{-1} 12$	=	1.5070	47. 45×14	=	−0.451
14. bC	=	−0.3098	48. 46×15	=	1.256
15. bC_n	=	1.6740	49. $47 + 48$	=	0.805
16. $\sqrt{bC_n^2 + bC_n^2}$	=	1.7025	50. a_n'	=	0.6500
17. $14/16$	=	−0.1820	51. a_n''	=	−0.0593
18. $\theta_{Cb} = \cos^{-1} 17$	=	1.7538	52. $a_n = a_n' - a_n''$	=	0.7183
19. $\sin \theta_{Cb} = 15/16$	=	0.9833	53. $a_n' + b_{Ln} = 50 + 8$	=	2.1457
20. $\sin^2 \theta_b = 19^2$	=	0.9668	54. $\cos (a_n' + b_{Ln})$	=	−0.5435
21. $\cos^2 \theta_{Cb} = 17^2$	=	0.03312	55. $a_n'' + \theta_{Bn} = 51 + 13$	=	1.5477
22. M_g	=	18.29	56. $\cos(a_n'' + \theta_{Bn})$	=	0.0231
23. M_c	=	3.325	57. $26 + 29$	=	0.2732
24. $1/(22 \times 6)$	=	0.0710	58. $26 - 29$	=	−0.1892
25. $1/(22 \times 16)$	=	0.0327	59. $+2 \times 24 \times 54$	=	−0.03862
26. 3×25	=	0.0420	60. $-2 \times 27 \times 56$	=	−0.01620
27. $3/(23 \times 11)$	=	0.7015	61. $-1 \times 24 \times 34/6$	=	−0.00668
28. $3/(23 \times 16)$	=	0.2266	62. $+3 \times 27 \times 39/11$	=	0.01668
29. 1×28	=	0.2312	63. $+1 \times 25 \times 44/16$	=	0.00532
30. d_{Ln}	=	0.8872	64. $-3 \times 28 \times 49/16$	=	−0.13750
31. d_{Ln}	=	0.0180	65. $\Sigma 59$ to 64, inc.	=	−0.17700
32. 30×4	=	0.0583	66. 57^2	=	0.0746
33. 31×5	=	0.0141	67. 58^2	=	0.0358
34. $32 + 33$	=	0.0724	68. 65^2	=	0.03132

69. 67×21	=	0.001186		
70. 66×20	=	0.0722		
71. $69 + 70$	=	0.07339		
72. $71 - 68$	=	0.04207		
73. 69×72	=	0.0000499		
74. $= \sqrt{73}$	=	0.00706	−0.00706	
75. $65 \times 57 \times 19$	=	−0.0476		
76. $= 74 - 75$	=	0.0547	0.0405	
77. $76/71 = \sin \delta_2$	=	0.746	0.552	
78. $\delta_2 = \sin^{-1} 77 > \pi/2$	=	2.2996	2.5567	
79. $\delta_2 + \theta_{Cb} = 78 + 18$	=	4.0534	4.3105	
80. $\delta_2 - \theta_{Cb} = 78 - 18$	=	0.5458	0.8029	
81. $\cos (\delta_2 + \theta_{Cb})$	=	−0.6124	−0.3911	
82. $\cos (\delta_2 - \theta_{Cb})$	=	0.8543	0.6943	
83. 26×81	=	−0.0257	−0.0164	
84. 29×82	=	0.1973	0.1605	
85. $83 - 84 = 65$	=	−0.2230	−0.1769	
86. $\sin (\delta_2 + \theta_{Cb})$	=		−0.9201	
87. $\sin (\delta_2 - \theta_{Cb})$	=		0.7192	
88. $59 + 60$	=		−0.05482	
89. 88^2	=		0.00300	
90. f = freq.	=		50	

Note: From item *74* to *85* tabulate 2 sets of values. Choose both values of δ_2, item 78 in the second quadrant, that is, greater than $\pi/2$. In order to determine which is correct, note which one satisfies condition in item *85*. Use the correct value for remaining work.

91. t	=	0.29	0.33	0.337
92. $\pi f t^2$	=	13.21	17.11	17.82
93. -92×88	=	0.7238	0.9380	0.9762
94. $\delta_1 = 93 + 52$	=	1.4421	1.6563	1.6945
95. $\delta_1 + \theta_{Cb} = 94 + 18$	=	3.1959	3.4101	3.4483
96. $\delta_1 - \theta_{Cb} = 94 - 18$	=	−0.3117	−0.0975	−0.0593
97. $\sin (\delta_1 + \theta_{Cb})$	=	−0.0543	−0.2650	−0.3020
98. $\sin (\delta_1 - \theta_{Cb})$	=	−0.3068	−0.0975	−0.0593
99. $87 - 98$	=	1.0260	0.8167	0.7785
100. $86 - 97$	=	−0.8658	−0.6551	−0.6181
101. $\delta_2 = \delta_1 = 78 - 94$	=	1.1146	0.9004	0.8622
102. 101×65	=	0.1972	−0.1592	−0.1525
103. 29×99	=	0.2372	0.1890	0.1800
104. -26×100	=	0.0364	0.0275	0.0260
105. $102 + 103 + 104$	=	0.0764	0.0573	0.0535
106. 92×89	=	0.0396	0.0514	0.0535
107. t for $105 = 106$	=			0.337

Note: *Italic* numbers refer to item numbers.

cludes the terminal voltage and the transient reactance drop. It is assumed, for the period of the disturbance, that this voltage remains constant. This assumption is in accordance with that made by most writers on the subject of stability. The reference voltage will be that at the point of short circuit, previous to the short circuit.

To facilitate the description of the phenomena, a 3-phase fault will be used as an example. In Fig. 1, curve A is a power angle diagram showing the power sent from the internal voltage of the generator at the sending end of the line to the point of short circuit before the disturbance. The values are on a per unit basis, which is similar to a percentage basis except that the decimal value is used. Curve B shows a similar relationship between the synchronous machine at the receiving end and the point of short circuit. Curves C and D show the sending- and receiving-end power angle diagrams for power transmitted from the sending machine to the shaft of the receiving machine after the short circuit is cleared. It can be shown that the vertical offsets, from the zero axis, of the two cosine curves A and B correspond to the sending-end power during a 3-phase short circuit at the receiving end. Such values are designated by the horizontal lines ef and gh. Similar diagrams can be drawn for other types of short circuits.

Under normal load, steady conditions, the synchronous machine voltages and rotors will take relative positions corresponding to certain calculable angles with respect to the reference voltage, and will require certain shaft torques to maintain the assumed flow of power. Such points are indicated in Fig. 1 by a and b. Point b is on the zero line because the machine was a synchronous condenser and had no externally applied shaft torque.

During the short circuit, a torque equal to the difference between the shaft input and the electrical output, which for the 3-phase short circuit is represented by the distance between point a and line ef, is acting to accelerate the sending-end generator. Similarly a torque represented by the distance between point b and line gh is acting on the receiving machine. In this particular example it is retardation. For a given duration of short circuit and known moments of inertia of the rotors, the rotor movements can be calculated. Their new angles are designated as δ_1' and δ_1'' on Fig. 1. At this time the machines can be assumed to be connected together by a new circuit performing in accordance with curve C. The angle between rotors is $\delta_1' - \delta_1'' = \delta_1$. At this angle the output of the sending-end machine is greater than initially. This output tends to slow down the leading machine and speed up the lagging machine or to bring them closer to synchronism.

While the speed is changing, the machines have certain velocities with respect to each other. In reaching a state of synchronism, with a constant angle between the rotors, oscillations take place; some of the energy is consumed in losses and some in changing the total system speed. The stability can be checked at the end of the first oscillation. At this point the lagging machine is farthest in angular position from the leading machine, their relative velocity is zero, and their actual velocities are alike. Simultaneously the condition also should be fulfilled that the machines have the same absolute acceleration, i. e., the same tendency to change the total system speed. This may be stated also by saying the machines have zero relative acceleration. This criterion is in accordance with that expressed previously in a paper by Summers and McClure[2] (for numbered references see list at end of article), namely, that "the machines have come to rest with respect to each other before the acceleration becomes finally zero." The limit is of course as their relative acceleration becomes zero.

During the short circuit, the rotors reached an angular separation of δ_1, and their relative angular velocity increased from zero to some value designated as ω_1. In the interval following the removal of the short circuit and lasting until the end of the first oscillation, when the rotors again have the same velocity, their relative angular velocity has changed from ω_1 to zero. Equations expressing the accelerations during both of these intervals can be set up and solutions for ω_1 made. The accelerating torques during the second interval are shown in Fig. 1 as the vertical distance between curve C and line ac; and the distance between curve D and horizontal line point b, which in this case is the zero axis. The particular values used are those to the right of the angle δ_1, where this type of acceleration begins.

Referring to Fig. 1, curve C, this means that for stability the oscillation should not cause the machines to swing beyond points c and d at the angle δ_2 where the relative acceleration of the machines is zero. At δ_2 the torque acting on the sending-end machine is

Table II—Calculation Form to Test Stability of Transmission System for 2-Phase-to-Ground and 1-Phase-to-Ground Short Circuits

Use Table I for first 88 items

89. b_{T1}	=	104. *102 + 103*	=
90. b_{T2}	=	105. d_{T1}	=
91. $\sqrt{b_{T1}^2 + b_{T2}^2}$	=	106. d_{T2}	=
92. *89/91*	=	107. *105 × 89*	=
93. $\theta_{Tb} = \cos^{-1} 92$	=	108. *106 × 90*	=
94. *1/(22 × 91)*	=	109. *107 + 108*	=
95. *3 × 94*	=	110. Sin *98*	=
96. *3/(23 × 91)*	=	111. Sin *99*	=
97. *1 × 96*	=	112. *−(59+60+61+62)*	=
98. $\delta_6 + \theta_{Tb} = 52 + 93$	=	113. *−1 × 94 × 109/91*	=
99. $\delta_6 - \theta_{Tb} = 52 - 93$	=	114. *+ 3 × 96 × 104/91*	=
100. a_{T1}	=	115. *112 + 113 + 114*	=
101. a_{T2}	=	116. *−115 × 52*	=
102. *100 × 89*	=	117. *− 95 × 110*	=
103. *101 × 90*	=	118. *+ 97 × 111*	=
		119. *116 + 117 + 118*	=

120. δ_1 (Assumed)	=	132. Sin $(\delta_1 + \theta_{Cb})$	=
121. $\delta_2 - \delta_1 = 78 - 120$	=	133. *86 − 131*	=
122. $\delta_1 - \delta_6 = 120 - 52$	=	134. *87 − 132*	=
123. $\delta_1 + \theta_{Tb} = 120 + 93$	=	135. *− 133 × 26*	=
124. $\delta_1 - \theta_{Tb} = 120 - 93$	=	136. *+ 134 × 29*	=
125. Sin $(\delta_1 + \theta_{Tb})$	=	137. *121 × 65*	=
126. Sin $(\delta_1 + \theta_{Tb})$	=	138. *135 + 136 + 137*	=
127. *125 − 110*	=	139. *122 × 115*	=
128. *111 − 126*	=	140. *95 × 127*	=
129. $\delta_1 + \theta_{Cb} = 120 + 18$	=	141. *97 × 128*	=
130. $\delta_1 - \theta_{Cb} = 120 - 18$	=	142. *139 + 140 + 141*	=
131. Sin $(\delta_1 + \theta_{Cb})$	=	Vary δ_1 until *138*	= *142*

143. *95 + 97*	=	153. *(0.87) × 143 × 52*	=
144. *143 + 119*	=	154. *152 − 115*	=
145. *f*	=	155. *153 − 115*	=
146. *(1.74)ef × 143*	=	156. *154/151*	=
147. $\sqrt{146}$	=	157. *155/151*	=
148. *(1.74) × 143 × 144*	=	158. Sin^{-1} *156*	=
149. *115²*	=	159. Sin^{-1} *157*	=
150. *148 + 149*	=	160. *158 − 159*	=
151. $\sqrt{150}$	=	161. *160/147*	=
152. *(0.87) × 143 × 120*	=	Duration of short circuit is given by *161*	

Note: *Italic* numerals refer to item numbers.

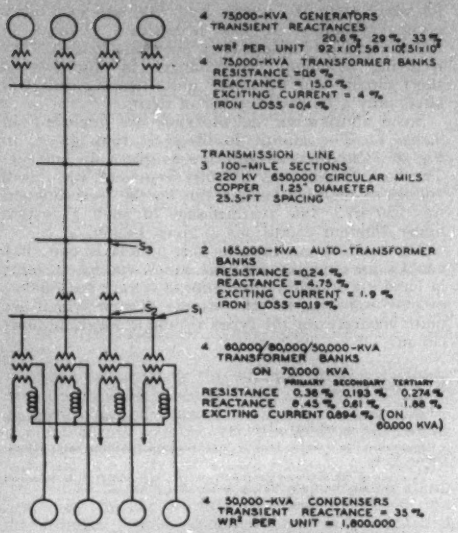


Fig. 2. Schematic diagram of a typical double circuit transmission system

represented by the distance between c on curve C and the horizontal line through initial load point a. The torque acting on the receiving machine is given by the distance between point d on curve D and the horizontal line through its initial load line, which in this case is the zero line. Accelerations of these machines are equal when their torques divided by their inertia constants are equal; δ_2 is calculated to fulfill this condition.

Calculation Form

Calculations for a 3-phase fault are made more readily by use of the forms given in Table I. For unbalanced faults use the supplementary form given in Table II. In these forms all voltages and the components of the general circuit constants are on a per-unit basis. All angles are expressed in radians. Loads are represented by shunt admittances and are combined into the general circuit constants. Duration of the short circuit is expressed in seconds.

A trial calculation is made in Table I for a specific duration of short circuit. If item 101 is larger than item 103 the system is stable for that time. If an accurate solution is required, different assumptions of time are made until those 2 items are the same. This requires 3 or 4 approximations. Only a few of the items change as the time is changed so that successive approximations are not as tedious as the first.

The list of symbols used is as follows;

E_s = internal voltage of sending-end generator.

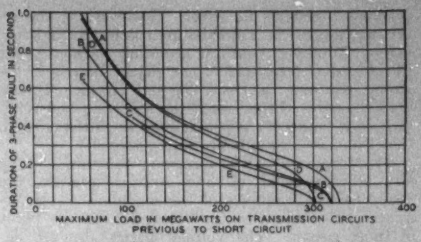


Fig. 3. Stability curves for pair of 300-mile 50-cycle 220-kv transmission circuits in Fig. 2

A. Short circuit at S_{1l} no line section lost; generator reactance 20.6%
B. Short circuit at S_{1l} no line section lost; generator reactance 29.0%
C. Short circuit at S_{1l} no line section lost; generator reactance 33.0%
D. Short circuit at S_{1l} one line section lost; generator reactance 20.6%
E. Short circuit at S_{1l} one line section lost; generator reactance 20.6%

E_r = internal voltage of receiving-end generator or motor.
E_r = reference voltage at point of short circuit.
f = system frequency in cycles per second.
t = duration of short circuit in seconds.
A_L, B_L, C_L, D_L = general circuit constants of circuit between E_s and E_r.
A_R, A_R, C_R, D_R = general circuit constants of circuit between E_s and E_r.
A_C, B_C, C_C, D_C = general circuit constants of circuit between E_s and E_r, after the short circuit.
A_F, B_F, C_F, D_F = general circuit constants of circuit between E_s and E_r at the time of the fault, and including the fault impedance in accordance with symmetrical component theory.

(The preceding 4 groups of constants are made up of components designated similar to the following: $B_R = b_{R1} + jb_{R2}$.)

δ_0' = initial angle between E_s and E_r.
δ_0'' = initial angle between E_s and E_r.
δ_0 = initial angle between E_s and E_r.
δ_1' = angle between E_s and E_r after short circuit.
δ_1'' = angle between E_s and E_r after short circuit.
δ_1 = angle between E_s and E_r after short circuit.
δ_2 = angle between E_s and E_r after short circuit and where relative acceleration of sending and receiving machines is zero.

Inertia constants of the sending-end and receiving-end rotors are designated by M_s and M_C and are found from the equation

$$M = \frac{0.462WR^2(\text{rpm}/1000)^2}{\text{base kw}}$$

where the WR^2 is expressed in pound-feet squared.[1] The remainder of the symbols are obvious from the operations directed in Table I. Where mathematical operations are designated by italic numerals, such as *32 + 33*, the quantities designated by those item numbers are to be used in that manner.

General circuit constants are calculated for the circuit between the internal voltage of each group of machines and the point of short circuit, with the short-circuit point being considered the receiving end. In calculating these constants all load admittances are included. If switching occurs to clear the short circuit thereby changing these constants, these new constants also are calculated. Constants of the final circuit between the 2 internal voltages then are calculated. It is convenient to do this by regarding the system as the 2 previously

calculated systems in series. However, as the receiving ends of the 2 circuits are connected together, before combining them it is necessary to interchange the A and D constants of the circuit that is in the wrong relation, the receiving-end circuit. It can be demonstrated that when the receiving and sending relationships of a general circuit are interchanged, the A and D constants are interchanged.

By proper use of the foregoing constants, or by any other method of line drop calculation, the initial internal voltages of the machines are determined with respect to the voltage E, at the point of short circuit. The voltage angles also are determined, in conformance with initial assumptions of output.

Substitutions then are made in the calculation form as shown in Table I. For item 76 2 values are possible depending on which sign is used. Two values result in items 77 and 78. Choose δ_2 for item 78 so that it is in the second quadrant, that is greater than $\pi/2$. Also choose δ_2 so that it satisfies the condition that $26 \times 81 - 29 \times 82 = 65$; this is a quick way of checking which is the proper solution to use.

Finally if item 105 is greater than item 106 the system is stable. By successive approximations the exact duration of short circuit can be determined for which item 105 equals item 106 and instability occurs. Changes in load necessitate changes in circuit constants unless they are shaft loads on the receiving machine, but changes in duration of short circuit can be made quite readily and will affect only a limited number of items.

Some illustrative calculations are included in Table I. The circuit involved is that given on Fig. 2. Circuit constants are as given in Table I. The base chosen was 250,000 kva, and the initial voltage at the high voltage bus on the receiving end was 220 kv. The performance of such a system under different conditions is given in Fig. 3.

The method outlined in this article is one that enables an engineer without much special training in handling stability problems to obtain reasonably quickly solutions for the simple system which are quite accurate for all types of single location short circuits.

References

1. System Stability as a Design Problem, R. H. Park and E. H. Bancker. A.I.E.E. Trans., v. 48, 1929, p. 170–94.

2. Electrical Characteristics of Transmission Circuits, third edition, William Nesbit.

3. Progress in the Study of System Stability, Appendix II, I. H. Summers and J. B. McClure. A.I.E.E. Trans., v. 49, 1930, p. 132–61.

Power Limits of 220-Kv Transmission Lines

By

ALEX A. KRONEBERG
ASSOCIATE A.I.E.E.
Southern Calif. Edison Co., Ltd., Los Angeles

MABEL MACFERRAN
ASSOCIATE A.I.E.E.
Metropolitan Water District of Southern California, Los Angeles. Formerly of Southern Calif. Edison Co., Ltd

For the transmission of power from Boulder Dam to the system of the Southern California Edison Company, numerous studies were made to determine the power limits of various designs of transmission lines, and the maximum generating capacity that could be installed safely at Boulder Dam without incurring instability. These studies were made for various design features and types of load and faults. The results of the studies are presented in this paper, a description of the method used being included in the appendixes.

THERE will be available to the Southern California Edison Company, Ltd., at the Boulder Dam project a maximum of 860,000,000 kwhr per year, which corresponds to 98,000 kw at 100 per cent load factor. This block of power must be transmitted to the load center of the company some 280 miles away. Study indicated that the best voltage for economical transmission lies between 154 and 220 kv. In considering the amount of energy available, the distance of transmission, and investment costs, it at once becomes apparent that the generating plant at Boulder Dam must be a large capacity peak plant in order to be justified at all.

A tentative installation of 250,000 kw was assumed at first. The design of the installation was varied and the safe operating limits of the transmission system were determined for various designs. The safe operating limit was considered to be that value of transmitted power for which the system will remain stable through a 2-conductor-to-ground fault cleared in 0.2 sec. A number of solutions were made in-

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, January 23–26, 1934. Manuscript submitted April 17, 1933; released for publication August 28, 1933. *Not published in pamphlet form.*

volving various designs and sizes of installation and various classes and sizes of system load. As a result it was possible to estimate the size of an installation of given design which would be equal to the safe operating limit of the transmission system.

The results of the studies are expressed in Figs. 1 and 2. They can be summarized as follows:

1. For direct transmission of Boulder Dam power to the system, 2 220-kv lines tied directly into the low reactance 220-kv backbone of the system will give the highest transient stability limit.

2. The safe operating limit for a 250,000-kw generator installation would vary from 163,000 kw to 270,000 kw, depending upon how many stabilizing factors are included in the design. These stabilizing factors, in the order of their relative economy, are as follows: (*a*) impedors in the neutrals of the transformer banks at Boulder Dam; (*b*) low generator transient reactance; (*c*) a second intermediate switching station; and (*d*) increased generator inertia.

3. When the size of the generator installation is made to be equal to the safe operating limit of the transmission system it is found to range from 80,000 kw to 296,000 kw depending upon the design as explained above.

It can be seen from this summary that a relatively small additional investment goes a long way toward making the plant stable during 2-conductor-to-ground faults. Also, the method of increasing stability of operation during faults by inserting a resistance in series with generator armature windings was found to give a tremendous gain in power limits not only during 2-conductor-to-ground faults but even during 3-phase short circuits. It was felt that although there are no installations at the present time incorporating this feature, the cheapness of the device and its large stabilizing effect made it worth considering.

Definition of Power Limit

The term "power limit" as used in this paper refers to what is considered to be the safe operating limit, allowing for the effect of such short circuits as ordinarily occur on the system. The calculations were made by the "transient stability" method, which considers the relative motion of the machinery on the system during and after a fault. This method is described in detail in the appendixes.

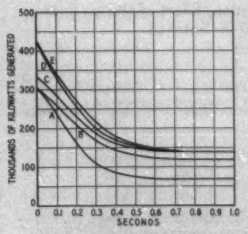
The criterion adopted for the safe operating limit was that the system must remain stable when subjected to a 2-phase-to-ground fault which is cleared in 0.2 sec. This speed of clearing could just about be attained at the present time with the most modern circuit breakers and the application of the carrier pilot system of relay protection; hence it is safe to assume it will be obtainable at the time the Boulder Dam lines are built. The highest possible speed of clearing is desirable not only because it has a very powerful effect in increasing stability but also because it prevents conductor burn-downs and reduces the tendency for faults which start as single-phase to develop into 2-phase and 3-phase trouble.

The use of a 2-phase-to-ground fault as the criterion for stability is reasonably conservative, because judging by experience on the Southern California Edison Company's Big Creek system, the majority of the faults will be single-phase-to-ground, and the limit for this type of fault is much higher than for the 2-phase-to-ground fault. However, a fairly large proportion of the latter may be expected on the Boulder Dam lines, especially in view of the lightning hazard, and therefore in order to maintain a good standard of service the transmitted power should be limited to such a value that these 2-phase-to-ground faults will not result in instability. As for the possibility of 3-phase faults, Big Creek experience shows 5 per cent of the total to fall in this class; but most of these faults only became 3-phase after the expiration of considerable time. Since the stability limit for 3-phase faults is far below that for 2-phase-to-ground faults, and since the probabilities are that 3-phase faults will occur very infrequently, it would hardly be justifiable from an economic standpoint to reduce the power limit to the 3-phase fault value.

Analysis of Power Limit Curves

The results of the power limit study are presented in the form of curves whose abscissas are the times of clearing the trouble, and whose ordinates are the maximum power that can be carried prior to the fault without instability resulting therefrom, assuming the trouble to be cleared in the time indicated by the abscissa. This mode of presenting the results was adopted because it arises naturally from the method of calculation, and also because it shows very strikingly the great advantage to be gained from rapid clearing of trouble.

In Fig. 1 are presented power limit curves for 2-phase-to-ground faults at or near the Boulder Dam end of the line, with an installation of 250,000 kw at Boulder Dam. Curve *A* of Fig. 1 is based upon



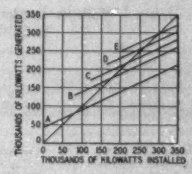


Fig. 1 (left). Power limits of a 250,000-kw installation versus time of clearing of a 2-conductor-to-ground fault at Boulder Dam power house

Fig. 2 (right). Power limits of 0.2-sec clearing of 2-conductor-to-ground fault at Boulder Dam power house versus installed generating capacity

Curves *A* based upon "simplest possible layout"
Curves *B* based upon equipment represented in curves *A* plus the addition of neutral impedors
Curves *C* based upon curves *B* plus a decrease in generator transient reactance
Curves *D* based upon curves *C* plus a second intermediate switching station
Curves *E* based upon curves *D* plus an increase in generator inertia

what might be termed the "simplest possible layout"—that is, generators of normal characteristics, no neutral impedors at Boulder Dam, and only one intermediate switching station. It is seen that for 0.2-sec clearing the limit of generation is 163,000 kw. Adding neutral impedors at Boulder Dam increases the limit to 212,000 kw as shown in curve *B*. Decreasing the generator transient reactance from 30 per cent to 21 per cent raises the limit to 233,000 kw (curve *C*) and adding a second intermediate switching station carries it to 255,000 kw (curve *D*). Increasing the generator inertia 50 per cent above the allowable minimum would add another 15,000 kw in generated power as shown by curve *E*.

In Fig. 2 is shown a chart for 0.2-sec speed of switching of a 2-conductor-to-ground fault. The abscissas are thousands of kilowatts installed at Boulder Dam and the ordinates are transient power limits for a 2-conductor-to-ground fault near Boulder Dam cleared in 0.2 sec. The curves represent various design factors added to those represented by the curve immediately below. The diagonal line through the origin is the line representing an installed capacity equal to the transient stability limit, and its intersections with the curves of design factors give values of installed capacity as used in Table II.

Table I is based upon curves shown in Fig. 1 for a 250,000-kw generating installation at Boulder Dam. In the first column the design factors producing improvement in power limit are tabulated in order of their cost. Each factor tabulated in column 1 is added to those shown above it, that is, the items are cumulative. The second switching station, for example, is added to a plant already equipped with transformer neutral impedors and low generator reactance. The safe generation limit is then read from curves of Fig. 1 for 0.2-sec clearing and tabulated in column 2. The power received at the load end then is computed from column 2 and line efficiency curves, the results being tabulated in column 3. The gain in power received at the load due to the introduction of the design factor is found easily by subtracting from the value in column 3 the one just above it. This gain is shown in column 4. Column 5 shows the cost of the design factor in per cent of the total cost of the project.

The outstanding items from Table I are the small percentage of the total spent for all the improvements and the large gain in power limit. The expenditure of about 3 per cent additional will increase the safe operating limit from 163,000 kw generated, or 65 per cent of installed generator capacity, to 270,000 kw, or 108 per cent of installed generator capacity.

All the above computations were carried out with an assumed installation of 250,000-kw generator capacity. The use of Fig. 2 permits the reverse process by varying the size and design of the generating station to fit the safe operating limit of the transmission system. For example: 80,000 kw is the size of generator installation of normal design which will not exceed the transient stability limit when fully loaded; and 296,000 kw is the size installation that includes all the stabilizing factors under discussion and will not exceed the transient stability limit when fully loaded. Table II is based upon Fig. 2 and is computed in a manner similar to that for Table I. Column 1 is identical with column 1 in Table I. Column 2 shows the size of installation which will permit full load to be carried on generators within safe operating limits and is read from Fig. 2 at the intersections of design curves with the diagonal through the origin. Column 3 is computed by applying line efficiency correction to column 2. Column 4 shows the total cost of the project in per cent of the cost of the basic installation.

Table I—220-kv Transmission, Effect of Design Factors, 250,000 kw Installed

1 Factor Producing Improvement	2 Total Generated Kw*	3 Total Received Kw*	4 Gain in Received Kw	5 Cost of the Factor in % of Total
None	163,000	148,000		
Neutral impedors at Boulder Dam	212,000	181,000	33,000	0.16
Lower generator reactance	233,000	197,000	16,000	0.38
Second switching station	255,000	214,000	17,000	1.00
Higher generator inertia	270,000	225,000	11,000	1.12
Peterson coils			Loss	

* Including effect of all factors preceding in the list, in addition to the one under consideration.

Table II—220-kv Transmission, Effect of Design Factors, Variable Installation

1 Factor Producing Improvement	2 Installed and Generated Kw	3 Total Received Kw	4 Total Cost %
None	80,000	75,000	100
Neutral impedors at Boulder Dam	176,000	150,000	114
Lower generator reactance	216,000	185,000	122
Second switching station	260,000	218,000	131
Higher generator inertia	296,000	245,000	137

Analysis of Design Factors

The "base design" assumed at the beginning of the study comprises generators of 30 per cent transient reactance and normal inertia, equipped with high speed excitation, step-up transformers of from 10 per cent to 12 per cent reactance with neutrals of the high voltage windings solidly grounded, and 2 220-kv transmission lines similar to the Southern California Edison Company's Vincent line, with one sectionalizing and paralleling switching station between Boulder Dam power house and Etiwanda 220-kv receiving substation. Six other design factors are discussed in the following paragraphs.

Transformer Neutral Impedors

An impedance connected from the neutral of the high voltage Y connection to ground is the most effective means of increasing the safe operating limit during faults to ground near the generating station. It has little if any effect when the fault is at the load end and no effect during faults that do

not involve ground returns. For the accepted criterion of stability, however, the transformer neutral impedors show the maximum improvement as compared to other design factors. Impedors of 3 times the transformer reactance or 30 per cent to 35 per cent were at first considered, but were found to limit ground currents to such a low value that it was doubtful whether even the carrier current protection would be capable of clearing the line. A lower value of impedance therefore is recommended, as it allows enough ground current to operate relays on the faulted line and still is quite effective in increasing the safe operating limit, as can be seen from a comparison of curves A and B, in Fig. 1. The value recommended is from 10 per cent to 12 per cent, or equal to the reactance of the transformers.

Lower Generator Reactance

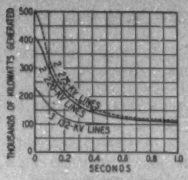
It can be stated that the amount of reactance in the circuit has roughly the same effect on transient stability limits as it has on steady state stability limits; that is, the maximum power that can be transmitted through the circuit is inversely proportional to reactance. In a circuit of 95 per cent reactance a 9 per cent reduction will mean approximately a 10 per cent increase in power limit. The desirability of lower reactance for increasing power limits is therefore quite apparent. The limitations of machine design do not permit, however, going below 20 per cent transient reactance of generators and 8 per cent reactance of transformers. The reduction assumed in this study is from 30 per cent generator transient reactance to 21 per cent generator transient reactance.

A Second Switching Station

This proposal is to add a sectionalizing and paralleling switching station to the base design of lines, thus splitting the lines between Boulder Dam power house and Etiwanda 220-kv substation into 3 nearly equal sections. Such an arrangement is more desirable from the point of view of maintenance than it is from the point of view of stability. However, with fast switching the number of switching stations becomes a stabilizing factor. While at 0.7-sec clearing of faults the number of switching stations is immaterial, nearly 20,000 kw are gained by a second switching station at 0.2-sec clearing.

High Generator Inertia

Variations in generator inertia affect only the time scale of curves of power versus speed of clearing the fault. The time varies as the square root of the relative inertia of the generating station and the system. For example, if the system inertia constant is 12.00 and the generating station inertia constant is 4.00, their relative inertia is $\frac{4 \times 12}{4 + 12} = 3$. Increasing the generator inertia 50 per cent makes the generator constant 6.00 and the relative inertia $\frac{6 \times 12}{6 + 12} = 4$. Hence, if 200,000 kw can be carried



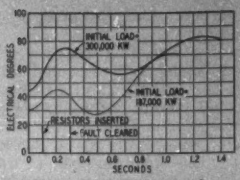


Fig. 3 (left). Power limits of a 250,000-kw installation with Peterson coils included in the design of the transmission system versus time of clearing of a 2-conductor-to-ground fault at Boulder Dam power house

Fig. 4 (right). Electrical degrees versus time curves of a 250,000-kw generating plant during a 2-conductor-to-ground fault with stabilizing resistors inserted in the circuit

through a fault cleared in 0.2 sec with generators of normal inertia, then with generators whose inertia is 150 per cent of normal the same amount of power can be carried through the same fault cleared in $\sqrt{\frac{4}{3}} \times 0.2 = 0.23$ sec. As the inertia of the generators is increased its beneficial effect decreases rapidly and further increase soon becomes uneconomical. It is not recommended that the inertia be made greater than 150 per cent of normal for the Boulder Dam installation, as the next 50 per cent of additional inertia will only add some 5,000 kw to the safe operating limit of the transmission system.

Peterson Coils

The use of Peterson coils at both ends of the Boulder Dam transmission system would be possible if the lines were isolated from the rest of the Southern California Edison system by the use of insulating transformers of 1:1 or perhaps some other ratio. With this arrangement, single-phase-to-ground faults would not exist, and 2-phase-to-ground faults would become 2-phase only. Hence in this case 2-phase faults should be considered the criterion of stability. The solid curve of Fig. 3 shows the power limits under this condition, assuming 220-kv operation. This curve shows a limit of 206,000 kw for a 0.2-sec clearing. This limit was compared to the one obtained with ordinary impedors at Boulder Dam power house and no insulating transformers at the load end, other items being identical. The latter was found to be 232,000 kw for 0.2-sec clearing. Thus the limit with the Peterson coils is seen to be 26,000 kw less than that obtainable with the neutral impedors under comparable conditions, and the Peterson coil arrangement would cost vastly more than the neutral impedors. The dotted curve and the dash curve of Fig. 3 are power limits of 3 132-kv and 2 275 kv lines with Peterson coils in the neutrals of terminal transformers. The reason the limit with the Peterson coils is so low is because of the effect

of the added reactance of the insulating transformers.

It is true that the Peterson coils would eliminate all single-phase-to-ground faults. However, calculations show that with neutral impedors at Boulder Dam there is no need to worry about stability on this type of fault for any installation under 275,000 kw. Hence it is safe to conclude that the possibility of using Peterson coils, at least in connection with 220-kv transmission, definitely should be rejected.

Stabilizing Resistance

The use of a series resistance introduced in the generator armature circuit during a fault on the transmission system has been fully described.[3] When a fault occurs on the transmission system between a hydroelectric power house and the load, the fault acts as a reactor of comparatively low reactance in parallel with the load. As a result the total current of the generator increases considerably but shifts in phase so that its real (or power) component is quite small. The power house becomes overloaded in amperes and loses kilowatts. With the kilowatt output reduced and the input at its original value, the generators overspeed and fall out of synchronism with the load end. A resistance connected in series with the armature circuit upon the occurrence of the fault accomplishes 2 effects. It reduces the total short-circuit current and at the same time it shifts its phase angle increasing its real (or power) component to a large value. The I^2R loss in the resistance must be supplied by the generator. The more severe the fault, the larger the current I and the I^2R loss. This new load on the generator reduces the net accelerating torque on the generator and during severe faults even acts as overload to slow it down. A 62,500-kw 13.8-kv generator would require resistors of 0.92 ohm per phase. A total of 12 resistors and 4 circuit breakers of 150,000-kva interrupting capacity would be required for the Boulder Dam power house. The comparison shown in Table III can be made to the base design installation of Table I.

Table III—Effect of Series Resistance

	Factor Producing Improvement	
	None	Series Resistance
Total generated kilowatts	163,000	300,000+
Total received kilowatts	148,000	250,000+
Total cost of project	100%	101%

It can be seen that a 20 per cent overload can be carried through a 2-conductor-to-ground fault when series resistors are added to the generator equipment. In Fig. 4 are shown 2 swing curves illustrating the action of series resistors. A 280,000-kva hydroelectric station connected through 2 220-kv transmission lines to a 600,000-kw load with load end generators was studied. A 2-conductor-to-ground fault was applied near the power house. In 0.1 sec after the fault was applied a 30 per cent resistance was inserted in series with the generator armatures. The fault itself was cleared in 0.3 sec. The solid curve shows the resulting swing when the initial load was 300,000 kw, and the dotted line shows the swing when the initial load was 187,000 kw. It can be seen that in both cases the system is stable with plenty to spare.

The use of series resistance alone would increase the transient stability of the Boulder Dam transmission system considerably more than any or all other design factors. This statement, however, is based on theory only. There are no installations at the present time equipped with stabilizing resistors. The tremendous gain in stability shown by calculations makes it desirable to try it out on an actual system or a miniature set-up to obtain confirmation of the theory.

3. For all numbered references see list at end of paper.

Appendix I—Description of Method

In a preliminary study of the problem of transient system stability, high speed records of 7 short circuits on the 220-kv system of the Southern California Edison Company were analyzed. Mathematical solutions necessarily require a large number of assumptions as to transient reactance, character of load, etc. Step by step solutions based upon assumptions which were to be used in further studies very closely approximated the high speed records obtained during the disturbances. The step by step method could not be used however because of the prohibitive amount of time it would require. Results obtained by various simplified methods of computations were compared to results of step by step solutions and the method described in the following paragraphs was adopted as most nearly approximating results obtainable by step by step solutions. Subsequently numerous solutions were made with the following values varied over the indicated range.

1. Character of load from 100 per cent lighting to 100 per cent induction motor load.
2. Size of load from 250,000 kw to 1,000,000 kw.
3. Location of fault at Boulder Dam power house and at the load.

From the preliminary studies and the above mentioned series of solutions a load of 600,000 kw was assumed, composed of 60 per cent induction motors and 40 per cent of resistance load. Faults occurring at the Boulder Dam end of the lines gave lower power limits and in the subsequent studies were applied at that point. Solutions made after the above assumptions were established involved the variation of the following items:

1. Character of fault.
2. Design factors of the transmission system.

It is believed that preliminary studies as described above should be made before a simplified method of computation is decided upon. A description of the method used by the authors follows.

The system to be investigated is first represented by a network of resistances and impedances.[4] (See Fig. 5.) The machines are represented by a constant voltage and an impedance in series with it. The system then is reduced through a series of paralleling star to delta, and delta to star, transformations to 2 equivalent machines with a shunt between them.

The negative and zero phase sequence impedances of the system to the assumed point of fault then are calculated. The combination of these 2 corresponding to the character of fault is applied as a shunt to the system at the point of fault and the system reduced to a simple circuit of 2 machines and a shunt. (See Fig. 6.) A third simple equivalent circuit of the system is calculated for conditions after the fault has been cleared.

Transient reactances of synchronous machines are used in the network diagram. The induction motor load is represented by a

voltage in series with an impedance calculated as follows: The connected (or capacity) motor load is assumed to be $2^1/_2$ times the load carried, then[1]

$$Z_{md} = \frac{\text{Base kva}}{\text{Connected kva}} \times 3.00$$

Using $\dot{Z}_1$, $\dot{Z}_2$, and $\dot{Z}_3$ (per unit impedances of the simplified equivalent circuits), the following are calculated:

$$\dot{Z}_{12} = \dot{Z}_1 + \dot{Z}_2 + \frac{\dot{Z}_1\dot{Z}_2}{\dot{Z}_3}$$

This is known as the transfer impedance.

$$\dot{Z}_{11} = \dot{Z}_1 + \frac{\dot{Z}_2\dot{Z}_3}{\dot{Z}_2 + \dot{Z}_3}$$

and

$$\dot{Z}_{22} = \dot{Z}_2 + \frac{\dot{Z}_1\dot{Z}_3}{\dot{Z}_1 + \dot{Z}_3}$$

are known as the driving point impedances. Presenting the above operators in polar form,

$$Z_{12}\angle\theta_{12};\quad Z_{11}\angle\theta_{11}\quad\text{and}\quad Z_{22}\angle\theta_{22}$$

calculate the following scalar values

$$Z_{12};\ \frac{\cos\theta_{11}}{Z_{11}};\ \frac{\cos\theta_{22}}{Z_{22}}$$

After all these values are obtained for conditions before, during, and after the fault, air gap voltages of the 2 machines must be evaluated for several load conditions (before fault). Voltage is assumed to be constant at a point of the system, usually at the junction of the shunt and the 2 machines. If this assumption cannot be made the calculations become slightly more complicated. This voltage is assumed in value and taken as a reference vector for all subsequent calculations. The reference voltage determines the current in the

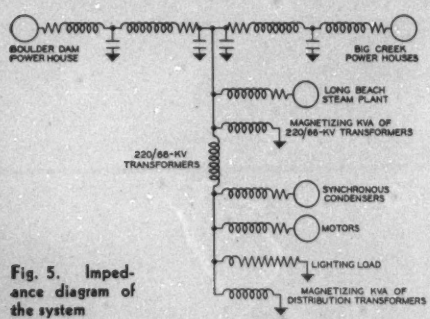


Fig. 5. Impedance diagram of the system

shunt. The current from one air gap to the reference point is varied through a desired range and for each value of this current the 2 air gap voltages are calculated; these voltages are $\dot{E}_1$ and $\dot{E}_2$ or $E_1\angle\delta_{11}$ and $E_2\angle\delta_{22}$. The angle between the two, $\delta_{11} - \delta_{22} = \delta_0$ is of importance and is expressed in radians. The sin δ_0 and cos δ_0 are tabulated, and sin δ_0 is the value of D.

The next step is to determine A, B, C, D, E, F, and G for the given problem.

A is the maximum synchronizing power that can be exchanged by the 2 machines. Its value is $\frac{E_1E_2}{Z_{12}}$ and it is taken as equal to unity.

B is the maximum synchronizing power than can be exchanged by the 2 machines with the fault applied to the system. It is calculated from the formula

$$B = \frac{Z_{12}\text{ before the fault}}{Z_{12}\text{ during the fault}}$$

C is the maximum synchronizing power that can be exchanged by the 2 machines after the fault has been cleared and is

$$C = \frac{Z_{12}\text{ before the fault}}{Z_{12}\text{ after the fault}}$$

D is the power driving the machines apart before the fault and is equal to sin δ_0.

E is the power driving the machines apart during the fault and is calculated from the formula

$$E = \frac{E_1}{E_2}K_1 - \frac{E_2}{E_1}K_2 + D$$

where

$$K_1 = \frac{Z_{12}\text{ before the fault}}{2} \times \left[\frac{\cos\theta_{11}}{Z_{11}}\text{ before the fault} - \frac{\cos\theta_{11}}{Z_{11}}\text{ during the fault}\right]$$

and

$$K_2 = \frac{Z_{12}\text{ before the fault}}{2} \times \left[\frac{\cos\theta_{22}}{Z_{22}}\text{ before the fault} - \frac{\cos\theta_{22}}{Z_{22}}\text{ during the fault}\right]$$

F is the power driving the machines apart after the fault has been cleared and is calculated from the same formula as E except that the values of $\frac{\cos\theta_{11}}{Z_{11}}$ and $\frac{\cos\theta_{22}}{Z_{22}}$ during the fault are replaced by their values after the fault.

G is a numerical value without physical meaning which is used in the solution for the critical angle of clearing δ_1. The calculation of G follows:

$$\delta_2 = \pi - \sin^{-1}\frac{F}{C}\text{ radians}$$

$$G = F\delta_2\text{ (radians)} - E\delta_0\text{ (radians)} + C\cos\delta_2 - B\cos\delta_0$$

After G has been determined the critical angle of clearing is found from the following equation:

$$\cos\delta_1 = \frac{E - F}{C - B}\delta_1 + \frac{G}{C - B}$$

where δ_1 is in radians.

The solution from this point on is based on the use of the M.I.T. integraph curves.[2] Four values must be determined to use these integraph curves, namely:

1. δ_1 as evaluated above but expressed in degrees.
2. Sin δ_0 as used in above solution.
3. $\frac{E}{B}$
4. K, the time constant.

$$K = \sqrt{\frac{M_0}{314 \times B}}\quad\text{(50 cycle system)}$$

where

$$M_0 = \frac{M_1M_2}{M_1 + M_2}$$

and

$$M_1 = \sum \frac{0.462WR^2\left(\frac{\text{rpm}}{1000}\right)}{\text{Base kw}}$$

(same formula for M_2)

M_1 and M_2 are summations of inertia constants of all the machinery combined into the 2 equivalent machines.

Then $\sin \delta_0$ determines the family of integraph curves to be used. $\frac{E}{B}$ determines the curve to be used and δ_1 determines the ordinate of a point on this curve whose abscissa multiplied by the time constant K gives the critical time of clearing in seconds.

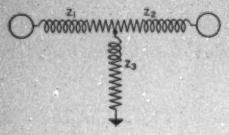


Fig. 6. Equivalent impedance diagram of the system

It was found very convenient to plot curves of δ_0, $\frac{E}{B}$, and δ_1 versus load or load current as it eliminated the necessity of interpolating between the M.I.T. integraph curves.[2]

The point of intersection of δ_0 and δ_1 determined the load carried through the disturbance of switching out a section of line (zero time switching). Families of M.I.T. integraph curves were available for $\sin \delta_0 = 0.00, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80$, and 0.90. Values of $\frac{E}{B}$ and δ_1 corresponding to δ_0 whose sines are among those tabulated above can be obtained from the curves plotted, and time obtained from the integraph curves with considerable accuracy.

Appendix II—Derivation of Formula for Solving the Critical Angle of Clearing

As stated in numerous articles, and particularly in articles by Park and Bancker,[1] and Summers and McClure,[3] the system will be stable when the 2 shaded areas of Fig. 7 are equal.

The equations of the 2 areas are

$$A' = \int_{\delta_0}^{\delta_1} E d\delta - \int_{\delta_0}^{\delta_1} B \sin \delta \, d\delta$$

$$A'' = \int_{\delta_1}^{\delta_2} C \sin \delta \, d\delta - \int_{\delta_1}^{\delta_2} F \, d\delta$$

integrating and equating the right sides

$$E(\delta_1 - \delta_0) - B(\cos \delta_2 - \cos \delta_1) = C(\cos \delta_1 - \cos \delta_2) - F(\delta_2 - \delta_1)$$

expanding

$$E\delta_1 - E\delta_0 - B \cos \delta_2 + B \cos \delta_1 = C \cos \delta_1 - C \cos \delta_2 - F\delta_2 + F\delta_1$$

rearranging

$$C \cos \delta_1 - B \cos \delta_1 = E\delta_1 - F\delta_1 + F\delta_2 - E\delta_0 - B \cos \delta_2 + C \cos \delta_2$$

taking

$$F\delta_2 - E\delta_0 - B \cos \delta_2 + C \cos \delta_2 = G$$

and substituting

$$C \cos \delta_1 - B \cos \delta_1 = E\delta_1 - F\delta_1 + G$$

factoring

$$(C - B) \cos \delta_1 = (E - F)\delta_1 + G$$

dividing by $(C - B)$

$$\cos \delta_1 = \frac{E - F}{C - B}\delta_1 + \frac{G}{C - B}$$

In this equation δ_1 is expressed in radians. To convert the equation to degrees

$$\cos \delta_1 = 0.0174 \frac{E - F}{C - B}\delta_1 + \frac{G}{C - B}$$

Appendix III—Mathematical Treatment of the Method

Let:

E_1 be the (air gap) voltage at the end of one impedance of the system ($\dot{Z}_1$)

E_2 be the (air gap) voltage at the end of the second impedance of the system ($\dot{Z}_2$)

P_1 be the air gap input to the stator of the generator

P_2 be the air gap output of the stator of the motor

Z_{11} the series impedance of the system from E_1 to all other points combined

Z_{22} be the series impedance of the system from E to all other points combined

Z_{12} be the transfer impedance from E_1 to E_2

$$\dot{Z}_{12} = \dot{Z}_1 + \dot{Z}_2 + \frac{\dot{Z}_1 \dot{Z}_2}{\dot{Z}_3}$$

δ_0 is the initial angle between $\dot{E}_1$ and E_2

P_{11} is power consumed in impedance Z_{11} due to voltage E_1

P_{22} is power consumed in impedance Z_{22} due to voltage E_2

α_{12} = angle equal to 90 deg less the angle of transfer impedance $\dot{Z}_{12}$

Then, for a stare of equilibrium,

$$P_1 = P_{11} + \frac{E_1 E_2}{Z_{12}} \sin (\delta_0 - \alpha_{12}) \tag{1}$$

$$P_2 = P_{22} - \frac{E_1 E_2}{Z_{12}} \sin (\delta_0 + \alpha_{12}) \tag{2}$$

$$\frac{E_1 E_2}{Z_{12}} \sin (\delta_0 - \alpha_{12}) = P_1 - P_{11} \tag{3}$$

$$\frac{E_1 E_2}{Z_{12}} \sin (\delta_0 + \alpha_{12}) = P_{22} - P_2 \tag{4}$$

adding both sides of eq 3 and eq 4

$$\frac{E_1 E_2}{Z_{12}} \left[\sin (\delta_0 - \alpha_{12}) + \sin (\delta_0 + \alpha_{12}) \right] = P_1 - P_{11} + P_{22} - P_2 \tag{5}$$

The trigonometric function in brackets reduces to

$2 \sin \delta_0 \cos \alpha_{12}$

$$\frac{E_1 E_2}{Z_{12}} \cos \alpha_{12} \sin \delta_0 = \frac{1}{2}(P_1 - P_{11} + P_{22} - P_2) \tag{6}$$

Making

$$A = \frac{E_1 E_2}{Z_{12}} \cos \alpha_{12} \tag{7}$$

$$D = \frac{1}{2}(P_1 - P_{11} + P_{22} - P_2) \tag{8}$$

we have:

$$A \sin \delta_0 = D \tag{9}$$

This represents the point of intersection of curve $A \sin \delta$ and line D plotted in the torque-angle coördinates.

When a fault (an impedance to ground) is applied suddenly to the system at some point $\dot{Z}_{12}$, $\dot{Z}_{11}$, and $\dot{Z}_{22}$ assume new values giving new values to $\frac{E_1 E_2}{Z_{12}} \cos \alpha_{12}$, P_{11} and P_{22} making

$$B = \frac{E_1 E_2}{Z_{12}} \cos \alpha_{12} \tag{10}$$

$$E = \frac{1}{2}(P_1 - P_{11} + P_{22} - P_2) \tag{11}$$

eq 9 does not hold. Equilibrium is disturbed and we can write

$$B \sin \delta = E \pm P_b \tag{12}$$

where the physical meaning of P_b is excess or deficiency in synchronizing power over the driving apart power. This power, when negative, is stored as kinetic energy in the mass of the machines, causing relative acceleration, and when positive is taken out of the mass of the machines, causing relative deceleration. By definition "the change in kinetic energy of a body equals the work done on the body" and "work done by a torque acting through an angle is proportional to both."

$$W_b = \int_{\delta_0}^{\delta_1} T_b d\delta \tag{13}$$

On the torque angle diagram this is represented by an area between $B \sin \delta$ and E (Fig. 7).

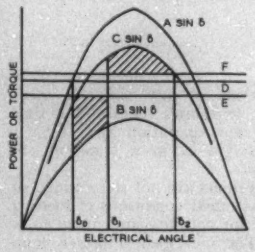


Fig. 7. Power or torque-angle diagram

When the fault is removed by switching out a faulty section, E_1 and E_2 are at some angle δ_1 out of equilibrium, and Z_{12}, Z_{11}, and Z_{22} assume new values. Two new values are then introduced.

$$C = \frac{E_1 E_2}{Z_{12}} \cos \alpha_{12} \tag{14}$$

$$F = \frac{1}{2} (P_1 - P_{11} + P_{22} - P_2) \tag{15}$$

and new resultant equations

$$C \sin \delta = F \pm P_e \tag{16}$$

$$W_e = \int_{\delta_1}^{\delta_2} T_e \, d\delta \tag{17}$$

W_b is represented on the torque-angle diagram by an area between $C \sin \delta$ and F. The equation

$$W_e = W_e \tag{18}$$

is the equal area criterion of stability[1] and is the basis of the method used in this study. The limiting angle δ_2 is found from relation

$$C \sin \delta_2 = F \tag{19}$$

The solution for angle δ_1 is described in Appendix II.

The fundamental equation for a rotating body acted upon by 2 torques is

$$T_1 + T_2 = J_m \alpha = J_m \frac{dw}{dt} = J_m \frac{d^2\theta}{dt^2} \tag{20}$$

where J_m is mass moment of inertia, α is acceleration in radians per second per second, W speed in radians per second, θ angle of displacement and t = time. Using the nomenclature of this paper

$$P_e + P_d = \frac{M}{2\pi f} \frac{d^2\delta}{dt^2} \tag{21}$$

with proper substitutions, eq 12 becomes

$$-B \sin \delta + E = \frac{M_s}{2\pi f} \frac{d^2\delta}{dt^2} \tag{22}$$

$$\tau = t \sqrt{\frac{2\pi f}{M_s} B} \tag{23}$$

we have

$$\frac{d^2\delta}{d\tau^2} + \sin \delta = \frac{E}{B} \tag{24}$$

Solutions of this equation are available in the form of integraph curves for several values of initial sin δ_0. The integraph curves present angle δ plotted against τ. The use of these curves is explained in Appendix I.

Appendix IV—Approximation Introduced by the Use of $M_s = \frac{M_1 M_2}{M_1 + M_2}$

Applying the torque equation to the 2 machines, we have

$$\frac{E_1 E_2}{Z_{12}} \sin (\delta - \alpha_{12}) - P_1 + P_{11} = -\frac{M_1}{2\pi f} \frac{d^2\delta_G}{dt^2} \tag{1}$$

$$\frac{E_1 E_2}{Z_{12}} \sin (\delta + \alpha_{12}) + P_2 - P_{22} = +\frac{M_2}{2\pi f} \frac{d^2\delta_m}{dt^2} \tag{2}$$

Dividing through by inertia constants

$$\frac{2\pi f E_1 E_2}{M_1 Z_{12}} \sin (\delta - \alpha_{12}) - \frac{2\pi f (P_1 - P_{11})}{M_1} = -\frac{d^2\delta_G}{dt^2} \tag{3}$$

$$\frac{2\pi f E_1 E_2}{M_2 Z_{12}} \sin (\delta + \alpha_{12}) - \frac{2\pi f (P_{22} - P_2)}{M_2} = +\frac{d^2\delta_m}{dt^2} \tag{4}$$

we know that

$$-\delta_G + \delta_m = -\delta \tag{5}$$

hence

$$-\frac{d^2\delta_G}{dt^2} + \frac{d^2\delta_m}{dt^2} = -\frac{d^2\delta}{dt^2} \tag{6}$$

Adding up both sides of eq 3 and eq 4

$$\frac{2\pi f}{M_1} \times \frac{E_1 E_2}{Z_{12}} \sin(\delta - \alpha_{12}) + \frac{2\pi f}{M_2} \frac{E_1 E_2}{Z_{12}} \sin (\delta + \alpha_{12}) - \frac{2\pi f (P_1 - P_{11})}{M_1} - \frac{2\pi f (P_{22} - P_2)}{M_2} = -\frac{d^2\delta}{dt^2} \tag{7}$$

Multiplying through by $\frac{M_1 M_2}{2\pi f}$ we have

$$M_2 \frac{E_1 E_2}{Z_{12}} \sin (\delta - \alpha_{12}) + M_1 \frac{E_1 E_2}{Z_{12}} \sin (\delta + \alpha_{12}) - M_2 (P_1 - P_{11}) - M_1 (P_{22} - P_2) = -\frac{M_1 M_2}{2\pi f} \frac{d^2\delta}{dt^2} \tag{8}$$

The first 2 terms can be expanded

$$M_2 \frac{E_1 E_2}{Z_{12}} \sin \delta \cos \alpha_{12} - M_2 \frac{E_1 E_2}{Z_{12}} \cos \delta \sin \alpha_{12} + M_1 \frac{E_1 E_2}{Z_{12}} \sin \delta \cos \alpha_{12} + M_1 \frac{E_1 E_2}{Z_{12}} \cos \delta \sin \alpha_{12} = (M_1 + M_2) \frac{E_1 E_2}{Z_{12}} \cos \alpha_{12} \sin \delta + (M_1 - M_2) \frac{E_1 E_2}{Z_{12}} \cos \delta \sin \alpha_{12} \tag{9}$$

The first approximation is introduced by neglecting the last term of the above equation. α_{12} is usually quite small and so is $\sin \alpha_{12}$. The second approximation is introduced when $(P_1 - P_{11})$ and $(P_{22} - P_2)$ are replaced by $\frac{1}{2} (P_1 - P_{11} + P_{22} - P_2)$ in eq 8.

$$(M_1 + M_2)\frac{E_1E_2}{Z_{12}}\cos\alpha_{12}\sin\delta - (M_1 + M_2)$$

$$\frac{1}{2}(P_1 - P_{11} + P_{12} - P_2) = -\frac{M_1M_2d^2\delta}{2\pi f\,dt^2} \quad (10)$$

and dividing through by $(M_1 + M_2)$

$$\frac{E_1E_2}{Z_{12}}\cos\alpha_{12}\sin\delta - \frac{1}{2}(P_1 - P_{11} + P_{22} - P_2) = -$$

$$\frac{M_1M_2}{2\pi f(M_1 + M_2)}\frac{d^2\delta}{dt^2} \quad (11)$$

The above equation is

$$B\sin\delta - E = -\frac{M_s}{2\pi f}\frac{d^2\delta}{dt^2} \quad (12)$$

where $M_s = \dfrac{M_1M_2}{M_1 + M_2}$

A numerical example will illustrate the approximation.

α_{12}	= 1.8 deg	B	= 0.552
M_1	= 4	P_1	= 0.593
M_2	= 12	P_{11}	= 0.102
$\frac{E_1E_2}{Z_{12}}$	= 0.552	P_{22}	= 0.446
$\cos\alpha_{12}$	= 0.9995	P_2	= 0.053
$\sin\alpha_{12}$	= 0.0314		

Approximate equation:

$$0.552\sin\delta - 0.495 = \frac{-3}{2\pi f}\frac{d^2\delta}{dt^2}$$

Correct equation:

$$0.552\sin\delta - 0.0087\cos\delta - 0.493 = \frac{-3}{2\pi f}\frac{d^2\delta}{dt^2}.$$

Power Limits of Synchronous Machines

This paper presents methods for determining steady state power limits of electric power systems composed of shunt impedance loads and any number of ideal cylindrical-rotor synchronous machines. In order to apply these methods to practical systems, the actual machines are represented by equivalent ideal machines corresponding to a given operating condition. The methods are said to be simpler and easier to apply than previous methods.

By
EDITH CLARKE
MEMBER A.I.E.E.

R. G. LORRAINE
ASSOCIATE A.I.E.E.

Both of the General Elec. Co., Schenectady, N. Y.

METHODS for determining steady state power limits of systems composed of shunt impedance loads and ideal cylindrical-rotor synchronous machines are presented in this paper. These methods, based upon a stability criterion that is independent of machine inertias, are simpler and easier to apply than any previously published. They are applicable to systems of any size. It seems appropriate, therefore, to submit them at this time, when the trend in system operation and design is toward a narrower margin between transient and steady state power limits.

Stability limits of systems are not determined directly; but, for any assumed conditions of loading, the systems are tested for stability and found to be stable or unstable. The incremental power equations with which the tests are made are developed for systems consisting of 2, 3, 4, and 5 machines and can be extended to those having any number of machines. These equations are arranged so that it is necessary to determine only the signs of the incremental power coefficients for the various machines, to decide whether a system is stable or unstable.

In practical systems, synchronous machines, whether of the cylindrical-rotor or salient-pole type, can be reduced to equivalent or near equivalent ideal machines corresponding to given operating conditions. Similarly, loads may be represented approximately by shunt impedances alone or in combination with synchronous machines. Some principles that can be used in combining machines or machines and impedance shunts are stated in Appendix III; an equivalent circuit for the synchronous condenser, saturation included, is given in Appendix IV; and in Appendix V is presented an equivalent circuit for a constant power induction machine for use when testing the synchronous machines of the system for stability. In a companion paper[1] by S. B. Crary, the methods presented here are generalized and applied to induction machines, composite loads, and interconnected systems.

There are at least 2 conditions under which the steady state stability limits of a system, or part of a system, are of importance in determining loads that normally can be transmitted. When total loss of power can be tolerated, steady state stability limits are of primary importance in determining the maximum power that can be delivered to a load center. When firm power is required, steady state stability limits indicate the power limits that may be ap-

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention Jan. 23–26, 1934. Manuscript submitted June 6, 1933; released for publication Oct. 10, 1933.

1. For all numbered references see bibliography at end of paper.

proached by improved apparatus and system arrangements.

This last condition is of somewhat recent origin. In the past, where 2 or more lines were operated in parallel between important load centers, it usually was found that the steady state stability limit was well above the limit of the load that could be carried through a severe disturbance in which a line was switched out. However, with faster and better switching and relaying, and more advantageous arrangements of equipment and circuits, transient stability limits can be increased to such an extent that they frequently approach the maximum power that can be transmitted under steady state conditions after the disturbance. Thus, the steady state stability limit is often of importance as the upper limit of power that can be transmitted through a disturbance, and consequently is helpful in determining the safe operating load.

Cut-and-Try Method

The method proposed for determining the steady state stability limits of a system of interconnected synchronous machines and shunt loads is a "cut-and-try" one. The stability limit of the system, of a certain machine, or of a part of the system is not determined directly, but for any assumed condition of loading the system is tested for stability and pronounced either stable or unstable. If the system is found to be stable under the conditions assumed, the load is increased and the test repeated. The stability limit will lie between the greatest load for which the system is stable and the smallest for which it is unstable.

The steady state power limit calculated in this way is not a practical operating limit, since any disturbance, even a small one such as would be occasioned by a switching operation or load change, might cause instability. Consequently, systems must operate with loadings less than those corresponding to the calculated limits. Also, it is evident that there is a different power limit for each set of operating conditions on a system. Frequently a different distribution of power among the generators will raise the stability limit appreciably.

The method is applicable to a system in which there are shunt impedance loads and any number of cylindrical-rotor synchronous machines having no saturation. It may be applied also to a system in which the following assumptions can be made:

1. Synchronous machines can be treated as cylindrical-rotor machines with reactances that remain constant during the test for stability.

2. Loads can be represented by shunt impedances, equivalent synchronous motors, or synchronous motors combined with impedance networks.

3. Groups of synchronous machines can be combined into one equivalent machine. (Appendix III.)

4. Portions of the system can be replaced by a single equivalent machine. (Appendix III.)

Criterion for Stability

The criterion for steady state stability used in this paper is that an increase in the electric power of any machine accompany an increase in the angular displacement of its rotor in the direction of rotation for a generator and opposite to the direction of rotation for a motor, field currents of all machines of the system remaining constant and the governor settings being readjusted to maintain system frequency.

An increment of mechanical load added to the shaft of a machine, say a motor, will cause a momentary slowing down of the motor thereby increasing the relative angular displacement of its rotor. If the electrical input to the motor be increased by this increase in angle, the motor will cease to slow down, and if the governors of one or more of the other machines have been readjusted to supply the additional power required, so that frequency will be maintained, the motor will be stable. If the electrical output of the generator whose governor has been readjusted to supply the additional power also is increased with an increase in angle between generator and motor, the generator likewise will be stable.

A system will be stable if all the machines of the system are stable; it will be unstable if any machine is unstable.

Test for Stability

The electric power of a synchronous machine may be expressed in terms of its internal voltage, the internal voltages of the other machines of the system, the angles between these voltages, and the impedances of the system. The internal voltage of a machine for steady state calculations is the voltage behind synchronous reactance, or some equivalent reactance to be discussed later. In a cylindrical-rotor machine of zero saturation, the internal voltage is in quadrature with the axes of the poles. Angular displacement between the internal voltages of 2 such synchronous machines is, therefore, the same as that between their corresponding rotor positions.

Equations for determining the stability of a machine take their simplest form when it is assumed that the increment of power supplied to a motor is furnished by one generator only, or the increment of power furnished by a generator is taken by one motor only. Division of load in accordance with governor characteristics is discussed in a companion paper.[1] The assumption that the increment of power is supplied by one machine only is usually acceptable, since in general it will result in slightly lower steady state stability limits than would be obtained if the load were proportioned in accordance with the load-speed characteristics of the machines.

Therefore, to test for stability it is assumed that all the machines except 2, one to be treated as a generator and the other as a motor, are fixed power machines and consequently will take up angular positions to maintain constant power as the angle between the generator and the motor is increased. If the electric power of either generator or motor decreases with an increase in the angle between their internal voltages, the system is unstable. If the electric power of both generator and motor increases with an increase in angle, both machines are stable for the condition imposed. As this test applied to

only 2 machines at a time, theoretically it is necessary to repeat it, taking the machines 2 at a time so that each machine is tested with every other machine. Practically, however, one test is usually sufficient, that for the 2 machines between which there is the largest angular displacement as determined from the system voltage vector diagram. This test for stability is equivalent to increasing the mechanical load on the motor and the mechanical input to the generator by slight amounts. The procedure of increasing the angular displacement between motor and generator that would result from an increase in mechanical load is the means selected for testing, since it can be applied directly by means of mathematical equations for power flow.

Wagner and Evans have shown[2] that it is theoretically possible under certain conditions to operate a machine when its electric power decreases with an increase in its relative angular displacement. Such operation is possible if the disturbance be caused by an increase in angular displacement, the inertias of the machines being such that the initial operating conditions can be regained. However, should the increase in angular displacement be caused by an increment of load, it would not be possible for the system to return to a state of equilibrium at normal system frequency by readjustment of governor settings.

Representation of Machines and Loads

It is customary in the one-line diagram of a system to represent a synchronous machine by a voltage to neutral acting through a series impedance. For a cylindrical-rotor machine of negligible saturation, this representation will give accurate results. The salient-pole machine with and without saturation, and the cylindrical-rotor machine with saturation, cannot be represented by a single value of impedance for all conditions of steady state operation. Although no one value of impedance can be used to represent a synchronous machine under all conditions of operation, corresponding to each condition there will be a particular value of equivalent impedance that will give the same response (change in power factor and current) for a small change in terminal voltage as the actual machine connected to the system. This subject is treated in another paper.[3]

In the present paper it will be assumed that there is a value of equivalent impedance for each synchronous machine corresponding to any given operating condition, which will remain constant during the test for steady state stability. An alternate method of determining the equivalent reactance to be used for a condenser operating at specified terminal voltage and field current is given in Appendix IV.

Lighting loads, loads due to magnetizing currents in transformers, and line charging currents can be represented by shunt impedances. An induction machine, when treated as a fixed power machine, can be represented by an impedance network in combination with a synchronous machine. An equivalent circuit for the induction machine as a fixed power machine is given in Appendix V.

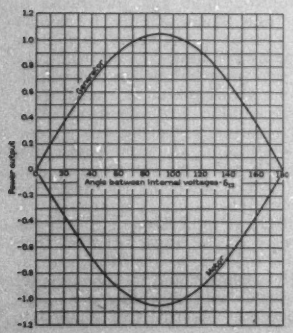
Methods given in this paper are extended in a companion paper[1] to the treatment of induction machines and the effects of composite loads upon the stability of the other machines of the system. The composite load may be composed of induction machines, synchronous machines, and impedance shunts; or it may represent an interconnected system or a portion of the system. The induction machine is treated both as a fixed and as a variable shaft-load machine, and may itself be tested for asynchronous stability.

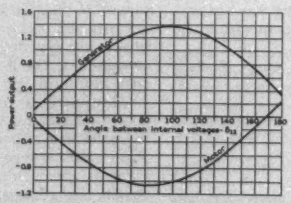
Power Equations for Synchronous Machines

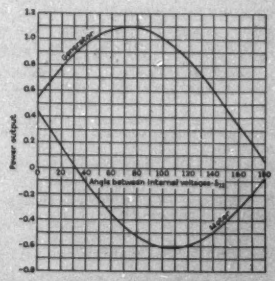
Two Synchronous Machines. When a system has only 2 synchronous machines, one a motor and the other a generator, the equations for their power outputs in terms of the scalar values of the internal voltages and driving point and transfer impedances are:[4]

$$P_1 = \frac{E_1^2}{Z_{11}} \sin \alpha_{11} + \frac{E_1 E_2}{Z_{12}} \sin (\delta_{12} - \alpha_{12}) \tag{1}$$

$$P_2 = \frac{E_2^2}{Z_{22}} \sin \alpha_{22} + \frac{E_1 E_2}{Z_{12}} \sin (\delta_{21} - \alpha_{12}) \tag{2}$$







Figs. 1, 2, and 3. Power angle characteristics of a generator and motor connected: (left) by a network of zero resistance; (middle) through a line containing reactance and resistance; and (right) to a shunt resistance load

where

P_1 = power out of machine 1
E_1 = magnitude of voltage behind synchronous reactance of machine 1
Z_{11} = magnitude of driving point impedance of machine 1, i. e., ratio of voltage at 1 to current at 1 with no other voltage applied to the system
$Z_{12} = Z_{21}$ = magnitude of transfer impedance between machines 2 and 1, i. e., ratio of voltage at 1 to current at 2, with no other voltage applied to the system
$\theta_{12} = \theta_{21}$ = impedance angle of Z_{21}
$\alpha_{12} = \alpha_{21} = 90 - \theta_{21}$
δ_1 = angle E_1 makes with the reference vector
$\delta_{12} = \delta_1 - \delta_2$

Positive power is taken as power out of a machine. Normal power for a generator therefore will be positive, and for a motor negative.

Replacing δ_{21} in eq 2 by $-\delta_{12}$,

$$P_2 = \frac{E_2}{Z_{22}} \sin \alpha_{22} - \frac{E_1 E_2}{Z_{12}} \sin (\delta_{12} + \alpha_{12}) \qquad (2a)$$

It can be seen by inspection of eq 1 that the generator power P_1 will be a maximum when $\delta_{12} = 90 + \alpha_{12}$; and from eq 2*a* that P_2, the motor power, will reach a maximum when $\delta_{12} = 90 - \alpha_{12}$.

When there is no resistance in the network between E_1 and E_2, $\theta_{12} = 90°$ and $\alpha_{12} = 0$. The power outputs of both generator and motor will be maximum when $\delta_{12} = 90°$; and since $\alpha_{11} = \alpha_{22} = 0$, the first term on the right-hand side in eqs 1 and 2*a* will disappear, and

$$P_{1(\max.)} = \frac{E_1 E_2}{X_{12}}$$

$$P_{2(\max.)} = -\frac{E_1 E_2}{X_{12}}$$

The power-angle characteristics of a generator and motor with constant internal voltages, connected by a network having no resistance, are given in Fig. 1. For this case the power output of the motor is the negative of the power output of the generator, and both are maximum when δ_{12} is 90°.

When the only resistance is series resistance, the impedance angle of the transfer impedance between generator and motor, θ_{12}, will be less than 90° and α_{12} will be positive. The power output of the generator will be maximum when δ_{12} is greater than 90°, and of the motor when δ_{12} is less than 90°; i. e., for the generator when $\delta_{12} = 90 + \alpha_{12} = 180 - \theta_{12}$, and for the motor when $\delta_{12} = 90 - \alpha_{12} = \theta_{12}$.

Figure 2 gives the power-angle characteristics of the generator and motor with constant internal voltages, connected by series impedance, i. e., resistance and reactance. The power output of the generator will be maximum when δ_{12} is greater than 90°, and of the motor when δ_{12} is less than 90°.

When the only resistance is shunt resistance, θ_{12} will be greater than 90° and α_{12} negative. In this case, the power output of the motor will be maximum when δ_{12} is greater than 90°, and of the generator when δ_{12} is less than 90°.

Figure 3 gives the power-angle characteristics of the generator and motor with constant internal voltages, connected to a shunt impedance load, but with no resistance in series. Under these conditions, the power output of the generator will be maximum when δ_{12} is less than 90°, and of the motor when δ_{12} is greater than 90°.

In a system having resistance, the particular machine that will reach its maximum power first, as δ_{12} is increased, will depend upon whether the resistance is in series or shunt. When resistance is both in series and shunt, α_{12} may be positive, negative, or zero.

Three Synchronous Machines. Although the steady state stability limit of the 2-machine system can be found readily from the general power equations, such is not the case where more than 2 machines are

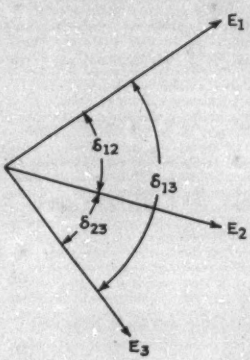


Fig. 4. Voltage vector diagram

operating under specified conditions. When there are 3 machines the power equations become:

$$P_1 = \frac{E_1^2}{Z_{11}} \sin \alpha_{11} + \frac{E_1 E_2}{Z_{12}} \sin (\delta_{12} - \alpha_{12}) + \frac{E_1 E_3}{Z_{13}} \sin (\delta_{13} - \alpha_{13}) \qquad (3)$$

$$P_2 = \frac{E_2^2}{Z_{22}} \sin \alpha_{22} + \frac{E_1 E_2}{Z_{12}} \sin (\delta_{2.} - \alpha_{12}) + \frac{E_2 E_3}{Z_{23}} \sin (\delta_{23} - \alpha_{23}) \qquad (4)$$

$$P_3 = \frac{E_3^2}{Z_{33}} \sin \alpha_{33} + \frac{E_1 E_3}{Z_{13}} \sin (\delta_{31} - \alpha_{13}) + \frac{E_2 E_3}{Z_{23}} \sin (\delta_{32} - \alpha_{23}) \qquad (5)$$

These expressions are the equations for power output from machines 1, 2, and 3. Figure 4 gives the voltage vector diagram of the internal voltages of the 3 machines and their displacement angles for an assumed operating condition which may or may not be stable. In the illustration used, machine 1 leads machines 2 and 3, and machine 2 leads machine 3, the greatest phase displacement being between generator 1 and motor 3.

The test for stability will be applied by arbitrarily increasing the angle δ_{13} between machines 1 and 3 by an increment, $\Delta\delta_{13}$. During the test the power output (or input) of machine 2 will remain constant. When the angle δ_{13} is increased, machine 2 to maintain constant power must take up a new angular position relative to machines 1 and 3. If the power out of the generator 1 and the power into the motor 3 both increase with an increase in δ_{13}, the power out of machine 2 remaining constant, machines 1 and 3 are operating at an angle, δ_{13}, less than their maximum power angle. If the power for either machine decreases with an increase in δ_{13}, the machines are operating at an angle greater than their maximum power angle and the system is unstable.

Power Increment Equations

Equations for the increments of power for small changes in machine angles are obtained from the power output eqs 3, 4, and 5. For small changes in the relative angular positions of the internal voltages of the 3 machines, the power equations may be differentiated and the differentials replaced by infinitesimals giving,

$$\Delta P_1 = \frac{E_1E_2}{Z_{12}} \cos(\delta_{12} - \alpha_{12})\, \Delta\delta_{12} + \frac{E_1E_3}{Z_{13}} \cos(\delta_{13} - \alpha_{13})\, \Delta\delta_{13} \tag{6}$$

$$\Delta P_2 = \frac{E_1E_2}{Z_{12}} \cos(\delta_{21} - \alpha_{12})\, \Delta\delta_{21} + \frac{E_2E_3}{Z_{23}} \cos(\delta_{23} - \alpha_{23})\, \Delta\delta_{23} \tag{7}$$

$$\Delta P_3 = \frac{E_1E_3}{Z_{13}} \cos(\delta_{31} - \alpha_{13})\, \Delta\delta_{31} + \frac{E_2E_3}{Z_{23}} \cos(\delta_{32} - \alpha_{23})\, \Delta\delta_{32} \tag{8}$$

Let

$$K_{12} = \frac{E_1E_2}{Z_{12}} \cos(\delta_{12} - \alpha_{12}) \qquad K_{23} = \frac{E_2E_3}{Z_{23}} \cos(\delta_{23} - \alpha_{23})$$

$$K_{13} = \frac{E_1E_3}{Z_{13}} \cos(\delta_{13} - \alpha_{13}) \qquad K_{31} = \frac{E_1E_3}{Z_{13}} \cos(\delta_{31} - \alpha_{13})$$

$$K_{21} = \frac{E_1E_2}{Z_{12}} \cos(\delta_{21} - \alpha_{12}) \qquad K_{32} = \frac{E_2E_3}{Z_{23}} \cos(\delta_{32} - \alpha_{23})$$

The equations for power change become

$$\Delta P_1 = K_{12}\Delta\delta_{12} + K_{13}\Delta\delta_{13} \tag{9}$$

$$\Delta P_2 = K_{21}\Delta\delta_{21} + K_{23}\Delta\delta_{23} \tag{10}$$

$$\Delta P_3 = K_{31}\Delta\delta_{31} + K_{32}\Delta\delta_{32} \tag{11}$$

Replacing $\Delta\delta_{21}$ by $-\Delta\delta_{12}$, $\Delta\delta_{31}$ by $-\Delta\delta_{13}$, and $\Delta\delta_{32}$ by $-\Delta\delta_{23}$ gives

$$\Delta P_1 = K_{12}\Delta\delta_{12} + K_{13}\Delta\delta_{13} \tag{12}$$

$$\Delta P_2 = -K_{21}\Delta\delta_{12} + K_{23}\Delta\delta_{23} \tag{13}$$

$$\Delta P_3 = -K_{31}\Delta\delta_{13} - K_{32}\Delta\delta_{23} \tag{14}$$

Since P_3 remains constant during the test for stability, $\Delta P_3 = 0$. Making this substitution in eq 13,

$$-K_{21}\Delta\delta_{12} + K_{23}\Delta\delta_{23} = 0 \tag{15}$$

$$\therefore\ \Delta\delta_{12} = \frac{K_{23}}{K_{21}}\, \Delta\delta_{23} \tag{16}$$

From Fig. 4

$$\Delta\delta_{12} + \Delta\delta_{23} = \Delta\delta_{13} \tag{17}$$

Solving eqs 16 and 17 for $\Delta\delta_{12}$ and $\Delta\delta_{23}$ in terms of $\Delta\delta_{13}$,

$$\Delta\delta_{12} = \frac{K_{23}}{K_{23} + K_{21}}\, \Delta\delta_{13} \tag{18}$$

$$\Delta\delta_{23} = \frac{K_{21}}{K_{23} + K_{21}}\, \Delta\delta_{13} \tag{19}$$

Substituting these values of $\Delta\delta_{12}$ and $\Delta\delta_{23}$ in the equations for ΔP_1 and ΔP_3, 12 and 14, give

$$\Delta P_1 = \left[\frac{K_{12}K_{23} + K_{13}K_{23} + K_{13}K_{21}}{K_{23} + K_{21}}\right] \Delta\delta_{13} \tag{20}$$

$$\Delta P_3 = -\left[\frac{K_{31}K_{23} + K_{31}K_{21} + K_{32}K_{21}}{K_{23} + K_{21}}\right] \Delta\delta_{13} \tag{21}$$

If the signs of the expressions in brackets in eqs 20 and 21 are both positive, machines 1 and 3 are operating at an angle less than their maximum power angle; if the sign of either expression is negative, the machines are operating beyond their maximum power angle and the system is unstable.

The same equations may be used to determine the stability of machine 2, since the assignment of numbers to the machines was arbitrary. Interchanging subscripts 2 and 3 in eqs 20 and 21, the equations become those for machines 1 and 2. Thus,

$$\Delta P_1 = \left[\frac{K_{12}K_{32} + K_{12}K_{23} + K_{13}K_{21}}{K_{32} + K_{31}}\right] \Delta\delta_{12} \tag{20a}$$

$$\Delta P_2 = -\left[\frac{K_{21}K_{32} + K_{21}K_{31} + K_{23}K_{31}}{K_{32} + K_{31}}\right] \Delta\delta_{12} \tag{21a}$$

The values of the K's, however, used in eqs 20a and 21a should correspond to the original subscripts.

Relations similar to those of eqs 20 and 21 are given in Appendix I for 4 machines and in Appendix II for 5 machines.

Procedure for Determining Power Limit

1. Reduce the system to its simplest form, preserving the identity of points at which specified voltages are maintained. The reduction of a system to its simplest form and some of the principles used in combining machines, or machines and shunts, are given in Appendix III.
2. For an assumed load, under given operating conditions, calculate the internal voltages of all machines in magnitude and phase.
3. Calculate the transfer impedances between all machines.
4. From the magnitudes of the internal voltages, the δ-angles between them, and the magnitudes and α-angles of the transfer impedances, calculate the K's.
5. Substitute the K's in the formulas to test for stability.
6. If the system is stable for the load assumed, increase the load and proceed as before until the stability limit is reached.

Appendix I—4 Machines

For 4 machines the power increment equations, for a test of machines 1 and 4, are:

$$\Delta P_1 = K_{12}\Delta\delta_{12} + K_{13}\Delta\delta_{13} + K_{14}\Delta\delta_{14}$$
$$\Delta P_2 = K_{21}\Delta\delta_{21} + K_{23}\Delta\delta_{23} + K_{24}\Delta\delta_{24}$$
$$\Delta P_3 = K_{31}\Delta\delta_{31} + K_{32}\Delta\delta_{32} + K_{34}\Delta\delta_{34}$$
$$\Delta P_4 = K_{41}\Delta\delta_{41} + K_{42}\Delta\delta_{42} + K_{43}\Delta\delta_{43}$$

Replacing ΔP_2 and ΔP_3 by 0, $\Delta\delta_{21}$ by $-\Delta\delta_{12}$, $\Delta\delta_{31}$ by $-\Delta\delta_{13}$, etc.,

$$\Delta P_1 = K_{12}\Delta\delta_{12} + K_{13}\Delta\delta_{13} + K_{14}\Delta\delta_{14}$$
$$0 = -K_{21}\Delta\delta_{12} + K_{23}\Delta\delta_{23} + K_{24}\Delta\delta_{24}$$
$$0 = -K_{31}\Delta\delta_{13} - K_{32}\Delta\delta_{23} + K_{34}\Delta\delta_{34}$$
$$\Delta P_4 = -K_{41}\Delta\delta_{14} - K_{42}\Delta\delta_{24} - K_{43}\Delta\delta_{34}$$

Assuming E_1 leads E_2 in phase, E_2 leads E_3, and E_3 leads E_4

$$\Delta\delta_{13} = \Delta\delta_{12} + \Delta\delta_{23}$$
$$\Delta\delta_{14} = \Delta\delta_{12} + \Delta\delta_{23} + \Delta\delta_{34}$$
$$\Delta\delta_{24} = \Delta\delta_{23} + \Delta\delta_{34}$$

The power increment equations can be expressed in terms of $\Delta\delta_{12}$, $\Delta\delta_{23}$, and $\Delta\delta_{34}$.

$$\Delta P_1 = (K_{12} + K_{13} + K_{14})\Delta\delta_{12} + (K_{13} + K_{14})\Delta\delta_{23} + K_{14}\Delta\delta_{34}$$
$$0 = -K_{21}\Delta\delta_{12} + (K_{23} + K_{24})\Delta\delta_{23} + K_{24}\Delta\delta_{34}$$
$$0 = -K_{31}\Delta\delta_{12} - (K_{31} + K_{32})\Delta\delta_{23} + K_{34}\Delta\delta_{34}$$
$$\Delta P_4 = -K_{41}\Delta\delta_{12} - (K_{41} + K_{42})\Delta\delta_{23} - (K_{41} + K_{42} + K_{43})\Delta\delta_{34}$$

Using the 2 equations for ΔP_2 and ΔP_3 and the relation

$$\Delta\delta_{14} = \Delta\delta_{12} + \Delta\delta_{23} + \Delta\delta_{34}$$

the Δ-angles are expressed in terms of $\Delta\delta_{14}$ by means of determinants.

Let

$$A = \begin{vmatrix} 1 & 1 & 1 \\ -K_{21} & (K_{23} + K_{24}) & K_{24} \\ -K_{31} & -(K_{31} + K_{32}) & K_{34} \end{vmatrix}$$

Then

$$\Delta\delta_{12} = \frac{\begin{vmatrix} (K_{23} + K_{24}) & K_{24} \\ -(K_{31} + K_{32}) & K_{34} \end{vmatrix}}{A}\, \Delta\delta_{14}$$

$$\Delta\delta_{23} = -\frac{\begin{vmatrix} -K_{21} & K_{24} \\ -K_{31} & K_{34} \end{vmatrix}}{A}\, \Delta\delta_{14}$$

$$\Delta\delta_{34} = \frac{\begin{vmatrix} -K_{21} & (K_{32}+K_{34}) \\ -K_{31} & -(K_{31}+K_{32}) \end{vmatrix}}{A} \Delta\delta_{14}$$

Let the ratios of the Δ-angle to $\Delta\delta_{14}$ be expressed by B with the corresponding double subscript, then

$$\Delta\delta_{12} = B_{12}\Delta\delta_{14}$$
$$\Delta\delta_{23} = B_{23}\Delta\delta_{14}$$
$$\Delta\delta_{34} = B_{34}\Delta\delta_{14}$$

Substituting these values in the expressions for ΔP_1 and ΔP_4,

$$\Delta P_1 = [(K_{12} + K_{13} + K_{14})B_{12} + (K_{13} + K_{14})B_{23} + K_{14}B_{34}]\Delta\delta_{14}$$
$$\Delta P_4 = -[K_{41}B_{12} + (K_{41} + K_{42})B_{23} + (K_{41} + K_{42} + K_{43})B_{34}]\Delta\delta_{14}$$

These are the incremental power equations for machines 1 and 4, assuming that the other machines hold constant power. In a similar way expressions for incremental power may be developed for other pairs of machines of a 4-machine system or for systems of more than 4 machines.

Appendix II—5 Machines

By a procedure similar to that for 4 machines given in Appendix I, the test equations for machines 1 and 5 are obtained for a system of 5 machines.

$$\Delta P_1 = [(K_{12} + K_{13} + K_{14} + K_{15})B_{12} + (K_{13} + K_{14} + K_{15})B_{23} + (K_{14} + K_{15})B_{34} + K_{15}B_{45}]\Delta\delta_{15}$$

$$\Delta P_5 = -[K_{51}B_{12} + (K_{51} + K_{52})B_{23} + (K_{51} + K_{52} + K_{53})B_{34} + (K_{51} + K_{52} + K_{53} + K_{54})B_{45}]\Delta\delta_{15}$$

where

$$A = \begin{vmatrix} 1 & 1 & 1 & 1 \\ -K_{21} & (K_{23}+K_{24}+K_{25}) & (K_{24}+K_{25}) & K_{25} \\ -K_{31} & -(K_{31}+K_{32}) & (K_{34}+K_{35}) & K_{35} \\ -K_{41} & -(K_{41}+K_{42}) & -(K_{41}+K_{42}+K_{43}) & K_{45} \end{vmatrix}$$

$$B_{12} = \frac{\begin{vmatrix} (K_{23}+K_{24}+K_{25}) & (K_{24}+K_{25}) & K_{25} \\ -(K_{31}+K_{32}) & (K_{34}+K_{35}) & K_{35} \\ -(K_{41}+K_{42}) & -(K_{41}+K_{42}+K_{43}) & K_{45} \end{vmatrix}}{A}$$

$$B_{23} = -\frac{\begin{vmatrix} -K_{21} & (K_{24}+K_{25}) & K_{25} \\ -K_{31} & (K_{34}+K_{35}) & K_{35} \\ -K_{41} & -(K_{41}+K_{42}+K_{43}) & K_{45} \end{vmatrix}}{A}$$

$$B_{34} = \frac{\begin{vmatrix} -K_{21} & (K_{23}+K_{24}+K_{25}) & K_{25} \\ -K_{31} & -(K_{31}+K_{32}) & K_{35} \\ -K_{41} & -(K_{41}+K_{42}) & K_{45} \end{vmatrix}}{A}$$

$$B_{45} = -\frac{\begin{vmatrix} -K_{21} & (K_{23}+K_{24}+K_{25}) & (K_{24}+K_{25}) \\ -K_{31} & -(K_{31}+K_{32}) & (K_{34}+K_{35}) \\ -K_{41} & -(K_{41}+K_{42}) & -(K_{41}+K_{42}+K_{43}) \end{vmatrix}}{A}$$

Appendix III—Equivalent Systems

The practical value of the method of testing for stability given in this paper depends upon the ease and degree of accuracy with which the internal voltage, E_1, E_2, ... E_n and the transfer impedances Z_{12}, Z_{13}, ... Z_{1n}, etc., can be determined. Since the amount of labor involved depends upon the number of synchronous machines and shunt impedances in the system, it is important that the number of each be reduced to the minimum consistent with the accuracy required.

Principles Used in Combining Machines or Machines and Shunts

First: It has been shown[6] that a synchronous machine whose internal vector voltage is constant in magnitude, with an impedance shunt at its terminals, may be replaced by an equivalent synchronous machine, for determining their effect upon the other machines of the system. The impedance of the equivalent machine will be the impedance of the machine and the shunt in parallel; its internal vector voltage will be $\frac{EZ_s}{Z+Z_s}$, where E and Z are the internal vector voltage and impedance, respectively, of the given machine and Z_s is the impedance of the shunt.

When the shunt contains resistance, power out of the equivalent machine (which is the power out of the shunt plus the power out of the given machine) bears no fixed relation to power out of the actual machine. Consequently, although the shunt and the machine can be replaced by an equivalent machine when their effect upon other machines of the system is being considered, they cannot be replaced by an equivalent machine when maximum power out of the machine itself is under consideration or fixed power is maintained.

Should the shunt have no resistance, such as an inductive or capacitive reactance shunt, power out of the equivalent machine will be the same as that out of the actual machine; consequently, maximum power out of the equivalent machine will be maximum power out of the actual machine. The equivalent machine, therefore, may replace the actual machine, even when maximum power out of the machine itself is being considered or fixed power is being maintained.

Second: Two synchronous machines with their terminals at a common point, whose internal voltages are constant in magnitudes and differ by a constant angle as the machines of the system change their relative angular positions, may be replaced by an equivalent synchronous machine without altering the power delivered or received bythe other synchronous machines of the system. The impedance of the equivalent machine will be the parallel value of the impedances of the 2 given machines. Its internal vector voltage will be $\frac{E_1Z_2 + E_2Z_1}{Z_1 + Z_2}$, where E_1 and E_2 are the internal vector voltages of machines 1 and 2, respectively, and Z_1 and Z_2 are their impedances.

Third: Two synchronous machines with their terminals separated by a series impedance, whose internal vector voltages are constant and equal in magnitude and do not differ in phase as the machines of the system change their relative angular positions, may be replaced by an equivalent synchronous machine without changing the power delivered or received by the other machines of the system. The equivalent machine will have the same internal voltage as the actual machine, and its impedance will be determined by replacing the "Δ" made up of the impedances of the 2 machines and the series impedance by an equivalent "Y."

Appendix IV—Reactance of an Equivalent Synchronous Condenser

A synchronous condenser with constant field current operating at a given voltage can be replaced *exactly* in steady state stability calculations by an equivalent condenser with constant reactance. If the current in per unit of rated current is plotted versus the terminal voltage in per unit of rated voltage for any constant field current, the negative of the slope of the curve at the given voltage $(-dV/dI)$ will be the reactance of the equivalent condenser in per unit based on its rating. This may be shown as follows: Since steady state stability limit is defined as maximum power at the given operating voltage, the equivalent machine is required to replace the actual machine only when operating in the region of normal voltage. If the equivalent machine for a slight change in terminal voltage provides the same current at the same power factor as the actual machine, then it will represent it exactly in steady state stability calculations.

Let

X = reactance of equivalent condenser corresponding to any given field current in per unit based on its rating
V_t = terminal voltage of condenser in per unit of rated voltage
E_n = internal voltage of equivalent condenser in per unit of rated voltage
I = current of condenser in per unit of rated current

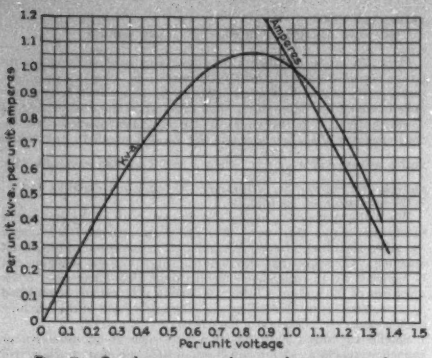


Fig. 5. Synchronous condenser characteristics for field current corresponding to rated current at rated voltage

Then

$$E_s = V_1 + IX \tag{D-1}$$

For a small change in terminal voltage, there will be a small change in current; consequently,

$$E_s = V_1 + \Delta V + (I + \Delta I)X \tag{D-2}$$

Subtracting eq D-2 from eq D-1 and transposing,

$$X(\Delta I) = -\Delta V$$

$$\therefore X = -\frac{\Delta V}{\Delta I}$$

In the limit

$$X = -\frac{dV}{dI} \tag{D-3}$$

The reactance of the equivalent condenser corresponding to any given field current and terminal voltage is, therefore, the negative of the slope of the volt-ampere curve at the given operating voltage.

The volt-ampere characteristic of a condenser may be obtained from its V-curves. In Fig. 5 are plotted the kva-volt and ampere-volt characteristic of a synchronous condenser for a field current that will give rated leading current at rated voltage. The direct axis synchronous reactance (x_d) of this machine is 1.64. The reactance of the equivalent condenser at rated voltage and rated kva is determined from the slope of the volt-ampere curve at unity voltage. It is

$$X = -\frac{dV}{dI} = 0.56$$

The internal voltage of the equivalent condenser is

$$E_s = E_t + i_d X = 1.0 + 1.0 \times 0.56 = 1.56$$

In a manner similar to this, the reactance of the equivalent condenser for any particular field excitation and terminal voltage may be determined from the volt-ampere characteristics of the condenser.

Appendix V—
Induction Machines as Fixed Power Machines

An induction machine can be represented[5] by the equivalent circuit given in Fig. 6A or by the less exact one of Fig. 6B. If a synchronous machine of the proper reactance X, and internal voltage E replace that part of the equivalent induction machine circuit to the right of point O in Fig. 6A, or to the right of point O' in Fig. 6B, the synchronous machine together with the impedance network to the left of O or O' will represent correctly the induction machine with fixed power on its shaft for small changes in its terminal voltage.

The reactance of the synchronous machine is determined in the following way: The power at O, Fig. 6A, is the power on the shaft of the motor; this power must remain constant with changes in current and voltage at O. With a drop in voltage at O, there will be a change in current and in slip for constant power; there will be also a change in power factor at O. Knowing the constants of the equivalent circuit for the induction machine, it is possible to determine the power factor and voltage at O corresponding to any given shaft power and terminal voltage. These may be determined more readily at O' in the approximate induction machine circuit given in Fig. 6B. From either circuit, it is possible from given initial conditions of terminal voltage, V_1, and power on the shaft of the machine, P, to calculate initial voltage and power factor at O or O'. Change of power factor with change in voltage at O and O', shaft power remaining constant, also may be determined.

The equivalent fixed power synchronous machine for small change in voltage at O or O' must give the same current at the same power factor as will be obtained from the standard equivalent induction machine circuit.

Let

X = reactance of equivalent synchronous machine to be connected at O or O'
E = internal voltage of equivalent synchronous machine
θ = $\cos^{-1}$ (power factor at O or O')
P = power on shaft of machine
V = voltage at O or O' corresponding to initial terminal voltage V_1 and shaft power P

Then

$$I_2 = \frac{P}{V}(1 \pm j \tan\theta)$$

The negative sign is used with $\tan\theta$ when the power factor at O is lagging, the plus sign when leading. For lagging power factor,

$$E = V - jXI_2 = V - j\frac{XP}{V}(1 - j\tan\theta)$$

$$= \left(V - \frac{XP}{V}\tan\theta\right) - j\frac{XP}{V}$$

$$|E|^2 = V^2 - 2XP\tan\theta + \frac{X^2P^2}{V^2}(1 + \tan^2\theta)$$

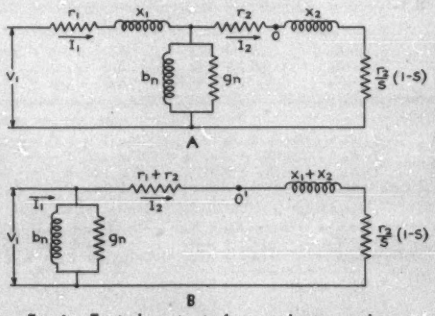


Fig. 6. Equivalent circuits for an induction machine

The absolute value of E must remain constant for small changes in V.

$$\therefore \frac{d|E|^2}{dV} = 0 = 2V - 2XP\frac{d\tan\theta}{dV} + \frac{X^2P^2}{V^4}\left[2V^2\tan\theta\frac{d\tan\theta}{dV} - 2V(1 + \tan^2\theta)\right]$$

Transposing and dividing through by $-2V$, and letting $\frac{d\tan\theta}{dV} = n$

$$X^2\left(\frac{P}{V^2}\right)^2 [\tan^2\theta - (nV)\tan\theta + 1] + X\left(\frac{P}{V^2}\right)(nV)^2 - 1 = 0$$

Solving,

$$X = \frac{V^2}{P}\left[\frac{-nV + \sqrt{(nV)^2 + 4\,[\tan^2\theta - (nV)\tan\theta + 1]}}{2\,[(\tan^2\theta - \tan\theta\,(nV) + 1)]}\right] \quad \text{(E-1)}$$

If power is constant at the terminals of the induction machine, or shaft power is constant but losses are neglected, eq E-1 will give the reactance of the equivalent synchronous machine which replaces the induction machines at its terminals, point O being at the terminals. For the usual operating conditions, $\tan\theta$ then will decrease with a decrease in voltage and $n = \frac{d\tan\theta}{dV}$ will be positive. If $\tan\theta$ increases with a decrease in voltage, n will be negative.

Bibliography

1. Steady State Stability of Composite Systems, S. B. Crary. Elec. Engg., v. 52, Nov. 1933, p. 787–92.

2. Static Stability Limits and the Intermediate Condenser Station, C. F. Wagner and R. D. Evans. A.I.E.E. Trans., v. 47, 1928, p. 94–121.

3. Equivalent Reactance of Synchronous Machines—Steady State Characteristics as Affected by Saturation, S. B. Crary, L. P. Shieldneck, and L. A. March. A paper scheduled for discussion at the A.I.E.E. 1934 winter convention.

4. Progress in the Study of System Stability, I. H. Summers and J. B. McClure. A.I.E.E. Trans., v. 49, 1930, p. 132–58.

5. Steady State Stability in Transmission Systems, Edith Clarke. A.I.E.E. Trans., v. 45, 1926, p. 22–41.

6. Principles of Alternating Current Machinery (a book), R. R. Lawrence. McGraw-Hill Book Co., Inc., first ed., 1916, p. 452–4.

Steady State Stability of Composite Systems

Composite loads and induction machines are included in the study of steady state stability characteristics of power systems reported in this paper. Reactive power characteristics must be considered when induction machines are involved, in addition to the real power characteristics which are considered for synchronous machine groups. A determination of the synchronizing power coefficients under various operating conditions, as described herein, provides a comparatively simple method of determining the safe and dangerous regions of steady state operation.

By
S. B. CRARY
ASSOCIATE A.I.E.E.

General Elec. Co.
Schenectady, N. Y.

A MEASURE of the steady state stability of a synchronous machine, or an equivalent synchronous machine group, can be obtained from equations for real power alone, by calculating the rate of change of electrical power with change in relative angular displacement. This factor, hereinafter called the synchronizing power coefficient $\frac{dP}{d\delta}$, is described and discussed in the companion paper,[1] and for a given operating condition its magnitude and sign indicates the degree of stability.

When machines other than the synchronous type are studied, most important of which is the induction machine, the reactive power characteristics must be considered in addition to the real power characteristics. The real power-voltage and reactive power-voltage characteristics of any load or machine are sufficient to determine its stabilizing influence on the remaining machines. Using a method of analysis similar to that of the companion paper, expressions based upon real and reactive power in a network are derived in Part I of the present paper, for the synchronizing power coefficient when the system contains composite loads which include induction machines. In Part II is presented a method for determining whether or not an induction machine can operate at the assumed or specific operating condition; this makes it possible to determine the degree of asynchronous stability of an induction machine. In the appendixes are presented methods of determining for a composite load which may include synchronous machines, impedance loads, and induction machines, the real and reactive power-voltage characteristics, $\frac{dP}{dE}$ and $\frac{dQ}{dE}$. The general equations given may be applied for any combination of loads and machines of a system, their application not being limited to the specific examples presented in the paper.

Part I—Synchronizing Power Coefficients of Systems Involving Composite Loads

A composite load consists of a large number of individual loads which would involve a great deal of labor if treated separately when studying the stability characteristics of the major machine groups. The effect of composite loads on the system may be

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted June 5, 1933; released for publication Oct. 11, 1933.

1. For all numbered references see list at end of paper.

evaluated by determining their real power and reactive power characteristics with change in voltage. Synchronous converters, heating and lighting loads and loads due to transformer magnetizing currents can be represented approximately by equivalent shunt impedances. The real power-voltage and reactive power-voltage characteristics of an impedance load can be calculated as described in Appendix II. Appendixes III and IV give methods for determining the real and reactive power characteristics of induction and synchronous machines. Knowing the characteristics and proportions of the various types of load, the real and reactive power-voltage characteristics of each composite load can be determined.

The nomenclature used in this paper is as follows. All quantities are expressed in per unit on the system kilovoltampere and voltage bases:

E = voltage
I = current
P = real power into the system (normal power for a generator will therefore be positive, for a motor negative)
Q = reactive power (reactive power into the system from an overexcited machine is negative)
s = slip (positive for a motor, negative for a generator)
r = resistance
x = reactance
Z = impedance
Z_{jj} = driving point impedance from point j
Z_{jk} = Z_{kj} = transfer impedance between points j and k
θ_{jj} = impedance angle of Z_{jj}
θ_{jk} = θ_{kj} = impedance angle of Z_{jk} or Z_{kj}
α_{jj} = 90 deg $- \theta_{jj}$
α_{jk} = 90 deg $- \theta_{jk}$
δ_{jk} = $\delta_j - \delta_k$, angular displacement between voltages E_j and E_k
α_n = per unit governor regulation of machine group n
C_n = per unit generator kva of machine group n

Assuming that the characteristics of the composite loads are known or obtainable, the following general equations may be written for n synchronous machine groups and z composite loads, where the numerical and nth subscripts refer to synchronous machines or machine groups, and the letters to composite loads. (See Appendix I for derivation of power equations.)

$$\left.\begin{aligned}
P_1 &= H_{11} + H_{12} \ldots + H_{1n} + H_{1a} \ldots + H_{1z} \\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
P_n &= H_{nn} + H_{n1} \ldots + H_{n(n-1)} + H_{na} \ldots + H_{nz} \\
P_a &= H_{aa} + H_{a1} \ldots + H_{an} + H_{ab} \ldots + H_{az} \\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
P_z &= H_{zz} + H_{z1} \ldots + H_{zn} + H_{za} \ldots + H_{zy} \\
Q_a &= -K_{aa} + K_{a1} \ldots + K_{an} + K_{ab} \ldots + K_{az} \\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
Q_z &= -K_{zz} + K_{z1} \ldots + K_{zn} + K_{za} \ldots + K_{zy}
\end{aligned}\right\} \quad (1)$$

Since $E_1, E_2, \ldots E_n$ are constant, eq 1 yields for small changes,

$$\left.\begin{aligned}
dP_1 &= f(d\delta_{12} \ldots d\delta_{1n}, d\delta_{1a} \ldots d\delta_{1z}, dE_a \ldots dE_z) \\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
dP_n &= f(d\delta_{n1} \ldots d\delta_{n(n-1)}, d\delta_{na} \ldots d\delta_{nz}\, dE_a \ldots dE_z) \\
dP_a &= f(d\delta_{a1} \ldots d\delta_{an}, d\delta_{ab} \ldots d\delta_{az}, dE_a \ldots dE_z) \\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
dP_z &= f(d\delta_{z1} \ldots d\delta_{zn}, d\delta_{za} \ldots d\delta_{zy}, dE_a \ldots dE_z) \\
dQ_a &= f(d\delta_{a1} \ldots d\delta_{an}, d\delta_{ab} \ldots d\delta_{az}, dE_a \ldots dE_z) \\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
dQ_z &= f(d\delta_{z1} \ldots d\delta_{zn}, d\delta_{za} \ldots d\delta_{zy}, dE_a \ldots dE_z)
\end{aligned}\right\} \quad (2)$$

The following relations exist between the incremental angles:

$$\left.\begin{aligned}
d\delta_{nm} &= -d\delta_{mn} \\
d\delta_{13} &= d\delta_{12} + d\delta_{23} \\
d\delta_{14} &= d\delta_{12} + d\delta_{24}, \text{ etc.}
\end{aligned}\right\} \quad (3)$$

Equations 2 and 3 may be solved simultaneously for any particular case to determine any synchronizing power coefficient. The use of these general equations can best be demonstrated by 2 relatively simple cases.

Case 1—Two Synchronous Machine Groups and One Composite Load

For this case,

$$\left.\begin{aligned}
P_1 &= H_{11} + H_{12} + H_{1a} \\
P_2 &= H_{22} + H_{21} + H_{2a} \\
P_a &= H_{aa} + H_{a1} + H_{a2} \\
Q_a &= -K_{aa} + K_{a1} + K_{a2}
\end{aligned}\right\} \quad (4)$$

$$0 = d\delta_{12} + d\delta_{2a} - d\delta_{1a} \quad (5)$$

Since

$$\frac{\partial H_{jk}}{\partial \delta_{jk}} = K_{jk} \qquad \frac{\partial K_{jk}}{\partial \delta_{jk}} = -H_{jk}$$

$$\frac{\partial H_{ja}}{\partial E_a} = \frac{H_{ja}}{E_a} \qquad \frac{\partial K_{ja}}{\partial E_a} = \frac{K_{ja}}{E_a}$$

$$\frac{\partial H_{aa}}{\partial E_a} = \frac{2H_{aa}}{E_a} \qquad \frac{\partial K_{aa}}{\partial E_a} = \frac{2K_{aa}}{E_a}$$

for small changes, eq 4 yields

$$\left.\begin{aligned}
dP_1 &= K_{12}d\delta_{12} + K_{1a}d\delta_{1a} + H_{1a}\frac{dE_a}{E_a} \\
dP_2 &= K_{21}d\delta_{21} + K_{2a}d\delta_{2a} + H_{2a}\frac{dE_a}{E_a} \\
dP_a &= K_{a1}d\delta_{a1} + K_{a2}d\delta_{a2} + (2H_{aa} + H_{a1} + H_{a2})\frac{dE_a}{E_a} \\
dQ_a &= -H_{a1}d\delta_{a1} - H_{a2}d\delta_{a2} + (-2K_{aa} + K_{a1} + K_{a2})\frac{dE_a}{E_a}
\end{aligned}\right\} \quad (6)$$

Replacing $d\delta_{21}$, $d\delta_{a1}$ and $d\delta_{a2}$ in eq 6 by $-d\delta_{12}$, $-d\delta_{1a}$ and $-d\delta_{2a}$, respectively, and rearranging,

$$dP_1 = K_{12}d\delta_{12} + K_{1a}d\delta_{1a} + H_{1a}\frac{dE_a}{E_a} \quad (7)$$

$$dP_2 = -K_{21}d\delta_{12} + K_{2a}d\delta_{2a} + H_{2a}\frac{dE_a}{E_a} \quad (8)$$

$$0 = -K_{a1}d\delta_{1a} - K_{a2}d\delta_{2a} + A_a\frac{dE_a}{E_a} \quad (9)$$

$$0 = H_{a1}d\delta_{1a} + H_{a2}d\delta_{2a} + B_a\frac{dE_a}{E_a} \quad (10)$$

where

$$A_a = 2H_{aa} + H_{a1} + H_{a2} - \frac{dP_a}{dE_a}E_a$$

$$B_a = -2K_{aa} + K_{a1} + K_{a2} - \frac{dQ_a}{dE_a}E_a$$

Solving eqs 5, 7, 9, and 10 simultaneously, the synchronizing power coefficient for machine 1 is

$$\frac{dP_1}{d\delta_{12}} = \frac{\begin{vmatrix} K_{12} + K_{13} & -K_{12} & H_{1a} \\ -K_{a1} & -K_{a2} & A_a \\ H_{a1} & H_{a2} & B_a \end{vmatrix}}{\begin{vmatrix} -K_{a1} & -K_{a2} & A_a \\ H_{a1} & H_{a2} & B_a \\ 1 & -1 & 0 \end{vmatrix}} \quad (11)$$

Solving eqs 5, 8, 9, and 10 simultaneously, the synchronizing power coefficient for machine 2 is

$$\frac{dP_2}{d\delta_{21}} = \frac{\begin{vmatrix} -K_{21} & K_{2a} + K_{21} & H_{2a} \\ -K_{a1} & -K_{a2} & A_a \\ H_{a1} & H_{a2} & B_a \end{vmatrix}}{\begin{vmatrix} -K_{a1} & -K_{a2} & A_a \\ H_{a1} & H_{a2} & B_a \\ -1 & 1 & 0 \end{vmatrix}} \quad (12)$$

Equations 11 and 12 can be used as a measure of the ability of machines 1 and 2 to remain in static equilibrium for any given set of load conditions. That is, the larger the value of $dP/d\delta$ when positive, the greater will be the forces developed to keep the particular machine in question in synchronism. It will be noted that a change in the characteristics of the composite load affects only the terms A_a and B_a. This makes it possible to readily investigate the stability of machines 1 and 2 with change in the composite load characteristics.

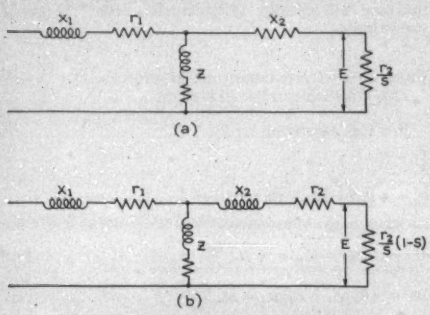


Fig. 1. Equivalent circuits of induction machines

If the composite load consists of an individual induction machine or a group of induction machines and E_a is the voltage across the equivalent secondary load resistance, $\frac{r_2}{s}$, of the induction machine equivalent circuit as in Fig. 1(*a*),

$$\frac{dQ_a}{dE_a} = 0 \text{ and } \frac{dP_a}{dE_a} = -\frac{2s^2nE_a}{r_2(sn - s + 1)} \text{ (Derived in Appendix VI.)}$$

Where n is defined by the equation,

$$T_m \propto (1 - s)^n$$

for the mechanical shaft torque of the induction machine. For example, $n = 0$ and $\frac{dP_a}{dE_a} = 0$ for a constant shaft torque load.

Case 2—Three Synchronous Machine Groups and One Composite Load

For this case,

$$\left.\begin{aligned} P_1 &= H_{11} + H_{12} + H_{13} + H_{1a} \\ P_2 &= H_{21} + H_{21} + H_{23} + H_{2a} \\ P_3 &= H_{31} + H_{31} + H_{32} + H_{3a} \\ P_a &= H_{a1} + H_{a2} + H_{a3} + H_{a3} \\ Q_a &= -K_{aa} + K_{a1} + K_{a} + H_{a3} \end{aligned}\right\} \quad (13)$$

For small changes eq 13 gives,

$$dP_1 = K_{12}d\delta_{12} + K_{13}d\delta_{13} + K_{1a}d\delta_{1a} + H_{1a}\frac{dE_a}{E_a} \quad (14)$$

$$dP_2 = -K_{21}d\delta_{12} + K_{23}d\delta_{23} + K_{2a}d\delta_{2a} + H_{2a}\frac{dE_a}{E_a} \quad (15)$$

$$dP_3 = -K_{31}d\delta_{13} - K_{32}d\delta_{23} + K_{3a}d\delta_{3a} + H_{3a}\frac{dE_a}{E_a} \quad (16)$$

$$0 = -K_{a1}d\delta_{1a} - K_{a2}d\delta_{2a} - K_{a3}d\delta_{3a} + A_a\frac{dE_a}{E_a} \quad (17)$$

$$0 = H_{a1}d\delta_{1a} + H_{a2}d\delta_{2a} + H_{a3}d\delta_{3a} + B_a\frac{dE_a}{E_a} \quad (18)$$

where for this case,

$$A_a = 2H_{aa} + H_{a1} + H_{a2} + H_{a3} - \frac{dP_a}{dE_a}E_a \quad (19)$$

$$B_a = -2K_{aa} + K_{a1} + K_{a2} + K_{a3} - \frac{dQ_a}{dE_a}E_a \quad (20)$$

The independent relations between the differential angles $d\delta_1$, $d\delta_2$, $d\delta_3$, and $d\delta_a$ are

$$\left.\begin{aligned} d\delta_{13} &= d\delta_{12} + d\delta_{23} \\ d\delta_{1a} &= d\delta_{13} + d\delta_{3a} \\ d\delta_{3a} &= d\delta_{32} + d\delta_{2a} \end{aligned}\right\} \quad (21)$$

If machines 1 and 2 divide their increments in load in the ratio

$$\frac{dP_2}{dP_1} = R,$$

$$dP_2 = RdP_1 \quad (22)$$

The ratio R may be determined by eq 27*a* of Appendix V.

$$R = \frac{C_2\alpha_1}{C_1\alpha_2} \quad (23)$$

If machine 2 is a constant power machine, $R = 0$.

Equations 14, 15, 17, 18, 21, and 22 may be solved simultaneously to determine $dP_1/d\delta_{12}$ or $dP_2/d\delta_{23}$; and 14–18, 21, and 22 for $dP_2/d\delta_{21}$ or $dP_3/d\delta_{32}$. The evaluation of the resulting determinants can be accomplished numerically without a great deal of difficulty for any given problem.

Additional Cases

Additional cases for any combination of machines and loads may be worked out by applying the general equations and the method outlined above.

Part II—Asynchronous Stability of Induction Machines

In certain cases it may be necessary to determine whether or not an induction machine when connected to a network, will operate at the specified operating conditions. An induction motor or generator will operate satisfactorily[6,7] if

$$\frac{dT_e}{ds} > \frac{dT_m}{ds} \quad (24)$$

where

T_e = electrical shaft torque
T_m = mechanical shaft torque
s = slip

The following analysis is based upon the assumption that the electrical shaft torque of an induction machine can be expressed by either of the 2 equations

$$T_e = \frac{I^2r_2}{s} \quad (25)$$

and

$$T_e = EI \quad (26)$$

where I is the secondary current, r_2 the secondary resistance, s the slip, and E the voltage across the equivalent secondary load resistance r_2/s. See Fig. 1(*a*).

Equations 25 and 26 yield for small changes,

$$dT_e = 2EdI - \frac{I^2 r_2}{s^2}\,ds \tag{27}$$

$$dT_e = EdI + IdE \tag{28}$$

Solving eqs 27 and 28 for ds in terms of T_e and dE,

$$ds = \frac{s^2}{I^2 r_2}\left[dT_e - 2IdE\right] \tag{29}$$

therefore,

$$\frac{dT_e}{ds} = \frac{I^2 r_2}{s^2}\left[\frac{\dfrac{dT_e}{dE}}{\dfrac{dT_e}{dE} - 2I}\right] \tag{30}$$

In the above analysis power into the induction motor has been considered positive; but, since the convention has been adopted that power into a machine from the system is negative, eq 30 becomes, in terms of network power,

$$\frac{dT_e}{ds} = \frac{I^2 r_2}{s^2}\left[\frac{\dfrac{dP_a}{dE_a}}{\dfrac{dP_a}{dE_a} + \dfrac{2E_a s}{r_2}}\right] \tag{31}$$

P_a and E_a are power from point a into the network and voltage at point a, respectively, E_a being the voltage across the equivalent induction motor load resistance, r_2/s.

Substituting eq 31 and 29*a* of Appendix VI in eq 24 and simplifying, the criterion for satisfactory operation of the induction machine is

$$\left[\frac{\dfrac{dP_a}{dE_a}}{\dfrac{dP_a}{dE_a} + \dfrac{2E_a s}{r_2}}\right] > -\frac{sn}{(1-s)} \tag{32}$$

Where n is defined by the equation,

$$T_m \propto (1-s)^n \tag{33}$$

$\dfrac{dP_a}{dE_a}$ in eq 32 depends upon the connected system and can be determined for any given case by means of the general equations for real and reactive power flow. Two relatively simple cases will be used to illustrate the method of determining $\dfrac{dP_a}{dE_a}$.

Case 1—One Synchronous Machine and One Induction Machine

For this case, from eq 1,

$$\left.\begin{aligned} P_1 &= H_{11} + H_{1a} \\ P_a &= H_{aa} + H_{a1} \\ Q_a &= -K_{aa} + K_{a1} \end{aligned}\right\} \tag{34}$$

For small changes eq 34 yields,

$$dP_1 = K_{1a}d\delta_{1a} + H_{1a}\frac{dE_a}{E_a} \tag{35}$$

$$dP_a = -K_{a1}d\delta_{1a} + (2H_{aa} + H_{a1})\frac{dE_a}{E_a} \tag{36}$$

$$dQ_a = H_{a1}d\delta_{1a} + (-2K_{aa} + K_{a1})\frac{dE_a}{E_a} \tag{37}$$

Since E_a is the voltage across the secondary load resistance of the induction machine, $\dfrac{dQ_a}{dE_a} = 0$. Equations 36 and 37 therefore can be written as follows,

$$\frac{dP_a}{dE_a} = -K_{a1}\frac{d\delta_{1a}}{dE_a} + \frac{2H_{aa} + H_{a1}}{E_a} \tag{38}$$

$$0 = H_{a1}\frac{d\delta_{1a}}{dE_a} + \frac{-2K_{aa} + K_{a1}}{E_a} \tag{39}$$

Solving eqs 38 and 39 simultaneously for $\dfrac{dP_a}{dE_a}$ in terms of the H and K constants,

$$\frac{dP_a}{dE_a} = \frac{1}{E_a}\left[\frac{K_{a1}}{H_{a1}}(-2K_{aa} + K_{a1}) + (2H_{aa} + H_{a1})\right] \tag{40}$$

For any given set of operating conditions dP_a/dE_a may be determined from eq 40 and then substituted in eq 33 to determine whether or not the induction machine will operate satisfactorily under the given conditions.

Case 2—Two Synchronous Machines and One Induction Machine

For this case from eq 1,

$$\left.\begin{aligned} P_1 &= H_{11} + H_{12} + H_{1a} \\ P_2 &= H_{22} + H_{21} + H_{2a} \\ P_a &= H_{aa} + H_{a1} + H_{a2} \\ Q_a &= -K_{aa} + K_{a1} + K_{a2} \end{aligned}\right\} \tag{41}$$

For small changes eq 41 yields,

$$dP_1 = K_{12}d\delta_{12} + K_{1a}d\delta_{1a} + H_{1a}\frac{dE_a}{E_a} \tag{42}$$

$$dP_2 = -K_{21}d\delta_{12} + K_{2a}d\delta_{2a} + H_{2a}\frac{dE_a}{E_a} \tag{43}$$

$$dP_a = -K_{a1}d\delta_{1a} - K_{a2}d\delta_{2a} + (2H_{aa} + H_{a1} + H_{a2})\frac{dE_a}{E_a} \tag{44}$$

$$dQ_a = H_{a1}d\delta_{1a} + H_{a2}d\delta_{2a} + (-2K_{aa} + K_{a1} + K_{a2})\frac{dE_a}{E_a} \tag{45}$$

Also

$$d\delta_{1a} = d\delta_{12} + d\delta_{2a} \tag{46}$$

$$dQ_a = 0 \tag{47}$$

$$dP_2 = RdP_1 \tag{48}$$

where R is the ratio of the division of the increment in power between the two synchronous machine groups, and is approximately equal to $\dfrac{C_2}{C_1}\dfrac{\omega_1}{\omega_2}$. (See Appendix V.) If synchronous machine 2 is a fixed power synchronous machine, $R = 0$.

Equations 42 to 48 can be solved simultaneously to obtain $\dfrac{dP_a}{dE_a}$.

Additional Cases

Additional cases of any combination of synchronous machines, induction machines, or composite loads, may be worked out by applying the methods presented above.

Appendix I—Equations for Real and Reactive Power

Equations for the real[3] and reactive power[3] in a balanced network may be derived as follows,

$$\bar{I}_j = \text{current at point } j = \frac{\bar{E}_j}{\bar{Z}_{jj}} - \frac{\bar{E}_k}{\bar{Z}_{jk}} \cdots - \frac{\bar{E}_n}{\bar{Z}_{jn}} \tag{1a}$$

$$P_j = \text{real power} = \overline{E}_j \cdot \overline{I}_j$$
$$= \frac{E_j^2}{Z_{jj}} \cos \theta_{jj} - \frac{E_j E_k}{Z_{jk}} \cos (\delta_{jk} + \theta_{jk}) \ldots - \frac{E_j E_n}{Z_{jn}} \cos (\delta_{jn} + \theta_{jn})$$
$$= \frac{E_j^2}{Z_{jj}} \sin \alpha_{jj} + \frac{E_j E_k}{Z_{jk}} \sin (\delta_{jk} - \alpha_{jk}) \ldots + \frac{E_j E_n}{Z_{jn}} \sin (\delta_{jn} - \alpha_{jn})$$
$$= H_{jj} + H_{jk} \ldots + H_{jn} \tag{2a}$$

$$Q_j = \text{reactive power} = \text{scalar value of } \overline{E}_j \times \overline{I}_j$$
$$= -\frac{E_j^2}{Z_{jj}} \cos \alpha_{jj} + \frac{E_j E_k}{Z_{jk}} \cos (\delta_{jk} - \alpha_{jk}) \ldots + \frac{E_j E_n}{Z_{jn}} \cos (\delta_{jn} - \alpha_{jn})$$
$$= -K_{jj} + K_{jk} \ldots + K_{jn} \tag{3a}$$

where

$$H_{jj} = \frac{E_j^2}{Z_{jj}} \sin \alpha_{jj}$$

$$H_{jk} = \frac{E_j E_k}{Z_{jk}} \sin (\delta_{jk} - \alpha_{jk})$$

$$K_{jj} = \frac{E_j^2}{Z_{jj}} \cos \alpha_{jj}$$

$$K_{jk} = \frac{E_j E_k}{Z_{jk}} \cos (\delta_{jk} - \alpha_{jk})$$

Appendix II—Real and Reactive Power-Voltage Characteristics of an Impedance Load

The real and reactive power into the system from an impedance load can be expressed as follows,

$$P_a = -\frac{E_a^2}{Z} \cos \theta \tag{4a}$$

$$Q_a = \frac{E_a^2}{Z} \sin \theta \tag{5a}$$

where

Z = impedance of load
θ = impedance angle of Z

Therefore,

$$\frac{dP_a}{dE_a} = -\frac{2E_a}{Z} \cos \theta = \frac{2P_a}{E_a} \tag{6a}$$

$$\frac{dQ_a}{dE_a} = \frac{2E_a}{Z} \sin \theta = \frac{2Q_a}{E_a} \tag{7a}$$

Equations 6a and 7a define the real and reactive power-voltage characteristics of an impedance load.

Appendix III—Real and Reactive Power-Voltage Characteristics of Induction Machine

An induction machine may be represented[4] by the circuit of Fig. 2, where E_a is the terminal voltage and E_b the voltage across the equivalent shaft load resistance. From eq 1, the following relations can be written,

$$\left.\begin{aligned} -P_a &= H_{aa} + H_{ab} \\ -Q_a &= -K_{aa} + K_{ab} \\ P_b &= H_{bb} + H_{ba} \\ Q_b &= -K_{bb} + K_{ba} \end{aligned}\right\} \tag{8a}$$

For small changes these equations yield,

$$-dP_a = K_{ab} d\delta_{ab} + (2H_{ab} + H_{ab}) \frac{dE_a}{E_a} + H_{ab} \frac{dE_b}{E_b} \tag{9a}$$

$$-dQ_a = -H_{ab} d\delta_{ab} + (-2K_{aa} + K_{ab}) \frac{dE_a}{E_a} + K_{ab} \frac{dE_b}{E_b} \tag{10a}$$

$$dP_b = -K_{ba} d\delta_{ab} + (2H_{bb} + H_{ba}) \frac{dE_b}{E_b} + H_{ba} \frac{dE_a}{E_a} \tag{11a}$$

$$dQ_b = H_{ba} d\delta_{ab} + (-2K_{bb} + K_{ba}) \frac{dE_b}{E_b} + K_{ba} \frac{dE_a}{E_a} \tag{12a}$$

Since Q_b is constant and equal to zero, $dQ_a = 0$. Substituting this value in eq 11a and solving eq 11a and 12a simultaneously with 9a and 10a, respectively, there results,

$$\frac{dP_a}{dE_a} = -\frac{(2H_{aa} + H_{ab}) + AK_{ab} + BH_{ab}}{E_a} \tag{13a}$$

$$\frac{dQ_a}{dE_a} = +\frac{(2K_{aa} - K_{ab}) + AH_{ab} - BK_{ab}}{E_a} \tag{14a}$$

where

$$A = \frac{2H_{bb}K_{ba} + 2K_{bb}H_{ba} - K_{ba}E_b \dfrac{dP_b}{dE_b}}{+K_{ba}(2K_{bb} - K_{ba}) - H_{ba}\left(2H_{bb} + H_{ba} - E_b \dfrac{dP_b}{dE_b}\right)} \tag{15a}$$

$$B = \frac{K_{ba}^2 + H_{ba}^2}{+K_{ba}(2K_{bb} - K_{ba}) - H_{ba}\left(2H_{bb} + H_{ba} - E_b \dfrac{dP_b}{dE_b}\right)} \tag{16a}$$

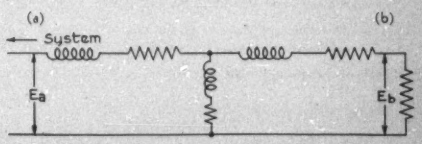


Fig. 2. Equivalent circuit of an induction machine

Equations 13a and 14a define the real and reactive power-voltage characteristics of the induction machine. $\frac{dP_b}{dE_b}$ depends upon the mechanical shaft load of the induction machine and as shown in Appendix VI can be expressed in terms of the initial quantities as follows, when E_b is the voltage across the equivalent secondary load resistance r_2/s,

$$\frac{dP_b}{dE_b} = -\frac{2s^2 n E_b}{r_2(sn - s + 1)} \tag{17a}$$

where

$n = 0$ for constant shaft torque
$n = 1$ for a shaft torque which varies directly with the speed.

If E_b is taken as the voltage across the equivalent shaft load resistance, $\frac{r_2}{s}(1 - s)$ instead of across $\frac{r_2}{s}$, $\frac{dP_b}{dE_b} = 0$ for a constant shaft power load. (See Fig. 1(*b*).)

Equations 9a to 12a inclusively, may be used in reducing or simplifying a complicated composite load network, as well as determining the characteristics of induction machines. That is, if $\frac{dP_b}{dE_b}$ and $\frac{dQ_b}{dE_b}$ are known at a point *b* in a network $\frac{dP_a}{dE_a}$ and $\frac{dQ_a}{dE_a}$ at point *a* may be determined.

Appendix IV—Power-Voltage Characteristics of a Constant Power Synchronous Machine (Saturation and Resistance Neglected)

The steady state vector diagram of a salient pole synchronous machine[6] is shown in Fig. 3. E_a is the terminal voltage and E_i the internal voltage.

From Fig. 3,

$$\bar{E}_a = E_a \cos \delta_{1a} - jE_a \sin \delta_{1a} \tag{18a}$$

$$\bar{i}_a = i_q - ji_d = \frac{E_a \sin \delta_{1a}}{x_q} - j\frac{E_1 - E_a \cos \delta_{1a}}{x_d} \tag{19a}$$

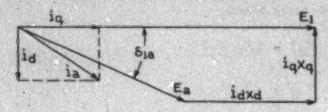


Fig. 3. Vector diagram of salient pole synchronous machine

The real and reactive power into the system may be expressed as

$$P_a = \bar{E}_a \cdot \bar{i} = \frac{E_1 E_a}{x_d} \sin \delta_{1a} + \frac{E_a^2(x_d - x_q)}{2x_d x_q} \sin 2\delta_{1a} \tag{20a}$$

$$Q_a = \text{scalar value of } \bar{E}_a \times \bar{i}_a = -\frac{E_1 E_a}{x_d} \cos \delta_{1a} + E_a^2 \left[\frac{1}{x_d} + \frac{x_d - x_q}{x_d x_q} \sin^2 \delta_{1a}\right] \tag{21a}$$

For small changes and $dP = 0$, eq 20*a* yields

$$\frac{d\delta_{1a}}{dE_a} = -\frac{[E_1 x_q \sin \delta_{1a} + E_a(x_d - x_q) \sin 2\,\delta_{1a}]}{E_a[E_1 x_q \cos \delta_{1a} + E_a(x_d - x_q) \cos 2\delta_{1a}]} \tag{22a}$$

For small changes eq 21*a* yields,

$$\frac{dQ_a}{dE_a} = \frac{1}{x_d x_q}[-E_1 x_q \cos \delta_{1a} + 2E_a x_q + 2E_a(x_d - x_q) \sin^2 \delta_{1a}] + \frac{E_a}{x_d x_q}[E_1 x_q \sin \delta_{1a} + E_a(x_d - x_q) \sin 2\delta_{1a}] \frac{d\delta_{1a}}{dE_a} \tag{23a}$$

Substituting eq 22*a* in eq 23*a* and simplifying

$$\frac{dQ_a}{dE_a} = \frac{-E_1^2 x_q^2 + E_1 E_a x_q \cos\delta_{1a}[3x_q - x_d] + 2E_a^2(x_d - x_q)[x_q \cos^3\delta_{1a} - x_d \sin^2\delta_{1a}]}{x_d x_q[E_1 x_q \cos \delta_{1a} + E_a(x_d - x_q) \cos 2\delta_{1a}]} \tag{24a}$$

For the case of a cylindrical rotor machine, $x_d = x_q$, and

$$\frac{dQ_a}{dE_a} = \frac{1}{x_d}[2E_a - E_1 \sec \delta_{1a}] \tag{25a}$$

Equations 24*a* and 25*a* define the reactive power-voltage characteristics of a salient pole machine and a cylindrical rotor machine, respectively, with constant shaft load when resistance and saturation are neglected.

The real-power voltage characteristic of such machines is

$$\frac{dP}{dE_a} = 0$$

Appendix V—Proportioning of Load Between Generator Groups With Increase in System Load

When an additional load, dP, is placed on the system,[6] the following general equation may be used to determine approximately the load division between the generator groups,

$$dP_n = \frac{\dfrac{C_n}{\alpha_n}}{\dfrac{C_1}{\alpha_1} + \dfrac{C_2}{\alpha_2} \cdots + \dfrac{C_n}{\alpha_n}} dP \tag{26a}$$

where

dP_n = additional load on machine n
α_1 = per unit governor regulation of machine group 1
α_n = per unit governor regulation of machine group n
C_1 = per unit generator capacity of machine group 1
C_n = per unit generator capacity of machine group n

The ratio R between the power increment of any 2 generator groups is therefore simply,

$$R = \frac{dP_2}{dP_1} = \frac{C_2\alpha_1}{C_1\alpha_2} \tag{27a}$$

Appendix VI—Real Power-Secondary Voltage Characteristic of Variable Shaft Load Induction Machine

For the case when the mechanical shaft load is a function of the speed,

$$T_m = k(1 - s)^n \tag{28a}$$

and

$$dT_m = -kn(1 - s)^{n-1}\, ds$$

Since,

$$k = \frac{E^2 s}{r_2(1 - s)^n}$$

$$\frac{dT_m}{ds} = -\frac{E^2 sn}{r_2(1 - s)} \tag{29a}$$

where E is the voltage across the secondary load resistance r_2/s.

However, the electrical torque,

$$T_e = \frac{E^2 s}{r_2} \tag{30a}$$

and

$$dT_e = \frac{E^2}{r_2} ds + \frac{2Es}{r_2} dE \tag{31a}$$

Solving 29*a* for ds and substituting in eq 31*a*

$$dT_e = -\frac{(1 - s)}{sn} dT_m + \frac{2Es}{r_2} dE \tag{32a}$$

$dT_m = dT_e$ under steady state conditions, therefore,

$$\frac{dT_e}{dE} = \frac{2s^2 nE}{r_2(sn - s + 1)} \tag{33a}$$

or in terms of network power and voltage,

$$\frac{dP_a}{dE_a} = -\frac{2s^2 nE_a}{r_2(sn - s + 1)} \tag{34a}$$

Where $E_a = E$, the voltage across the secondary resistance r_2/s and P_a is the real power at point (a) into the network.

When $n = 0$, constant shaft torque load,

$$\frac{dP_a}{dE_a} = 0$$

References

1. Power Limits of Synchronous Machines, Edith Clarke and R. G. Lorraine. Electrical Engineering, Nov. 1933, p. 780–7.
2. Static Stability Limits and the Intermediate Condenser Station, C. F. Wagner and R. D. Evans. A.I.E.E. Trans., v. 47, 1928, p. 94–121.
3. Progress in the Study of System Stability, I. H. Summers and J. B. McClure. A.I.E.E. Trans., v. 49, 1930, p. 133–58.
4. Principles of Alternating Current Machinery (a book), R. R. Lawrence. McGraw-Hill Book Co., Inc., first ed., 1916, p. 452–4.
5. System Stability as a Design Problem, R. H. Park and E. H. Bancker, A.I.E.E. Trans., v. 48, 1929, p. 170–90.
6. Synchronous Machines—I; Part II. Steady State Power-Angle Characteristics, R. E. Doherty and C. A. Nickle. A.I.E.E. Trans., v. 45, 1926, p. 927–929.
7. Theory and Calculation of Electrical Apparatus (a book), C. P. Steinmetz. McGraw-Hill Book Co., Inc., first ed., 1917, chap. VI.